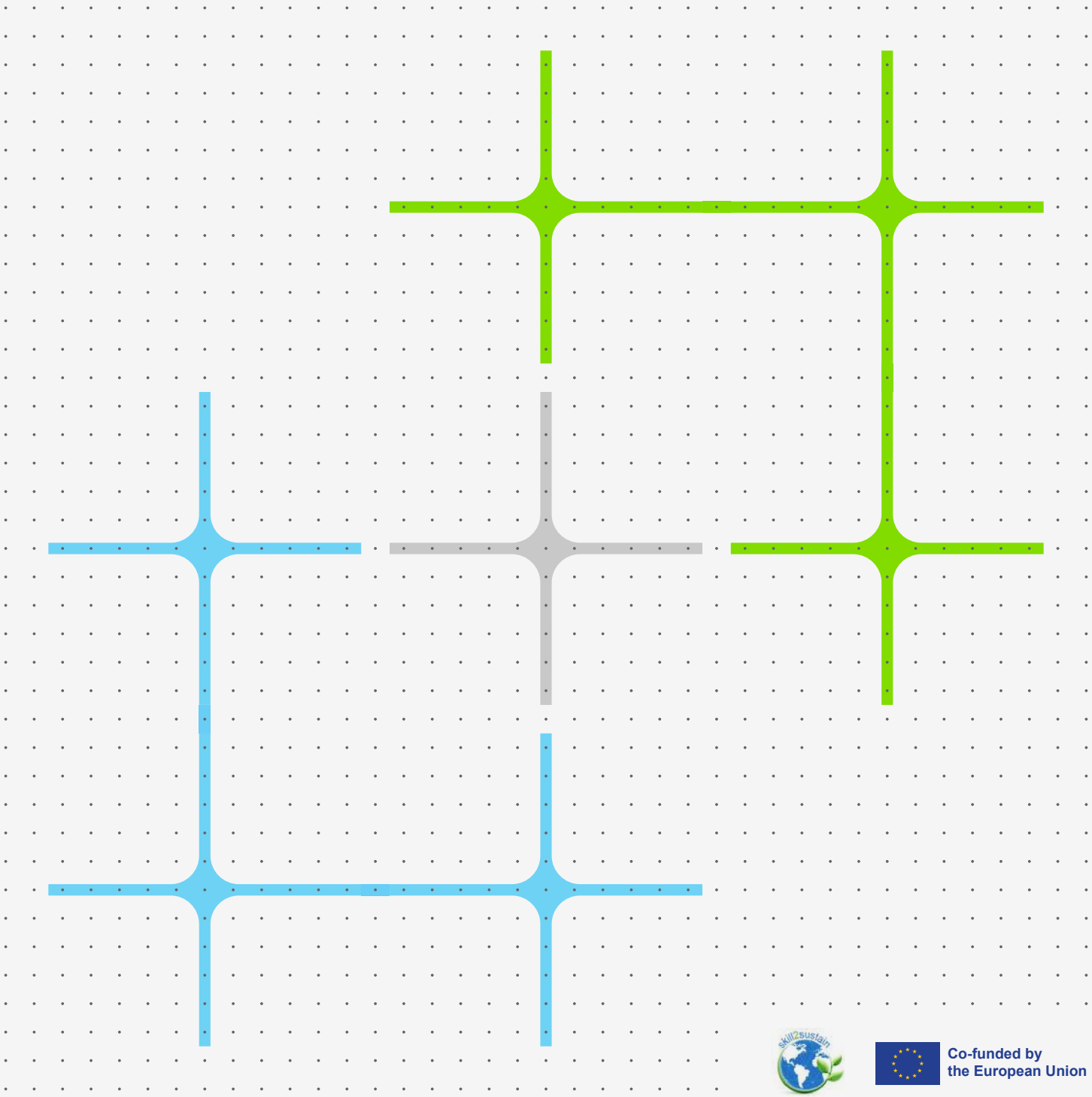
Boosting digital and green skills for a resilient and sustainable Western Balkan society

SKILL2SUSTAIN Symposium 2026 – Proceedings
1–3 September, 2026, Kotor (MNE)



Co-funded by
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Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.



Boosting digital and green skills for a resilient and sustainable Western Balkan society

SKILL2SUSTAIN Symposium 2026 – Proceedings
1–3 September, 2026, Kotor (MNE)

Publisher

NVO „Građevinarstvo – Nauka i praksa (GNP)“ (MNE)

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CIP - Katalogizacija u publikaciji
Nacionalna biblioteka Crne Gore, Cetinje

ISBN 978-9911-9616-1-7
COBISS.CG-ID 39153668

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Preface

The green and digital transitions are no longer separate processes shaping the future of our societies. They increasingly represent an interconnected transformation that requires new knowledge, new skills, and new forms of cooperation among universities, industry, public institutions, and society as a whole. For the Western Balkans, responding successfully to these changes is particularly important in the context of sustainable development, economic competitiveness, climate resilience, and stronger integration into the European research and education area.

This volume of proceedings, **Boosting Digital and Green Skills for a Resilient and Sustainable Western Balkan Society**, brings together **43 scientific and professional papers authored and co-authored by 86 researchers and professionals** from the Western Balkans and Europe. The diversity of topics, institutions, and professional backgrounds represented in this volume confirms that the green and digital transition requires an interdisciplinary approach and an exchange of knowledge that extends beyond the boundaries of individual disciplines and countries.

The contributions address a broad range of contemporary challenges – from the modernization of higher education, innovative curricula, and lifelong learning, through the application of BIM, GIS, artificial intelligence, and other digital technologies, to climate resilience, disaster risk management, circular economy, sustainable construction, and alignment with European policies. What connects these topics is the recognition that knowledge, competencies, and the ability to apply them in practice are among the key prerequisites for the sustainable transformation of the region.

The Symposium, held in **Kotor from the 1st to 3rd September 2026**, provides an opportunity to bring these different perspectives together and foster dialogue among researchers, educators, professionals, policymakers, and other stakeholders. Kotor itself offers a particularly meaningful setting for such discussions – a place where cultural heritage, the built environment, natural values, infrastructure, tourism, and the challenges of resilience coexist within a unique and sensitive context. It therefore provides an inspiring environment for considering how science, education, innovation, and responsible development can contribute to a more sustainable future.

We hope that these Proceedings will serve not only as a lasting record of the scientific and professional contributions presented at the Symposium, but also as a useful reference for future research, education, policy development, and practical cooperation. More importantly, we hope that the exchange of ideas initiated through these papers and the meetings in Kotor will continue through new joint initiatives and stronger connections among higher education institutions, researchers, professionals, businesses, public institutions, and students across the Western Balkans and Europe.

We would like to express our particular gratitude to the **European Union**, which through the **Erasmus+ Programme** co-funds the **SKILL2SUSTAIN – Boosting Digital and Green Skills for a Resilient and Sustainable Western Balkan Society (Project No. 101178204**) project, within which this Symposium is organized. We also extend our sincere appreciation to all authors, keynote lecturers, reviewers, members of the Scientific and Organizing Committees, project partners, and institutions whose knowledge, work, and commitment have made both the Symposium and these Proceedings possible.

The Editors
Miloš Knežević, Željka Beljkaš, Marina Rakočević
University of Montenegro (MNE)

T01

Keynote Lecturers

Sustainability of Cultural Heritage – Case Study of Kotor

[Ilija Lalošević][1]

Abstract

The paper is dealing with sustainability and structural characteristics of historic buildings in the old urban core of medieval town of Kotor, and its region, inserted on the World Heritage List after Montenegro earthquake 1979. Kotor case study proved that all historic buildings are not weak simply because they are old and made of stone masonry. Some historic buildings, like some modern buildings, are weak because they were poorly and unskillfully built, they were inadequately altered during their history, or because they were bad maintained. Some historic buildings are resilient due to good materials used, the quality of workmanship, design and disposition.

The configuration of the structure, as well as type and quality of materials and elements are often not sufficiently appreciated by engineers and architects dealing with renewal of historic buildings. Successful strengthening and repair of historic buildings should be based on an evaluation of sustainability and resistance of their original structure, and careful choice of strengthening techniques.

In the paper aspects of sustainability of traditional buildings are discussed, focusing on the most important Kotor historic buildings and seismic aspect. The principal seismic properties of traditional historic structures are presented based on their seismic behavior. Recommendations for improving the evaluation procedures and choosing appropriate strengthening techniques for similar historic structures are made.

Keywords

Cultural heritage, sustainability, Kotor, seismic resistance, structural characteristics, consolidation.

[1] *Full Prof, PhD, Faculty of Architecture, Univerity of Montenegro, ilalos@t-com.me, ilijal@ucg.ac.me*

1. Introduction

When dealing with structural consolidation and conservation of historic buildings, the extremely variable quality of building materials and construction systems is evident. Except for timber buildings, most historic structures are unframed masonry buildings, made of unburned earth, brick, or stone, connected with binding mediums. Each of these materials varies widely in form and mechanical and other properties.

Masonry structures generally are considered to be less resistant to earthquakes. Masonry materials, both mortar and stone/brick are stiff and brittle, have quite high compressive, but low tensile and shear strength. Masonry constructions have a high mass, hence their high inertial response to the earthquakes, they are rigid and have low ductility and low capacity for redistribution of stress.

However, the resistance of historic buildings can vary between quite good and poor, depending on the conditions of the building affected. The 1979 Montenegro earthquake brought to light, among disadvantages, numerous advantages and qualities of the traditional way of constructing historic buildings, especially in the Kotor region, included in the UNESCO's World Heritage List. Due to the conditions after the earthquake and treats of destructions, especially having in mind high concentration of the cultural heritage, the old urban core of Kotor (fig 1) within the medieval walls was also inserted in the World Heritage in Danger List. After successfully preservation and reconstruction works the town was withdrawn from the World Heritage in Danger List in 2003.



***Figure 1** – Kotor, Old Town with the fortress*

By exploring the previous earthquake history, by analyzing relevant data, dates of occurrences, intensities, magnitudes etc., and by "in situ" investigations, continuity and interruptions in the "local seismic culture" could be better understood and followed. The shorter the return periods are, the most widespread seismic culture is. Due to the numerous earthquakes (dates and intensities of the stronger earthquakes: 1559-IX, 1563-X, 1608-X, 1632-IX, 1639-IX, 1667-X, 1750-VIII, 1780-IX, 1979-X), [1], 15-17, good building tradition,

and economic prosperity during Byzantine, Serbian and Venetian role, in the Kotor region there are evidences of the appropriate construction technical procedures.

2. Location

One of the most significant issues to be analyzed regarding settlements, ensembles and individual buildings, is their location. The part of the old town of Kotor on the foot of San John Hill, funded on the rock, suffered slight damage during the earthquakes, and still have preserved the highest concentration of the oldest buildings from XII and XIII century. One of the reasons of collapse of the belfries and western facade of St. Tryphon's Cathedral in the 1667 earthquake, was different movement of the two parts of the building, due to the kind of soil (rock-send), fig. 5.

Settlements built on the rock (Perast, fig. 2., Drazin Vrt) suffered less damage than those funded on the mealy ground (Risan, Prcanj, Dobrota), even with identical or very similar design and quality of structures. It is interesting to point out the example of the churches built on the monolithic stone (St. George, Orahovac, fig. 3.) and island (St. George Monastery, Perast), suffered less damage than other similar relevant cases (Our Lady of the Rock Church on the artificial island etc.).



Figure 2 *– Perast, coastal settlement*



Figure 3 *– Orahovac, St. George Church, XIII-XIX c.*

3. Design and Disposition

Although criteria for earthquake resistant design have been established for the new buildings, [2], they can be usefully applied to the existing ones, both before the earthquake, to assess their vulnerability, and "post festum", to explain their behavior during the seismic events.

The building configuration, structural form, and design, have significant effects on the relevant conduct during an earthquake. The Montenegro 1979 earthquake, like many others, demonstrated that the simplest structures have the greatest chance of survival. *Simple* buildings are sustainable, can easily be built, maintained and repaired. On the other hand, their response to the earthquake can relatively easily be analyzed and determined.

It has been also recognized that the building plan in general is *symmetrical.* Symmetry simplifies construction and improves response to earthquakes. If center of mass, through which the earthquake forces act, coincide with the center of rigidity, which is the point of resistance to the earthquake forces, there will be no torsion forces affecting the building. On the contrary, lack of symmetry, which is rather rare case with historic buildings, produces torsion effects, which can be very destructive.

For the most number of the relevant historic buildings their overall shape is *compact* and *not too elongated.* Otherwise, there are more chances of different earthquake movements being applied to the terminals. Elongated plan (60 x 6 m), beside sand soil, and lot of changes during building history, has been the main reason for the collapse of the central part of the Prince's Palace at Kotor during the 1979 earthquake (fig 4). Fortunately, the cases with extreme discrepancy between horizontal dimensions in traditional architecture are rather rare.



***Figure 4** – Kotor, Pince's Palace, ("Palazzo del Provveditore") XVIc, 15.04.1979.*

Although the excitement and the damage of the building depend upon the relationship between its natural frequency and the frequency of the earthquake, general recommendation is: the building *should not be too high.* Actually, usual height of a historic building in the relevant region doesn't exceed its fourfold shorter horizontal dimension, recommended for the modern buildings. [2], 82. That's why overturning effects are rather rare in the case of historic buildings.

Of course the exceptions are belfries. For instance, as already mentioned, in the occasion of severe 1667 earthquake two belfries of the Romanesque St. Tryphon Cathedral

(fig. 5.) collapsed at all ("restanno atterati li doi Campanili del Duomo…").[2] The influence of that earthquake on the local seismic culture, can be seen in the fact that the belfries built after 1667 had no damage at all, during the recent 1979 earthquake. Much more damage suffered similar structures from XIX and the beginning of XX century, because of "seismic oblivion" and loss of traditional building techniques.

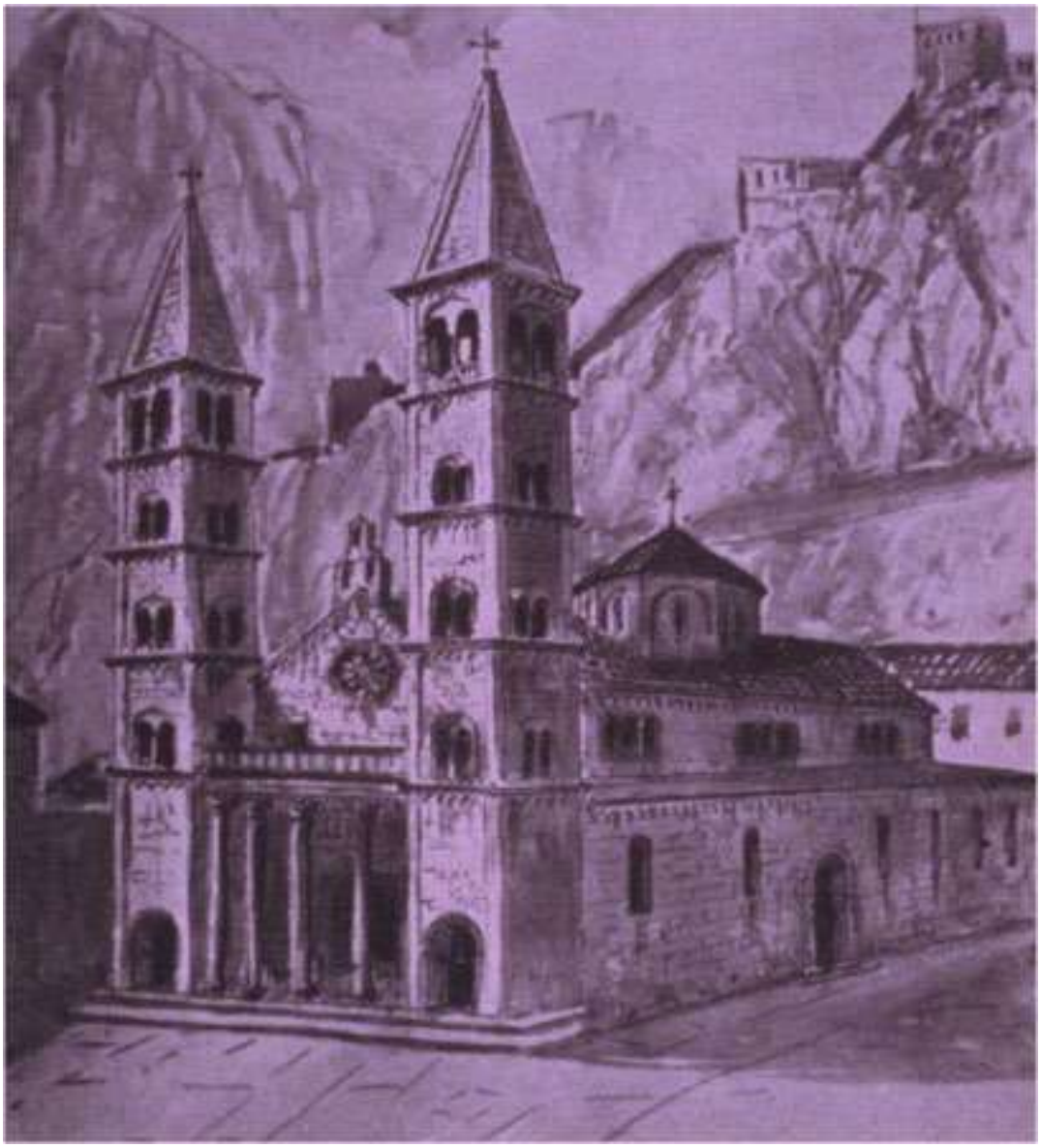


Figure 5 *– S. Tryphon Cathedral, Kotor, Ideal reconstruction, XII c.*

It is also important that the building *vertical cross-section is regular,* setbacks and especially reverse setbacks, i.e. enlargements in the building upper region should be avoided. Still, in some cases, functional reasons dictated exactly like irregular vertical cross section, for example at belfries. It is well known that St. Luke's Church belfry collapsed and was rebuilt a several times during 800 years of the building history (fig 11, 12.) [5], 59.

The most representative palaces in the Kotor Bay, built by captains and ship-owners under the influence of Venetian architecture, have the main facades with added central upper part which form loft (Italian: "belvedere"). Although originally there were attempts to connect this part with the rest of the building (with iron ties and wooden beams), during an earthquake the high stress concentration occurs at the region of discontinuity, producing cracks, partial,

[2] *Historical Archives, Kotor, SN, 934*

or even total collapse of the central part (fig 6). It is interesting to point out that palaces with "belvedere" mostly have been built in the second half of XVIII century, hundred years after the 1667 earthquake, enough to surmount the fear of destruction and to decrease "the local seismic culture", [4], 173.



Figure 6 *– Tripkovic Palace, Dobrota-Kotor, XVIII c., 15.04.1979.*

Irregularity is appearing in dome churches cross section too. However, these constructions vary radically in their seismic response, depending on their size, shape and whole construction system of upper parts of the building. For instance, at the primary dome of St. Tryphon's Cathedral, (fig. 5.), which was collapsed in 1667 earthquake, appeared problem of discontinuity of construction, and self-standing pillars, non-adequate elements carrying the heavy dome, and suffering from extreme seismic vibrations (effect of so called "soft ground-floor"), fig. 7.

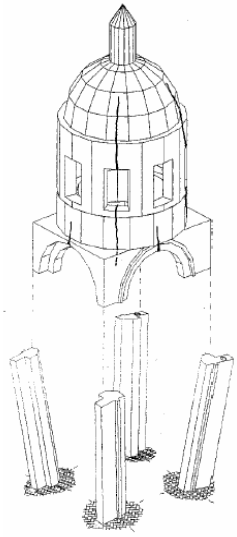


Figure 7 *– Typical Earthquake Damage to Cupola / Dome & Pillars*

The St. Mary of the River Church's (fig 8,9,10.) and St. Luke Church's domes have been conceived and built more adequately; their narrowing and discontinuity are less expressed. They have been carried by strong pilasters and transversal and attached arches, which are in monolith connection with walls and vaults. In the base of the dome, there is a ring made of long slates of excellent stone which successfully accepts forces and gathers all arches.



Figure 8 *– S. Marry of the River Church, Kotor, XIII c.*



Figure 9 *– S. Marry of the River Church, Kotor, XIII c, interior*

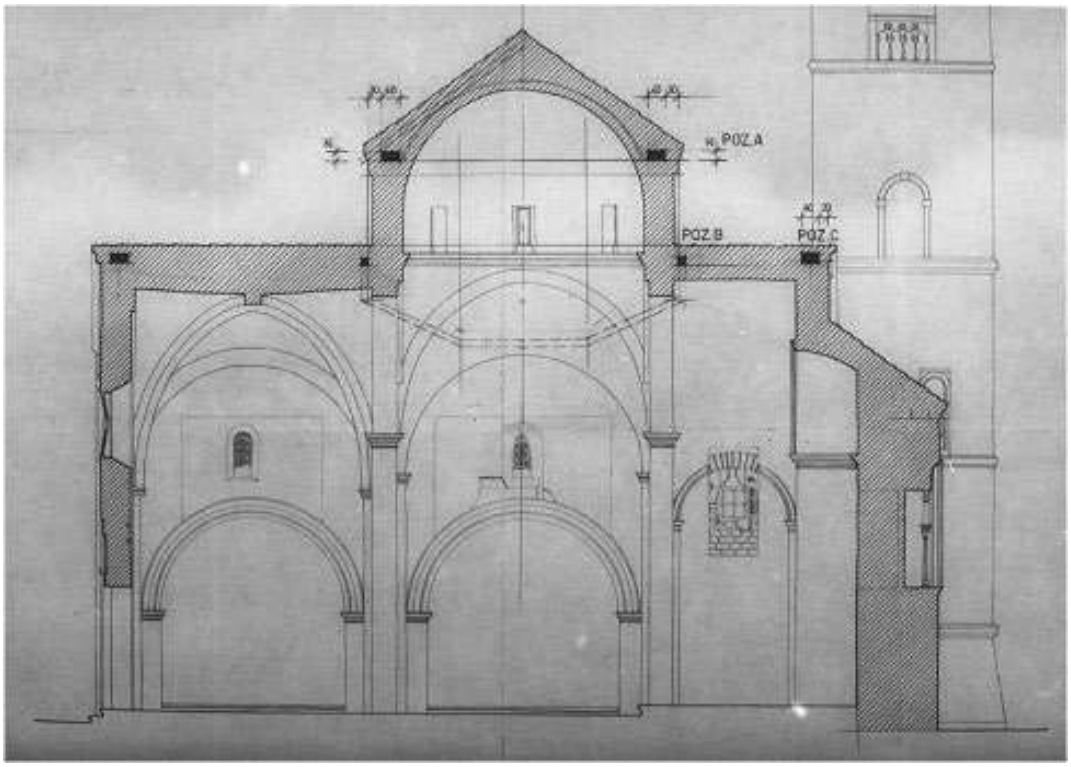
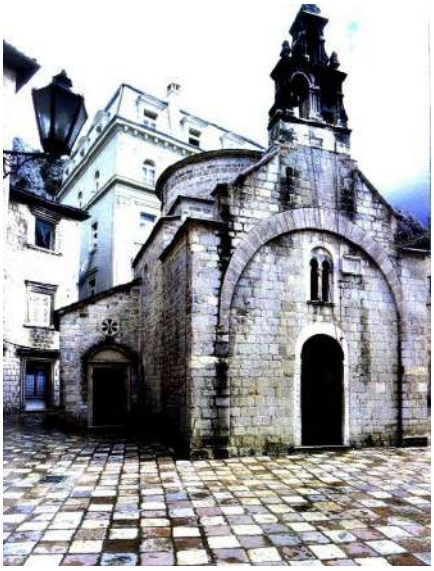


Figure 10 *– S. Marry of the River Church, Kotor, XIII c, cross section*

At St. Luke's Church, above the mentioned ring there are two additional rows of long (45-55 cm) and low (13, 10 cm) very precisely dressed slates of the same stone (fig 11, fig 12). This certain collar, made completely reconcile with contemporary theories, [5], 171,180, had a crucial role in reception tensile forces in the base of the dome, and had a significant contribution in stability of whole building [6], 58. Such a way of constructing a circular tie in the bottom of the dome is already known from the much older Byzantine buildings, where were some cases with stone blocks connected with iron anchors, so they can behave as a kind of a chain [7], 50. In order to improve overall, and in the same time seismic stability, upper part of the dome very often was made of lightweight stone, tuff.



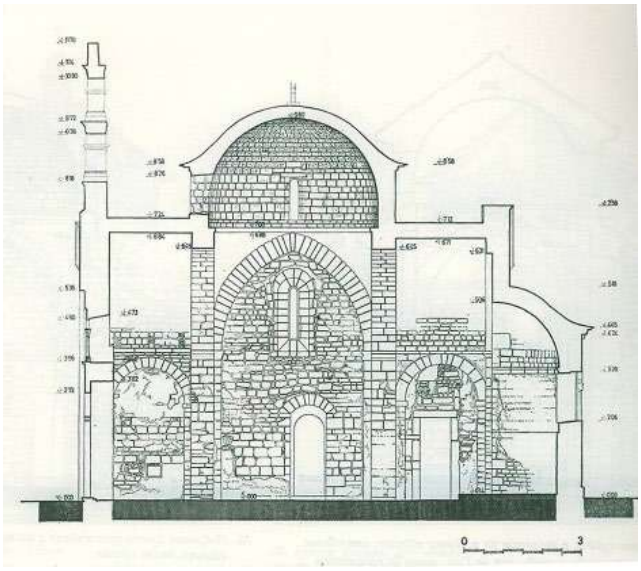


Figure 11 *– S. Luke Church, Kotor, XII c.*	***Figure 12*** *– Luke Church, Kotor, XII c, cross section*

St. Luke's and St. Mary of the River churches have during the eight centuries' long history kept the authentic structure, despite numerous strong earthquakes. However, during the period when these churches were built, there were no recorded strong earthquakes, while the seismic components were taken from the previous construction practice. This hypothesis would be in line with often mentioned relationship between those churches with the building constructions of Puglia (Italy) and Byzantine area, two seismically very sensitive regions [8], 148, 151 [9], 136. The good seismic response of these churches is closely connected with typological characteristics of the medieval Byzantine "inscribed cross churches," [10], as well as by local and Romanesque building practice.

Those, as well as other historic earthquake–proof buildings have quite *uniform and continuous distribution of strength*. Their load bearing elements are uniformly distributed, continuous and without changing section suddenly. Should be noted similarity of St. Luke's Church, the most successful seismic-proof historic building in Kotor, with the prescriptions of the much later Piro Ligurio's manuscript manual (fig 12.).[3]

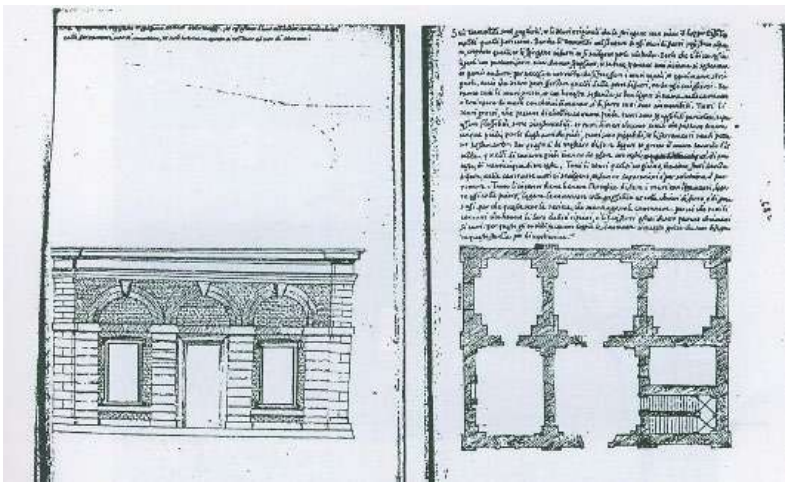


Figure 13 *– Pirro Ligorio: Delli rimedi contra I terremoti per la sicurezza degli edifici, vol.XVIII, State Archive Torino*

[3] *Proposal of an earthquake-proof house ("casa antisismica") in manuscript: Pirro Ligorio, Delli rimedi contra I terremoti per la sicurezza degli edifici, vol. XVIII, State Archive Torino, Published in: Costruire in Laterizio, 16/90, Interventi in zone sismiche, II, Milano, 1990, 249*

4. Elements and Techniques

Reasonable resistance of the historic buildings can be often explained by the evidence of suitable traditional techniques. Study of old techniques and elements is essential in the process of repair and strengthening of historic buildings, whatever traditional or modern techniques being applied.

The *walls* of the historic buildings in the Boka Kotorska Bay were made of the local limestone, as binding medium always was used lime mortar. The local limestone is too hard and non-adequate for the elements of more remarkable dimensions, that's why for the doors and windows frames, consoles, balconies, stairs etc., have been used limestone from Korčula island, near Dubrovnik. It is interesting to point out that the way of wall construction was almost the same from XIV to the end of XIX century.

There are two stone faces of the wall: external and internal; in the middle there is mixture of smaller pieces of stone and lime mortar. It wasn't practiced to connect two faces of the wall by bond headers, even this should be the case. Despite of this fact, evidence of detachment of the two faces of the wall is rather rare, due extremely good quality of *mortar* used. For instance, during restoration works sometimes stone cracks before the mortar in the joint. Due to the good quality of mortar and masonry, various phases of the building are not resulting cracks along the joint, even during strong earthquakes.

There were various types of mortar: with addition of oil, brick dust, red earth ('terra rossa") etc., They were used for the different purposes, from foundations, to the pointing, but the quality is usually very good. Wall mortar is one of the main reasons for the survival of masonry structures during earthquakes in the long building history of Boka Kotorska region.

Not earlier than in XIX century, were beginning both oblivion of traditional technologies for the preparation of mortar, as well as striving for becoming cheaper masonry and the building as a whole, causing lower constructive characteristics of the walls.

It is important to point out the difference between qualities of the walls, taking into account the sort, mechanical characteristics and the shape of stone blocks. For instance, the walls of Romanesque buildings have a very good seismic response, due to mechanical characteristics of the local limestone and its nature due to whom it is taking out of the quarry in the shape of the elongated blocks. Such walls, with good mortar applied; transmit horizontal seismic forces well, due to the resistance between the layers of masonry elements, depending on mortar shear strength, friction between contacting horizontal joints, and proportions of stone ashlars.

Walls strengthen with *pilasters*, especially in churches, carrying the dome, contribute to the raise of inertial moment of the building and to its overall stability. Those elements were suggested by mentioned old manuals for the improvement of the building earthquake resistance.[4]

Walls with similar elements, *buttresses* and *escarpments,* used for various purposes, for example fortifications (fig. 14)[5] of course, have also good seismic response, being conceived and designed to be strong enough to accept artillery shots.

[4] Proposal of an earthquake-proof house ("casa antisismica") in manuscript: Pirro Ligorio, op. cit.
[5] Archivio di Stato Venezia, Provveditori di Terra e da Mar, F. 432 / dis.1, a. Malacreda Cesare, 1616.

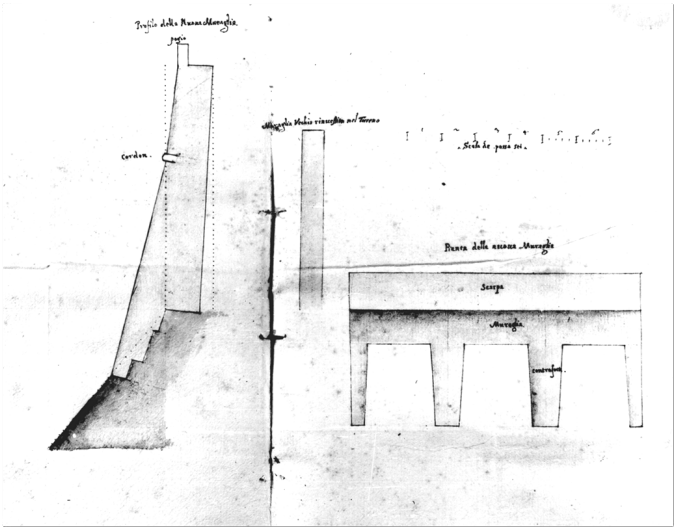


Figure 14 *– Archivio di Stato Venezia, Provveditori di Terra e da Mar, F. 432 / dis.1, a C. Malacreda, 1616.*

Vaults and *arches* are very often used constructive elements, playing crucial role in the earthquake stability of the buildings. Not adequately executed arches, especially vaults, usually cause strong damage and even collapse of the whole structure. On the other hand, some of them, especially pointed arches precisely cut out from the good limestone, with extremely thin joints, are seismic proof constructions, what was proved by their stability through numerous earthquakes, including the last one occurred 1979. Of course, iron ties have been very important additional, sometimes crucial element for their stability (fig 15).



Figure 15 *– S. Tryphon Cathedral, Kotor, interior*

In buildings with unconnected walls and wooden *floor structures,* they will separate, and cracks will develop along vertical joints, usually in the openings region. If the walls are connected properly with the floors, they have to oscillate harmoniously, and the behavior and earthquake response is much better. In the traditional workmanship in Boka Kotorska Bay, walls have been usually connected by ties, be iron, or wooden beams of the floor structure with iron terminals, “keys” (italian: “capochiave”) on the opposite facades (fig 16).



Figure 16 *– Gregorina Palace, Maritime museum, Kotor, XVIII c.*

Longitudinal beam inside the facade walls connecting perpendicular floor beams was rather rare because decay caused by humidity. Nevertheless, wooden floor beams of the larger buildings with internal constructive walls were properly connected on the medium walls by the oblique scarf joint and special iron anchors (fig 17).



Figure 17 *– Ivanovic Palace, Dobrota-Kotor, XVIII c., detail*

Taking into account the nature of the earthquakes movements and the seismic behavior of the buildings, it is evident that the level of the most desirable connection is in the top of the structure, under the roof (fig 18). Otherwise, roof timber rafters or vaults push and disintegrate the walls. Besides connecting it, is important that roof is stabile by itself, and as light as possible.



Figure 18 *– Radimiri Palace, Dobrota-Kotor, XVII c.*

Almost all buildings originally properly tied suffered no, or very little, acceptable damage. In these cases introducing numerous reinforced concrete elements was useless, even contra productive, not only for the building authenticity but also for the overall building stability. That's why reinforced concrete slabs, wall jackets, vertical internal or external pillars, sometimes destroying the very strong building corners, and especially heavy concrete roofs, should be avoided. The best practice would be: proper tying and connecting, rebuilding of collapsed parts, grouting, and only eventually, minimum, and wise introducing reinforced concrete elements when necessary.

It is important to point out attention paid by the old masons to the ***openings***. The vaults and arches have been constructed over the openings, in order not to load stone lintels of the doors/windows frames, but to distribute weight to the piers. That's because the fact that the lintels can crack even due to the static load. Moreover, due to dynamic seismic forces, lintels broke and walls crack around the openings, being weakened in those places. It should be remarked example of a special sort of this construction noticed on a palace at a maritime settlement Prčanj, near Kotor. The central console of the balcony, in the same time, is keystone of the arch above the door, in a way that long fragile lintel was successfully bridged over (fig 19).



Figure 19 *– Beskuca Palace, Prcanj-Kotor, XVIII c., detail*

5. Conclusions and Recommendations

Despite of widespread presumption that historic buildings, especially masonry structures in seismic prone regions are weak, it is a fact that sometimes they are very resistant. This is proved by the evidence of their existence so long time in those areas. In the region of Boka Kotorska Bay there is evidence of the numerous sustainable constructions and techniques, due to simultaneous strong seismic activity, economic prosperity and cultural links within wide Mediterranean region from Venice to Constantinople.

The most recent earthquake in the region, like in other similar cases, has demonstrated that we can usually rely on the most existing constructive elements: foundations, walls, vaults, floors etc. Although, there are evident attempts to tie the structure, generally insufficient anchorage and particularly inadequate interlocking between rafters, beams and walls, in the roof and floor levels, are often serious disadvantages.

However, it is important not to ignore entire traditional buildings or their parts, because some of them are weak. Contrary, solution for the strengthening and repair must be based on the actual resistance and capacity, structural conditions, and sustainability. From the historic preservation point of view, it is necessary to consider, analyze, assess and preserve and/or retrofit those elements relevant for structural stability of the traditional structures. For the successful preservation of an old structure, a team work of experts from different profiles is needed.

The main question in this process is how far we should go as to the level of safety and the extent of the interventions. Methods and techniques for repair and strengthening have to provide economically justified and technically consistent structural safety, as well as acceptable damage level in the future earthquakes. If structural interventions doesn't go beyond obtaining reasonable security, preventing sudden collapse and preserving human lives and building integrity, but not damage at all, original structural system usually can be satisfactory preserved.

In order to improve, not destroy authentic structural system, being the important value of historic building, a special approach in consolidation methodology must be developed taking into account the most important principles of historic preservation. Consolidation of these buildings cannot be performed using design codes for modern structures, and should consider traditional materials and techniques. Of course, modern technology can be used, but always having in mind that basic problem in structural consolidation of these buildings is compatibility of the introduced techniques and materials with old ones. Introduction of new elements for repair and strengthening should be minimum, possibly reversible, and must assure sustainability and authenticity preservation.

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Risk-Informed Decision Making in Wastewater Treatment Plant Construction: A Delphi-Based Preliminary Risk Assessment Model for Sustainable Infrastructure Delivery

[Jovana Topalić][1]

Abstract

Wastewater treatment plants are among the most consequential and most poorly served pieces of municipal infrastructure in the Western Balkans. Belgrade remains the only European capital without an operational wastewater treatment plant; around three-fifths of Serbia's population is connected to a sewer network, and less than 15 percent of the wastewater the country produces is treated before discharge. The construction of a treatment plant is a multi-year, multi-million-euro undertaking involving investors, designers, public utilities, and contractors, yet civil engineering risks in planning and design are rarely assessed using any structured method. This paper brings together and extends two previously published works. The first is a preliminary risk assessment model developed through a Delphi study with a panel of 29 experts from Serbia and Bosnia and Herzegovina, in which 37 risks were identified across six categories: legal, financial and economic, logistical, ecological, managerial, and design. Each risk carries a weighting coefficient derived from descriptive statistics, so a project's cumulative score can be compared against a provisional threshold of 50 points. The second is an extension of that diagnostic tool into a governance instrument, mapping the six risk categories against Sustainable Development Goals 6, 11, and 13 and examining how Serbia's institutional and regulatory environment shapes both risk exposure and mitigation capacity. The Belgrade project is read back through the model: its delays fall into the legal, financial, and managerial categories, which account for 46.8 of the 100 available points. The argument is straightforward: risk identification has to happen before the first line of a design is drawn, not after the first delay is logged.

Keywords

Wastewater treatment plants, Delphi method, risk assessment, sustainable infrastructure, Sustainable Development Goals, Western Balkans.

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1. Introduction

Every settlement produces wastewater, and every settlement above roughly two thousand inhabitants is legally required to treat it before discharge. The gap between that requirement and the reality on the ground remains wide. Recent global estimates put the number of people without access to safely managed sanitation at around 3.5 billion, with roughly 2.2 billion lacking reliably safe drinking water, while only about 11 percent of treated wastewater is reused anywhere in the world [1, 2].

Serbia sits inside this gap in a particularly visible way. Belgrade is the only capital city in Europe without an operational wastewater treatment plant. National coverage has not improved in a decade: 62.2 percent of the population was connected to a sewer network in 2017 [3], and the most recent official figures put the share at approximately 61.5 percent, compared with a European average of between 90 and 100 percent [4]. Less than fifteen percent of the wastewater the country produces receives any treatment at all, and of the roughly fifty treatment facilities that exist, about a third are out of service [4]. The country's path toward European Union membership makes closing this gap a matter of regulatory necessity rather than choice.

A wastewater treatment plant is a large, complex infrastructure project. It is a multi-year, multi-million investment that draws in investors, designers, contractors, public utility companies, environmental authorities, and, eventually, the population it serves. Existing design guidance addresses the technological side of the process: effluent quality, ammonia and nitrogen content, treatment train selection [5, 6]. What these guidelines do not address is the civil engineering side of the project, meaning the legal, financial, logistical, managerial, and design risks that determine whether a plant gets built at all, on time, at the planned capacity. A review of the literature confirms that no unified methodology exists for identifying and quantifying these construction-related risks in the wastewater sector [7].

This paper summarizes a model developed to close that gap: a Delphi-based preliminary risk assessment model for the planning and design phases of wastewater treatment plant construction [8]. It also describes two subsequent extensions of the model, presented in [9]: a mapping of its six risk categories onto Sustainable Development Goals 6, 11, and 13, and an institutional and policy contextualization focused on Serbia's regulatory landscape. The contribution of the present paper is the synthesis of these two strands and their reading in light of a specific claim: risk-informed decision-making is not an add-on to sustainable infrastructure delivery; it is a precondition for it.

2. Methodology

Risk management in construction is the process of identifying, prioritizing, and responding to uncertainties that threaten a project's objectives, followed by coordinated actions to reduce, monitor, and control their likelihood and impact [10]. In wastewater infrastructure specifically, the responsibility for identifying and responding to risk falls first on the investor and its management team, and risk analysis delivers the greatest value when it starts at the very beginning of the project, well before design work begins [11].

The Delphi method was chosen as the instrument for eliciting and quantifying these risks. Developed in the early 1950s at the RAND Corporation as a forecasting tool for the United States Air Force, the method structures group communication so that a panel of experts can reach consensus on a complex problem without the distortions that come from face-to-face debate [12]. Participants answer anonymously, in successive rounds, with statistical feedback between rounds, until their positions converge. The technique has since

been applied widely in construction management research: a review by Ameyaw and colleagues found that 29 of 88 construction-related Delphi studies concerned project management and planning, with panels ranging from 3 to 93 experts across 3 to 6 rounds [13]. A related study used the method with fourteen experts to assess factors affecting the safety of decentralized wastewater treatment systems, providing a direct precedent for its use in this sector [14].

2.1. Establishing the Delphi Panel

Thirty-five candidate experts were identified across Serbia and Bosnia and Herzegovina, based in Novi Sad, Subotica, Belgrade, Bijeljina, Sarajevo, and Bihać, covering civil, electrical, mechanical, and architectural engineering, spatial planning, chemistry, and wastewater technology. To qualify as an expert for the study, a candidate had to satisfy at least three of eight criteria: published work in risk management or wastewater treatment, conference participation in the field, experience in spatial planning that included siting a treatment plant, experience preparing feasibility studies, five or more years of professional work experience in the sector, ten or more years of employment at a faculty, membership in a professional association, or a professional licence [15].

Thirty-three of the thirty-five candidates met this threshold. Twenty-nine of them completed the first scoring round and remained on the panel until consensus was reached. That final panel of twenty-nine consisted of fourteen civil engineers, five technology engineers, three spatial planners, two chemists, two environmental engineers, two architectural engineers, and one electrical engineer [8].

2.2. Risk Structure and Scoring

The risk structure was built around two phases identified in the literature on project risk: the concept-formation phase and the design phase [11]. Thirty-seven risks were identified in total and grouped into six categories: legal, financial and economic, logistical, ecological, managerial, and design. Each expert scored every risk on a five-point Likert scale, from negligible impact to extreme impact, where the project would no longer be sustainable. The scale measures impact alone; likelihood was not elicited separately, and Section 5 returns to what that means for how the resulting scores should be read. In the second scoring round, experts received the mean, median, range, mode, and level of agreement from the first round and were asked to either confirm the group means or submit a revised score.

Consensus was measured with the coefficient of variation, the ratio of the standard deviation to the mean of the responses for each risk. A coefficient below 0.5 and a small absolute difference between the coefficient of variation in the second round and the first indicate that the panel has converged and that further rounds are unnecessary [16, 17]. All thirty-seven risks in this study met that criterion after the second scoring round, so the process stopped there. Between 72 and 97 percent of experts rated every risk above a score of two, and mean scores across the full risk set ranged narrowly from 3.07, for inadequate assessment of the impact of public procurement on project timelines, to 4.14, for lack of data on the amount of wastewater to be treated [8].

2.3. Quantification

Weighting coefficients were derived using descriptive statistics. Each risk group was assigned a mean value based on the individual risk means within it, and each group's share of the total was expressed as a coefficient such that the coefficients across all six groups

sum to one hundred. Within each group, individual risks were weighted by their relative contribution to the group mean.

The working rule adopted for practical use is that a project should aim to keep its cumulative score, the sum of the weighting coefficients of the risks that actually apply to it, below fifty points; the higher the score, the greater the exposure to delay, cost overrun, and underperformance once operational [8]. Fifty points are half of the total available weight, and the threshold was adopted on that basis as a first working rule. It has not been calibrated against the observed outcomes of completed projects, and it should be treated as provisional until it has been.

3. Results: The Risk Assessment Model

Table 1 summarises the six risk categories, the number of risks in each, the sum of their weighting coefficients, and the highest-weight risk within each group. Two patterns stand out. First, the ecological and logistical categories carry the highest per-risk weight despite containing only two risks each, which reflects how directly plant siting and the availability of qualified designers determine downstream project viability. Second, within the design category, the single heaviest risk is the absence of reliable data on wastewater quantity, which is also the individual risk with the highest mean expert score across the entire set. Mean score and weighting coefficient are distinct: the coefficient distributes a category's weight across the risks that category contains, so a category holding two risks assigns each of them a larger share than one holding thirteen. Sizing a plant against a demographic estimate rather than a measurement propagates into every subsequent design decision.

Table 1 *– Risk categories, number of risks, aggregate weighting coefficients, and representative risks. Aggregate figures are sums of the individual risk coefficients reported in [8], each rounded to one decimal place*

Risk category	No. of risks	Sum of weighting coefficients	Representative risk (highest weight)
Legal	13	16.4	Inadequate criteria for selection of the project designer (1.4)
Financial and economic	5	14.1	Inadequate budget for building modern plants (3.7)
Logistical	2	17.1	Lack of qualified designers of wastewater treatment plants (8.9)
Ecological	2	18.3	Location not adequate for environmental protection (9.2)
Managerial	7	16.3	Unrealistic project deadline planning by the investor (2.5)
Design	8	16.4	Lack of data on the amount of wastewater (2.2)

4. From Risk Register to Sustainable Infrastructure Delivery

A risk register is only useful if it is read in light of the goals a project is meant to serve. To make that connection explicit, the six risk categories were mapped against three Sustainable Development Goals with direct relevance to wastewater infrastructure: SDG 6 on clean water and sanitation, particularly the targets on pollution reduction and integrated

water resource management; SDG 11 on sustainable cities and communities; and SDG 13 on climate action, understood here as infrastructure resilience [9]. The mapping was carried out by the authors rather than by the Delphi panel, drawing on established SDG-alignment methodologies [18]. Each risk category was assessed as having a strong, moderate, or no contribution to hindering or advancing these targets. Table 2 reproduces this mapping.

Table 2 *– Risk-SDG mapping matrix [9].*

Risk category	SDG 6 (6.3, 6.4, 6.5)	SDG 11 (11.5, 11.6)	SDG 13 (climate action)
Legal	Strong	Moderate	Moderate
Financial and economic	Strong	Strong	Moderate
Logistical	Moderate	Moderate	None
Ecological	Strong	Moderate	Strong
Managerial	Strong	Strong	Moderate
Design	Strong	Strong	Strong

The assessment is qualitative and deliberately coarse. Eleven of the eighteen cells return a strong rating, which limits how far the matrix discriminates between categories; it is better read as a statement of which risks are material to which goal than as a ranking among them. Within that limit, three readings are held. Legal, ecological, and design-related risks show the strongest alignment with SDG 6, acting through mechanisms such as project delays, poor site selection, and fragmented technical data [9], [19]. Managerial and financial risks show the strongest alignment with SDG 11, since under-budgeting, slow investor decisions, and weak stakeholder coordination directly threaten the delivery of resilient urban infrastructure [20]. SDG 13 is less directly tied to the wastewater treatment sector, but ecological, financial, and design risks still affect a plant's ability to cope with heavier precipitation or extended drought once it is built [9].

The ecological risk category deserves particular attention because it consistently returns the highest weighting coefficients in the underlying model. It contains two risks: a plant location that disturbs the surrounding ecosystem, and one that sits too close to, or too far from, a populated area [21]. Both can be expanded through further PESTEL and SWOT analysis, examining factors such as pollution from the treatment process itself, noise, impacts on surface water, groundwater, and soil stability, and the broader regulatory and climatic context in which the plant operates [22].

Alongside the SDG mapping, the model has also been extended with an institutional and policy reading of Serbia's governance framework, since a risk coefficient means little if the institutions responsible for acting on it cannot do so. That analysis examined Serbia's ongoing harmonization with [23], which introduces stricter requirements for micropollutants, expands coverage to smaller agglomerations, and sets targets for energy neutrality. Harmonization cuts both ways: it raises treatment standards and attracts investment, but it also introduces transitional compliance risk and the possibility of permitting delays. Administrative capacity was found to vary sharply across the local, provincial, and national levels, and overlapping mandates among municipal utilities, provincial agencies, and national regulators were identified as a direct driver of the legal and managerial risks already present in the model, particularly regarding procurement delays and unclear accountability [9].

5. Discussion: Implications for risk-informed decision-making

Design guidance for wastewater treatment plants is well developed on the technological side and effectively silent on the civil engineering side. Reviews of the field confirm that no unified methodology exists for identifying and quantifying the construction-related risks that determine whether a plant is delivered at all, on time, and at the planned capacity. The model presented here closes that gap with quantified weights: thirty-seven risks specific to the planning and design phases of wastewater treatment plant construction, grouped into six categories, each carrying a coefficient derived from expert consensus rather than from assumption. Delphi studies are common in construction management research [13], and resilience frameworks for water utilities exist at the operational level [24, 25]. What does not exist is a weighted, sector-specific risk structure for the phase in which decisions determining a project's fate are made.

The practical value follows directly from the weighting. A coefficient attached to a risk turns a qualitative concern, such as insufficient data on the existing sewer network, into a quantity that can be compared across projects and tracked as a project matures from concept to detailed design. Applied at the conceptual stage, before a design contract is signed, the model provides an investor with an early estimate of a given project's exposure and which risk category to address first. That estimate costs a few hours of structured assessment, set against projects whose delays are counted in years and whose cost overruns are counted in hundreds of millions of euros.

The scoring is designed for that stage. The Likert scale elicited impact rather than likelihood because, at the concept formation stage, likelihood estimates rest on too little information to carry weight, whereas an experienced panel can answer with confidence which exposures exist at all. A cumulative score is therefore a severity-weighted inventory of the risks a project carries. It is an instrument for comparing candidate projects, siting or delivery variants, and successive stages of the same project, and it sharpens as the project matures and individual risks are eliminated or confirmed.

The weighting also makes the model usable inside the frameworks that utilities are increasingly expected to work with. ISO 14091 on climate vulnerability and impact assessment and the Assessment Framework both require an inventory of exposures organized by type, along with an indication of relative severity [24, 25]. Neither supplies one for the construction phase of wastewater infrastructure. The six weighted categories provide exactly that input, which allows the model to function as a component of a wider resilience assessment rather than as a parallel exercise bolted on beside it.

The Belgrade case shows what the absence of such an assessment cost. A contract covering the central sewage system and the Veliko Selo plant was signed with China Machinery Engineering Corporation in January 2020 [26]. A memorandum of understanding under the Consortium, covering design, construction, financing, operation, and maintenance, was signed in June 2024 for a facility with a capacity of 423,000 cubic meters per day, equivalent to roughly 1.5 million inhabitants [27]. Reported cost estimates range between 700 and 800 million euros, and the completion date has been repeatedly moved [26]. Read through the categories in Table 1; the slippage sits in the legal, financial, and managerial groups: procurement route, financing structure, and the division of responsibility between national ministries, the city, and the public utility. None of them is a treatment technology problem. Those three categories together account for 46.8 of the 100 available points, so a project exposed across all of them approaches the 50-point threshold before a single ecological or design risk is counted. The model would have made that visible at the concept stage, on a project that has since been in preparation for six years without a plant.

Two conditions bound the present calibration and set the direction of further work. The weighting coefficients were derived from a panel based in Serbia and Bosnia and

Herzegovina, so the six-category structure is expected to travel further than the specific numbers attached to it; recalibration with panels in other regulatory environments would test that directly and is the natural next study. The fifty-point threshold is a working decision rule set at half the available weight, and validation against completed projects, currently underway on two case studies that will be followed through construction, will show whether it sits at the right level [9]. Neither condition changes what the model does at the conceptual stage: name and rank the exposures a project carries before the first design decision commits money to them.

6. Conclusion

The model presented here started with a narrow, practical question: which civil engineering risks threaten a wastewater treatment plant project during planning and design, and how much does each one matter relative to the others? Thirty-seven risks, six categories, and a Delphi panel of twenty-nine experts from Serbia and Bosnia and Herzegovina produced a quantified answer to that question. What follows is an attempt to connect that answer to the larger goals a conference like this one is organized around: mapping the same six risk categories to SDGs 6, 11, and 13, and assessing them against Serbia's institutional capacity to harmonize with EU water directives.

The two pieces belong together, and the next step for both is the same one. The weighting coefficients and the fifty-point threshold need to be tested against completed projects, and the SDG mapping needs a finer instrument than a three-level scale. A resilient and sustainable Western Balkan wastewater sector will be built project by project, and each project will be safer, cheaper, and more likely to reach its design capacity if the risks ahead are identified and weighted before design begins.

Acknowledgement

This research has been supported by the Ministry of Science, Technological Development and Innovation (Contract No. 451-03-34/2026-03/200156) and the Faculty of Technical Sciences, University of Novi Sad, through the project “Scientific and Artistic Research Work of Researchers in Teaching and Associate Positions at the Faculty of Technical Sciences, University of Novi Sad 2026” (No. 01-3609/1).

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T02

Green & Digital Transition in Higher Education

Digitalization of the Construction Sector Through Education in Montenegro: The Role of Lifelong Learning and BIM Technologies

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Abstract

The construction industry is undergoing a digital and green transformation driven by BIM and GIS technologies. However, formal higher education faces rigid administrative barriers that prevent curricula from keeping pace with market demands. This paper analyzes structural challenges within civil engineering education in Montenegro and proposes a sustainable mechanism based on Lifelong Learning (LLL) programs. By evaluating national initiatives for BIM standardization, the paper outlines a collaborative roadmap involving academia and the industry. The framework introduces ECTS-valued micro-credentials as a flexible tool for professional development, ensuring that engineers acquire the necessary competencies to remain competitive.

Keywords

Digital transformation, BIM, education, Lifelong Learning, micro-credentials, sustainable construction

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1. Introduction

The construction industry globally, and consequently within the Western Balkan region, is undergoing the most intensive and fundamental transformation in its modern history. This wave of change is primarily driven by profound digitalization processes (the so-called Construction 4.0) and increasingly stringent legal and environmental imperatives for sustainable construction, which demand a radical reduction in carbon footprints and resource optimization. In such an environment, traditional approaches to design, execution, and project management are rapidly losing market viability. Therefore, in contemporary engineering practice, they are being replaced by integrated digital workflows and information systems (Figure 1).



Figure 1 *– BIM Workflow, [1]*

In this new technological revolution, a central role is occupied by the synergy between Building Information Modeling (BIM) technologies, that provide an information-rich three-dimensional representation of a facility throughout its lifecycle and Geographic Information Systems (GIS), which anchor this data within a precise spatial and infrastructural context [1-3].

However, this new technological revolution opens a deep structural gap in the labor market. While the modern construction industry and investors urgently demand engineering staff who confidently master advanced parametric models, databases, and Common Data Environments (CDE), the formal education system exhibits rigidity and inertia. Academic institutions face serious structural and legal-administrative limitations regarding speed, flexibility, and agility when adapting existing curricula and accrediting new study programs [4-5].

In the specific context of Montenegro, this challenge gains an additional dimension of complexity and urgency. The domestic construction sector is under direct pressure to align with strict European Union standards and directives, including the mandatory implementation of modern standards and regulations, such as Eurocodes, into engineering practice. The inability to respond to these technical and legislative changes within a short timeframe creates a risk of inadequate technological development within the domestic industry.

For this reason, the focus of this paper is directed toward finding alternative and complementary educational models. The objective is to demonstrate, through detailed argumentation, how systematically designed Lifelong Learning (LLL) programs can serve as an efficient, agile, and self-sustaining bridge between education and market needs.

LLL programs can successfully bridge the gap between the necessary academic depth provided by formal higher education and the operational, high-tech requirements that engineers encounter in the modern construction sector [6].

2. Current status and challenges in Civil Engineering education in Montenegro

Formal education of engineering personnel in the field of civil engineering in Montenegro is primarily concentrated at the Faculty of Civil Engineering, University of Montenegro (UoM) in Podgorica. The teaching process is structured according to the principles of the Bologna Declaration, organized through three interconnected study levels: Bachelor, Master, and Doctoral studies.

- Regarding professional specialization at the second cycle of studies (Master's level), the curricula are traditionally divided into two main education majors:
- Structures: with specialized modules for concrete, masonry, steel, composite, and timber structures, geotechnics, as well as numerical modeling of structures.
- Infrastructures: within which students specialize through modules for roads (transportation infrastructure) and hydraulic engineering (water management systems and hydraulic structures).

In parallel, an interdisciplinary study program, Management in Civil Engineering, is organized at the second cycle, aiming to combine engineering skills with economic and organizational knowledge.

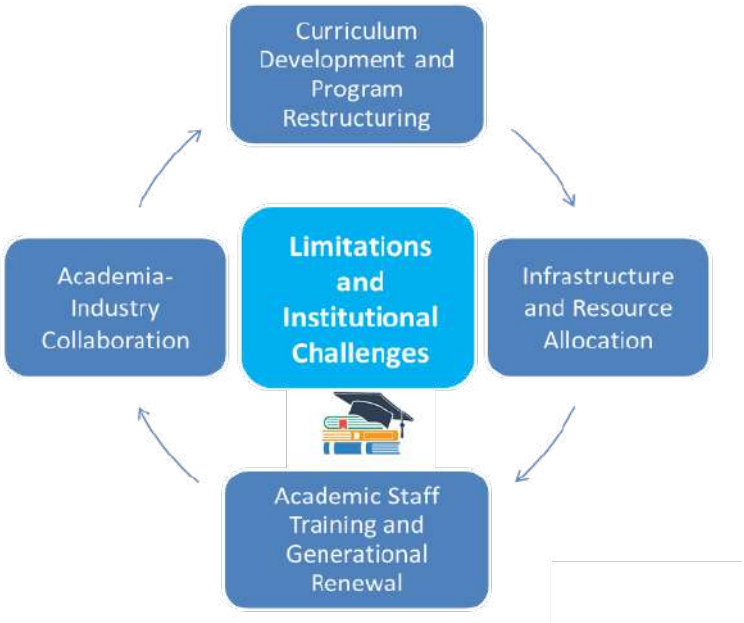


***Figure 2** – Education – Limitations and Challenges*

Although a system designed in this manner ensures enviable academic depth, mathematical-theoretical foundations, and continuity in education, it faces a series of complex challenges and structural limitations under the conditions of the Fourth Industrial Revolution. These can be classified into four distinct groups: Curriculum Development and Program Restructuring, Infrastructure and Resource Allocation, Academic Staff Training and Generational Renewal, and Academia-Industry Collaboration (Figure 2).

2.1. Curriculum development

The procedure for introducing new courses or implementing radical changes to existing curricula in higher education is subject to rigid legal and institutional procedures. This framework is primarily defined by the umbrella Law on Higher Education of Montenegro, the Statute of the University of Montenegro as well as accompanying rulebooks and decisions of the University [4].

In practice, the process of accreditation or re-accreditation of study programs requires extensive documentation, peer reviews, and institutional approvals, which demand significant time. By the time the entire administrative cycle from conception to program implementation is completed, software versions, standards, and digital tools on the global market have already evolved. This prevents accredited academic programs from keeping pace with rapid technological progress.

2.2. Education vs. labor market demands

Traditional curricula of the programs organized at the Faculty of Civil Engineering (UoM) focus on transferring fundamental theoretical knowledge and analytical engineering calculations. On the other hand, the market demands exceptional speed, operational efficiency, flexibility, and the ability to manage complex digital databases.

Upon obtaining a degree, formal education ceases for most engineers. Given the pace of technological advancement, the lifespan of acquired digital skills is significantly shorter; formal static knowledge becomes obsolete over time, creating a risk of digital exclusion and loss of competitiveness.

Today, driven by foreign investments and complex infrastructure projects, the Montenegrin construction sector demands engineers who follow technological shifts and possess high digital literacy. They are expected to understand data structures, manipulate 3D/4D/5D models, and manage digital processes through Common Data Environments (CDE) [3].

2.3. Infrastructure and resource allocation

The implementation of BIM and advanced GIS technologies in education does not merely imply software installation; it requires robust computer architecture, server support, and expensive commercial licenses.

The primary challenge in acquiring modern equipment and digital tools is the financial limitations encountered by public institutions in Montenegro.

2.4. Academic staff training and generational renewal

Beyond material resources, a significant challenge is the lack of teaching staff with practical and operational knowledge in digital construction. The faculty primarily concentrates on theoretical scientific research, which limits their ability to provide practical expertise. Without ongoing professional development for teaching staff, effectively imparting advanced digital skills to students becomes challenging.

2.5. Academia – Industry collaboration

The local labor market in Montenegro frequently suffers from a chronic lack of communication with higher education institutions. LLL programs can become the core platform supporting collaboration between academia and industry [7].

3. Status of digitalization and BIM implementation in Montenegro

The digital transformation of the construction sector in Montenegro stands on the borderline between sporadic, self-initiated software applications and attempts at systemic, institutional regulation. While the umbrella Digital Transformation Strategy of Montenegro recognizes digitalization as a pillar of economic growth, the implementation of specific BIM (Building Information Modeling) protocols in daily engineering practice still faces a pronounced imbalance between market demands and institutional support [8].

The current and future state of the Montenegrin market can be described through three key aspects: standardization, foreign investments, and institutional requirements.

3.1. Initiatives in standardization and national roadmaps

A significant step toward systemic regulation in this field was achieved through the activities of the Institute for Standardization of Montenegro (ISME). During April and May 2026, within the framework of the global InDiCo Global project (funded through the EU Horizon Europe program), the first interactive workshops and a major national conference dedicated to the introduction of international ICT and BIM standards were realized [9-11]. The main objective of these activities is the creation of a national roadmap for BIM implementation, thereby bridging the current legal vacuum in which the use of these technologies is not legally regulated [11].

3.2. Market dualism: foreign investments vs. local SMEs

In practice, a significant divide exists between major infrastructure projects and domestic micro, small, and medium enterprises (MSMEs). On large-scale capital projects driven or supported by foreign investors, such as the construction of highway sections (Mateševo–Andrijevica) or luxury tourist and residential complexes on the coast (Portonovi, Luštica Bay, etc.), BIM has become a mandatory standard. Foreign investors and a small number of state-owned enterprises (e.g., Monteput) enforce the use of BIM platforms for strict cost control, scheduling, and clash detection.

Conversely, local companies, domestic design studios, and contractors mostly apply BIM at Level 1 (where software such as Revit or ArchiCAD is used solely for 3D modeling and drafting, without full collaboration and information exchange within a Common Data

Environment (CDE)). The primary reasons include high software licensing costs, a shortage of trained staff, and management's perception that investment costs in digitalization outweigh immediate benefits within a small domestic market.

3.3. Institutional requirements and integration of public databases

In collaboration with the Chamber of Economy of Montenegro (PKCG) and the Chamber of Engineers of Montenegro (IKCG), the professional community has developed guidelines for the near future [11]. It is recommended that relevant ministries gradually implement the mandatory use of BIM methodology in public tenders for infrastructure projects of national significance, following the model of EU countries. Additionally, the Real Estate Administration should serve as a key element in this transition by developing an advanced underground utility cadastre and integrating spatial GIS data with digital BIM models of buildings and infrastructure. This would enable the creation of "Digital Twins" of Montenegrin cities, radically improving spatial planning and asset management.

It can be concluded that the Montenegrin construction industry is gradually realizing that BIM is not a technological whim but an organizational necessity for survival in the regional market. Bearing this in mind, the need for adequate and certified training for engineers is evident. It is precisely within this vacuum, while the state prepares legislation and the industry seeks standardized BIM managers—that LLL education programs at the Faculty of Civil Engineering (UoM) gain increasing importance as a key driver of digital and green transformation in Montenegro.

4. The concept of LLL programs as a mechanism for transformation

Overcoming the gap between the dynamic demands of the modern labor market and the current formal education system in Montenegro cannot be achieved by simply abolishing or reducing fundamental theoretical courses. Academic depth and theoretical foundations represent the core of the engineering mindset and must not be compromised. The solution is a flexible, complementary educational ecosystem through structured Lifelong Learning (LLL) programs.

For LLL programs in Montenegro to be implemented at full capacity and become sustainable, it is essential to execute legal-administrative reforms and intensify collaboration with the industry and state institutions.

4.1. Legal-administrative reforms and the introduction of micro-credentials

The key mechanism for educational modernization is the introduction and standardization of a system of micro-credentials-short, highly focused, and certified educational modules.

These micro-programs must be valued through the European Credit Transfer and Accumulation System (ECTS). A crucial advantage of this system is its cumulative nature: employed engineers can accumulate acquired micro-credentials over time, which can later be officially recognized and validated as part of a Master's degree program.

For the successful implementation of these programs, it is necessary to create more liberal enrollment procedures that allow working engineers to attend modules without redundant bureaucratic barriers.

A significant step would also be the establishment of a Center for LLL at the University of Montenegro, which would support the accreditation, quality control, and execution, to ensure uniform quality standards.

4.2. Collaboration with industry

To achieve collaboration with industry, the following actions are required:

- Joint Curriculum Development: Engineers from the leading Montenegrin construction industry and representatives of the Chamber of Economy of Montenegro should be actively involved in designing the syllabi of LLL programs, ensuring that the content and structure directly reflect real-world market needs.
- Establishment of Co-financing Funds: The costs of advanced software training present a significant financial burden. Establishment of co-financing funds through public-private partnerships, where companies will finance or co-finance tuition fees for their employees, recognizing their own long-term economic interest.
- Chamber of Engineers Partnership: The Chamber of Engineers of Montenegro (IKCG) could be a key partner in this system by officially recognizing and scoring LLL programs within the mandatory Continuous Professional Development (CPD) system required for the renewal of engineering licenses.

The Faculty of Civil Engineering (UoM), through the Erasmus+ project SKILL2SUSTAIN ("Boosting digital and green skills for a resilient and sustainable Western Balkan society"), is developing a specialized LLL program for BIM and GIS. The detailed structure, curricula, ECTS credit allocation, and specific learning outcomes of the LLL modular program will be the subject of a separate paper.

5. Conclusion

Our research indicates that digitalization in Montenegro's construction sector is no longer just a matter of technological prestige; it is essential for the domestic engineering industry to remain competitive in both regional and European markets. The existing divide between academic theory and practical construction operations often leaves newly graduated engineers lacking the skills currently needed by the industry. Given the limitations and slow administrative processes involved in modifying accredited academic programs, lifelong learning (LLL) programs have emerged as a crucial link between theory and practice, offering an efficient method for knowledge transfer.

To fully implement this concept within the Montenegrin legal and business environment, it is important to move beyond a purely declarative approach and take concrete actions. These actions should include:

- Legally recognizing a system of short, modular certificates (micro-credentials) that carry ECTS credits, allowing employed engineers to accumulate credits and validate them towards their master’s degrees.
- Gradually introducing the mandatory use of BIM protocols and digital standards (such as ISO 19650) into public procurement through legal regulations, thereby making the state the primary promoter and client of digital processes.
- Making strategic efforts to integrate BIM and GIS systems to establish a foundation for the development of an advanced digital cadastre and smart cities.

- Strengthening resources and staffing through relevant EU projects, ensuring the establishment of digital laboratories and training of teaching staff in collaboration with foreign centers of excellence.

The success of digital transformation in construction relies heavily on creating a strong institutional partnership among the Faculty of Civil Engineering, the Chamber of Economy of Montenegro, and the Chamber of Engineers of Montenegro. The digital revolution necessitates a new paradigm: the future of construction and spatial planning in Montenegro will not be driven solely by advanced machinery, but by engineers who, through a flexible educational system, embrace a culture of continuous learning and professional development throughout their careers.

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Evidence-Based Assessment of Digital Skills Needs in Montenegro's Construction Sector

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Abstract

The digital and green transition of the construction sector increasingly depends on the capacity of education, training and professional development systems to provide new skills for model-based collaboration, information management and data-driven project delivery. In Montenegro, Building Information Modelling (BIM) has recently gained policy relevance through several documents and policies. This paper analyses the need for BIM, digital construction and information management education in Montenegro's construction sector. The study is based on comparative policy analysis, using the Montenegrin Smart Specialisation Strategy, the Action Plan for 2026–2027, the European Training Foundation's skills analysis for the construction sector, and survey-based evidence from the national BIM Roadmap study. The paper also compares Montenegro with the example of Albania's experience gained through the BIM4WB project, which integrates BIM competences into vocational education and training. In addition, the analysis considers how these policy initiatives can contribute to strengthening institutional capacities, improving workforce readiness and supporting the wider digital transformation of the sector. The findings show a clear mismatch between policy ambition and existing capacity: digital design and modelling, monitoring and sensing technologies, and smart building systems are recognised as high-impact technological clusters, while practical BIM and information management skills remain fragmented. The paper proposes a four-level BIM education framework for Montenegro, covering awareness, applied modelling, information management for public clients, and specialised BIM for green and smart construction. The proposed approach links national policy priorities with practical learning pathways and supports the gradual development of BIM-ready professionals and public clients.

Keywords

Building Information Modelling, information management, digital skills, construction sector, smart specialization, Montenegro, Albania, vocational education and training

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1. Introduction

The construction sector is under increasing pressure to improve productivity, transparency, sustainability and lifecycle performance. Across Europe, this transformation is closely connected with digitalisation, the green transition and the emergence of new competence profiles in design, construction, operation and public procurement. Building Information Modelling (BIM) has become a key enabler of the digital and green transition of the construction sector by supporting the structured creation, management and exchange of information throughout the lifecycle of built assets [1,2]. However, BIM implementation is not primarily a software transition, but a transition in workflows, roles, responsibilities, data quality and information governance.

For Montenegro, this distinction is particularly important. The national construction sector benefits from strong engineering traditions and an established role in economic development, but recent policy and analytical documents identify slow technology uptake, skills shortages, insufficient practical training and fragmented institutional capacity as major constraints [3,4]. At the same time, the Smart Specialisation Strategy 2026-2031 defines construction as a priority area and explicitly connects its future development with digital tools, European standards, BIM, Common Data Environment (CDE) requirements where applicable, and green construction objectives [4].

This paper argues that Montenegro's main challenge is not only the lack of BIM users, but the lack of a broader BIM skills ecosystem. Such an ecosystem must include BIM-literate students and technicians, BIM-capable engineers and contractors, BIM-informed public clients, and educators able to translate information management principles into practice. The aim of the paper is therefore to identify the main BIM, digital construction and information management skills needed in Montenegro and to propose an education framework aligned with national policy priorities and regional experience.

2. Methodology and evidence base

The Montenegrin case is examined through four evidence sources: Smart Specialisation Strategy 2026-2031, the Action Plan for the implementation of the Strategy for 2026-2027, the European Training Foundation (ETF) report on skills for smart specialisation in the construction priority domain, and survey-based evidence from the national BIM Roadmap study [3-6]. These sources are complementary: Strategy defines the policy direction; the Action Plan operationalises measures; the ETF report translates technological priorities into skills needs, and the BIM Roadmap study provides stakeholder-based evidence on digital maturity and implementation barriers.

The comparative dimension is introduced through the example of Albania, using publicly available information on the BIM4WB - Building BIM Digital Competences project. BIM4WB is relevant because it focuses on integrating BIM methodologies into vocational education and training, developing BIM-focused curricula and training materials, and equipping students and professionals with competences needed by a digital construction sector [7,8].

The analysis is structured around three questions: which digital construction technologies and related skills are prioritised in Montenegro; which skills gaps constrain BIM implementation; and what kind of education and training framework could support gradual BIM adoption across universities, vocational education, adult learning, industry and public administration.

3. Results

3.1. Montenegro's policy context and skills gap

Montenegro's Smart Specialisation Strategy 2026-2031 positions the construction sector within a broader innovation, competitiveness and sustainability agenda. Through the Entrepreneurial Discovery Process, as a part of Strategy creation, the priority area was formulated as "Nature and Human Orieneted Construction", pointing to the need for safe, sustainable and innovative construction combining digital tools and European standards. The Strategy also highlights the relationship between construction and ICT and places special emphasis on BIM as a technology that enables a digital documentation base and a new approach to design, construction and maintenance, including CDE requirements where relevant [4].

The Action Plan translates this policy direction into more concrete measures. Under the operational objective related to improving the institutional-regulatory framework and human capacities, indicators include the share of institutions implementing digital tools such as BIM/GIS in everyday work, the number of trainings on digital tools in construction processes, and the share of updated or harmonised regulations enabling the use of digital technologies in the construction sector. Planned actions include analysis of the legislative and institutional framework for construction digitalisation, analysis of missing skills for the priority area, an eConstruction Innovation Lab, the BuildTech SkillsUp programme, and stronger coordination between the S3 innovation working group and the relevant sectoral commission [5].

The European Training Foundation's skills analysis strengthens the argument that skills are a central implementation bottleneck. The report identifies three high-impact technological clusters for Montenegro's construction sector: digital design and modelling tools, including CAD, BIM and Digital Twin; monitoring and sensing technologies, including sensors, non-destructive testing, drones and computer vision; and energy-efficient and smart building systems. At the same time, it identifies severe shortages of technicians and skilled trades, insufficient practical and job-ready skills, weak operational digital competences, fragmented competences for smart systems, underdeveloped adult learning pathways, and institutional capacity gaps in public administration [3].

Survey-based evidence from the BIM Roadmap study confirms that the gap is recognised by sector stakeholders. The national survey collected 102 valid responses from experienced stakeholders and showed that 77.5% of respondents rated the current level of digital maturity of the construction sector in the lower range of the scale. At the same time, 93.1% considered digital transformation either very urgent or partially urgent. More than 75% assessed cooperation among stakeholders in construction digitalisation as insufficient or very weak, while 98.1% expressed readiness to contribute to roadmap development and implementation [6]. This combination of low maturity and high urgency creates a favourable context for structured BIM education.

3.2. Priority BIM and information management competences

The competence gap in Montenegro should be understood across several professional layers. BIM education must go beyond teaching students or engineers how to create 3D models. According to ISO 19650-1, information management at the BIM maturity stage includes the exchange, recording, versioning and organisation of information for all actors [1]. Therefore, learning outcomes should address both model-based technical skills and

information management skills: how requirements are defined, how information is structured, checked, exchanged, approved and handed over.

Table 1 proposes a compact competence matrix for Montenegro. It is aligned with the ETF skills priorities, the S3 and Action Plan objectives, and the public-sector leadership approach promoted by the EU BIM Task Group [2-5].

***Table 1** – Proposed BIM and information management competence areas for Montenegro*

Target group	Digital construction skills	Information management skills
Students in civil engineering and architecture	BIM fundamentals, model-based design, coordination basics, openBIM, introductory 4D/5D and sustainability-related model uses.	CDE use, file naming, versioning, structured exchange, data quality and basic information requirements.
Designers, engineers and project managers	Discipline models, clash detection, model checking, BIM coordination, quantity take-off, digital collaboration workflows.	Exchange information requirements, BIM execution plan, delivery milestones, quality assurance and approval workflows.
Contractors, site managers and technicians	Digital site reporting, model interpretation, as-built updates, scanning, digital documentation, sensors and worksite workflows.	Structured data capture, issue tracking, document control, handover information and model maintenance.
Public administration and public clients	BIM in public procurement, digital permitting, basic model review, use of BIM/GIS information in administrative procedures.	Client information requirements, asset information needs, CDE governance, procurement clauses and information acceptance criteria.
VET and adult learners	Digital drafting, model interpretation, CAD/BIM basics, practical use of tablets, scanners and documentation tools.	File management, data entry standards, digital forms, quality-control routines and practical documentation workflows.

The matrix shows that Montenegro needs differentiated learning pathways. Higher education should strengthen integrated digital design, BIM coordination, Digital Twin applications and interdisciplinary links with ICT and energy efficiency and project management. VET and technician-level training should focus on practical digital workflows, model interpretation, data entry, site documentation and maintenance of digital information. Public administration requires a different set of competences: not advanced modelling, but informed-client capacity, procurement literacy, information requirements and the ability to

review and accept digital information. This is crucial because public clients can create demand signals that encourage industry investment in BIM.

3.3. Regional comparison: lessons from Albania and BIM4WB

The Albanian example is relevant to Montenegro because it demonstrates a project-based route for introducing BIM skills into vocational education and professional training. The BIM4WB project focuses on enhancing digital skills in the construction sectors of Albania and Kosovo by integrating BIM methodologies into education. Its activities include developing BIM-focused curricula and training materials, capacity-building activities for students, teachers and professionals, and stronger cooperation between education providers, vocational institutions, industry and innovation actors [7,8].

The comparison does not suggest that Montenegro should simply copy Albania. Montenegro currently has a stronger explicit policy basis through the Smart Specialisation Strategy, the Action Plan and the emerging national BIM Roadmap framework. However, Albania offer a useful implementation lesson: policy recognition should quickly be translated into learning outcomes, training materials, teacher capacity building, pilots and cooperation with industry. BIM4WB follows the sequence needs analysis - curriculum - platform/materials - training - pilot implementation. This sequence could be adapted in Montenegro through the eConstruction Innovation Lab, BuildTech SkillsUp programme, universities, VET schools, the Engineering Chamber, public administration and SMEs.

The main difference is therefore one of emphasis. Montenegro has a strategic and policy-driven entry point; Albania, through BIM4WB, provide a more operational VET and training model. Combining these approaches would allow Montenegro to avoid a common implementation gap: recognising BIM as a strategic priority without building the human capacity required for its everyday use.

4. Discussion

The evidence reviewed in this paper indicates that Montenegro's challenge is no longer whether BIM and digital construction should be introduced, but how the necessary skills, institutional capacities and learning pathways should be developed in a coordinated way. The Smart Specialisation Strategy and its Action Plan provide a clear policy direction by recognising construction digitalisation, BIM/GIS tools, regulatory adaptation and human-capacity development as part of the national innovation agenda. The ETF skills analysis further confirms that digital design and modelling, monitoring and sensing technologies, and smart building systems represent high-impact technology clusters for Montenegro's construction sector. However, these priorities cannot be implemented effectively without a systematic approach to education and training.

In this regard, BIM education in Montenegro should be developed as a layered and flexible framework rather than as isolated software training. At the basic level, decision-makers, public administration, investors, managers, professional chambers and SMEs need BIM awareness and digital construction literacy, with emphasis on BIM as a process of information management, the role of clients, CDE, openBIM, public procurement and links with green and smart construction. A second layer should focus on applied BIM modelling and coordination for students, designers, engineers, technicians and contractors, including discipline modelling, coordination, clash detection, model checking, quantities, basic 4D/5D, IFC exchange and issue management, preferably through project-based learning using Montenegrin building and infrastructure cases. A third layer should strengthen information management and public-client capacity, since public institutions do not need to become BIM

modellers but must be able to define information requirements, understand BIM execution plans, manage CDE workflows, evaluate digital submissions and request asset information for operation and maintenance. Finally, advanced training should connect BIM with green and smart construction applications, including Digital Twins, energy modelling, monitoring and sensing, drones, facility management, renovation, circularity and lifecycle data. Such a framework would connect university education, VET, micro-credentials, continuing professional development, public-sector training and company-based learning, while directly supporting the technology clusters and skills priorities identified for Montenegro's construction sector.

The comparison with Albania through the BIM4WB project is useful because it shows how regional skills-development initiatives can move from needs analysis towards curriculum development, online learning resources, teacher training and piloting. In this sense, the Albanian experience suggests that BIM education should be developed through partnerships between higher education institutions, VET providers, professional organisations, companies and public authorities, rather than by individual institutions acting separately.

The findings of the BIM4WB project also reinforce the argument that successful BIM implementation requires the development of a broader skills ecosystem rather than isolated training activities. Research conducted among stakeholders in Albania and Kosovo demonstrates that BIM adoption remains fragmented, with most organisations operating at a low level of BIM maturity and relying primarily on self-taught professionals or short private training courses. The study further identifies a shortage of trained personnel, limited institutional support, high software and training costs, and the absence of structured educational pathways as the main barriers to wider BIM implementation. At the same time, both surveys and stakeholder seminars reveal strong demand for practical, project-based BIM education, interdisciplinary learning, and closer cooperation between universities, vocational education providers, industry and public authorities. The BIM4WB project addresses these challenges by developing learner-centred BIM curricula, training teaching staff, creating online learning resources and establishing partnerships that align educational programmes with labour-market needs. Its emphasis on real problem-based learning, teacher capacity building and continuous stakeholder involvement illustrates how BIM competences can gradually become embedded within formal education and lifelong learning systems rather than remaining dependent on individual initiatives [9].

Another important discussion point is the role of the public sector. International BIM experience shows that public clients can strongly influence digital transformation when they define clear information requirements and gradually introduce BIM into public procurement and project delivery [2]. For Montenegro, this is particularly relevant because digital permitting, institutional use of BIM/GIS tools and regulatory harmonisation are already present in the Action Plan. If public authorities remain passive or insufficiently trained, BIM adoption will likely remain fragmented and voluntary. If, however, public institutions build basic information management capacity, they can become informed clients and create demand for better digital practices across the whole sector.

Finally, the proposed approach should be realistic for the Montenegrin context. Montenegro does not need an oversized BIM education system at the initial stage. It needs a coordinated and scalable skills ecosystem: introductory awareness modules for decision-makers, applied project-based modules for students and professionals, targeted training for public clients, and advanced specialised modules linked to green and smart construction. To avoid fragmented and disconnected initiatives, this process should be supported by clear national coordination, preferably through the relevant public authority or another mandated coordinating body. This would allow gradual capacity building while avoiding the common mistake of equating BIM implementation with the procurement of software. The long-term goal should be to embed BIM and information management competences into formal

education, professional development and public-sector practice, creating the human-capacity foundation required for the digital transformation of Montenegro's construction sector.

5. Conclusions

Montenegro needs a systematic BIM education and information management framework covering higher education, vocational education, adult learning, industry and public administration. The framework should start with awareness and shared terminology, progress towards applied modelling and coordination, build public-client capacity for information management, and support specialised applications in green and smart construction. Regional experience from BIM4WB in Albania and Kosovo shows how a project-based VET approach can translate BIM policy into curricula, training materials and pilot implementation.

Four recommendations follow from the analysis: BIM and information management modules should be embedded in civil engineering, architecture and related study programmes; VET curricula should be modernised to include hands-on digital drafting, model interpretation, digital documentation and data quality routines; short certified courses and micro-credentials should be developed for professionals, SMEs and public administration; and, Montenegro should link the proposed BIM education framework with ISO 19650 principles, open BIM standards and future public-sector digitalisation requirements. In this way, BIM education can become a strategic instrument for a more productive, transparent and sustainable construction sector. At the same time, successful implementation will depend on strong coordination between government institutions, higher education providers, vocational education and training centres, professional associations and the construction industry. Continuous dialogue with stakeholders will be essential to ensure that education and training programmes remain aligned with technological developments and labour market needs. By establishing a coordinated skills ecosystem rather than isolated training initiatives, Montenegro can create the human capacity required to accelerate digital transformation, improve project quality and productivity, and support the long-term competitiveness and sustainability of its construction sector.

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From Classroom to Sustainability: Student Readiness for Green and Digital Skills in Albania

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Abstract

The twin green and digital transition is determining the competences that are going to be needed in the labor market. Under such circumstances, understanding students' readiness to develop both digital and sustainability-related skills becomes increasingly relevant. This study analyses survey responses from 207 students of the two main public universities in Albania, enrolled mainly in the Engineering/Technology and Economics/Business programmes. The paper examines attitudes toward artificial intelligence (AI), the perceived importance of green skills, and willingness to participate in training that combines the two. The findings reveal high overall interest in both domains: about 80% of students express interest in AI and 85% consider green skills important or very important for their careers, while 65% are unconditionally willing to join combined digital–green training. Engineering students rate green skills and sustainability engagement significantly higher than Economics students ($p < 0.001$), yet digital self-confidence, AI interest and willingness do not differ significantly by field, indicating a broadly shared openness to integrated up-skilling. Correlation analysis identifies a digital–green nexus, with interest in AI and interest in sustainability projects moving together. In the regression model, interest in sustainability projects and self-rated digital ability are the strongest predictors of willingness to joining trainings and programs in the field. The study demonstrates that integrating digital and green competences into curricula is driven not only by the evolving demands of the labour market, but also by students themselves, who are becoming increasingly aware of economic, technological, social, and environmental developments.

Keywords

Green skills, digital skills, twin transition, higher education, sustainability, logistic regression.

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1. Introduction

The simultaneous acceleration of digitalisation and the transition to a low-carbon economy, often referred to as the “twin transition”, is reshaping the competences that graduates are expected to bring to the labour market. Employers increasingly seek workers who combine digital fluency, from data analysis to artificial-intelligence (AI) literacy, with an understanding of sustainability, resource efficiency and the circular economy [1], [2]. For universities in the Western Balkans, including Albania, aligning curricula with this dual demand is both a challenge and an opportunity, particularly as the region seeks closer integration with European skills and green-transition agendas.

Despite growing policy attention, comparatively little empirical evidence exists on how students in this context perceive digital and green skills and, crucially, whether they are willing to engage in training that integrates the two. Understanding student demand is a prerequisite for designing programmes, internships and student initiatives that are both attractive and effective.

This paper addresses that gap using original survey data from 207 students enrolled in two of largest public universities in Albania. It pursues three research questions: (i) how do students assess their digital skills and value green skills? (ii) do attitudes differ between fields of study, notably Engineering versus Economics? and (iii) which factors predict willingness to participate in combined digital–green training? The remainder of the paper reviews relevant competence frameworks, describes the data and methods, and presents descriptive, comparative, correlational and regression results before discussing implications for programme design.

2. Literature review

The literature increasingly emphasises the need for universities to align their curricula with evolving labour-market demands. At the same time, a growing share of research funding now prioritises areas such as digitalisation, the green transition and security. Under these conditions, universities face a difficult crossroads: whether to preserve their traditional programmes or to develop new offerings suited to a world undergoing profound technological, economic, social and environmental change. Institutions worldwide are responding by rethinking how they operate, with provision increasingly moving beyond conventional bachelor's and master's degrees toward short trainings, tailor-made and lifelong-learning formats, and other flexible modes of education designed around market needs. Addressing these challenges, [3] argue that conventional university quality assurance remains too heavily focused on standards, reporting and formal compliance. Such systems, they contend, do little to help institutions redesign programmes around emerging green and digital competence requirements. [4] examine the mismatch between university education and the needs of employers and society more broadly. Combining the Theory of Change with a Living Lab that engages actors from the quadruple helix — universities, business, government and civil society — their findings underscore the value of stronger and more continuous university–industry dialogue, active and flexible teaching methods, institutionalised multi-stakeholder governance, and greater attention to students' self-awareness, adaptability, entrepreneurship and career-management skills.

These challenges rarely stop at national borders, and cross-border cooperation between universities is emerging as a new mode of delivering education. [5] explore how European countries might cooperate on twin-transition skills despite uncertainty about future occupations and substantial differences between national education systems. Drawing on

the concepts of skills ecosystems and experimentalist governance, they identify a four-stage governance cycle:

1. European institutions set broad objectives and provide funding.
2. Responsibility is delegated to regional and transnational partnerships that experiment with locally appropriate solutions.
3. Reporting, peer review and communities of practice support mutual learning.
4. Objectives, instruments and methods are revised periodically, allowing successful practices to be scaled up.

Beyond the broad context of educational transition, a further critical question concerns how such education is delivered. [6] conduct a systematic literature review to identify teaching methods suited to developing circular-economy and twin-transition skills. Searching Scopus and Web of Science for studies published between 2012 and 2025, they screened 1,819 initial records and retained 38 that explicitly addressed teaching methods. The review links these methods to three broad competence groups: specialised and technical skills; resilience and transversal skills; and digital competences. Of the eleven teaching methods identified, the most common were case studies and problem-based learning, group work, cross-disciplinary teamwork and project-based learning; simulations, gamification and do-it-yourself activities appeared less frequently but were regarded as promising. The authors recommend combining several methods rather than relying on a single approach. They caution, however, that the reviewed studies vary considerably in design and seldom compare methods directly, leaving the evidence on their relative effectiveness underdeveloped.

In a complementary conceptual contribution, [7] proposes an institution-wide strategy for universities seeking to support the twin transition. The framework comprises four interconnected domains: a research culture oriented toward the twin transition; curricula that develop green and digital competences; university–industry partnerships; and university–government collaborations, all reinforced by wider inter-university networks. Suggested research priorities include artificial intelligence for renewable energy, smart agriculture, digital waste management, circular economy, smart cities, sustainable transport and climate-risk analysis. For teaching, the article advocates embedding sustainability and digital literacy across existing programmes while also creating interdisciplinary degrees and courses, with problem-based, experiential and challenge-based learning supported by simulations, gamification and virtual reality. Educator training is treated as essential. Industry can contribute through internships, joint research and curriculum co-design, while governments provide funding and policy challenges and universities offer evidence-based advice; institutions are also encouraged to demonstrate leadership through measurable sustainability goals for their own campuses.

Other authors emphasise that willingness to change does not remove the obstacles to it. [8] identify several major barriers — infrastructure and software costs, limited access to industrial data, data quality, cybersecurity and privacy concerns, an absence of standards, and insufficient staff expertise. They recommend gradual implementation, professional development for lecturers, and close collaboration between universities and technology firms. Their broader conclusion is that, while digital twins hold considerable educational promise, the field remains relatively immature and requires stronger empirical evidence on learning outcomes.

Taken together, this evidence indicates that universities engagement with sustainability is shaped by labor market demands and by the request for hands-on, applied learning. Yet the demand of digital and green competences — the extent to which a student

is inclined toward these new domains, remains under-examined empirically, particularly outside Western Europe. The present study contributes to this literature by quantifying these attitudes and their interrelationships in an Albanian university setting and by modelling the drivers of students' willingness to undertake integrated training.

3. The Albanian context: skill gaps and EU convergence

The Western Balkan region presents a distinctive setting for studying twin-transition competences. Albania, like its other neighbors, pursue EU accession, and successive Enlargement, Economic and Investment, and Growth Plan initiatives which explicitly link the region's convergence with the EU to progress on green and digital transitions. Yet the region continues to face structural skills challenges. An analysis of drivers of sustainability engagement in Albanian context, shows that the strongest external influences come from rising customer awareness, social values, and competitive pressure This indicates that businesses are increasingly recognizing the need to align with market and societal expectations. In contrast, government support measures such as financial incentives and technical assistance appear to have inconsistent impact and show that they are not sufficiently effective or well-implemented [9]. Pojani et al. [10] examined sustainability practices adopted by a selected sample of Albanian business representatives, focusing on (i) circular economy activities, (ii) sustainability reporting, (iii) risk management, and (iv) the alignment of business practices with environmental standards. The findings reveal substantial variation in sustainability practices across companies, with firm size emerging as an important determinant. These studies report that firms are increasingly embracing sustainability practices, but struggle to find workers with the right mix of skills.

The picture on digital skills is nonetheless improving among younger cohorts. Convergence scoreboards indicate that around two-thirds of 16–24-year-olds in the region possess at least basic digital skills. National digital agendas and Erasmus+ higher-education projects across Albania, Bosnia and Herzegovina, and Montenegro are actively working to modernise digital education, while European Digital Innovation Hubs are being established to support the green and digital transitions through programs such as Digital Europe[5]. Against this backdrop of policy momentum and residual skills gaps, student-level evidence on competence self-assessment and training demand is especially valuable for calibrating regional interventions.

4. Methodology and data

The analysis draws on 207 responses collected from students enrolled in the two largest universities of Albania through an online questionnaire on digital and green skills. The sample is predominantly at Master’s level (74.9%), with two well-balanced main fields of study: Engineering/Technology (99 students) and Economics/Business (98 students), plus 10 responses from other fields.

The study instrument was a questionnaire administered either online or in class to the selected sample during Winter 2025. It consisted of nine main questions exploring respondents’ self-reported digital skills, perceived importance of green skills, willingness to enroll in training courses or study programmes related to the twin transition, and specific areas of interest within both the digital and green domains.

[5] *https://www.digitaleurope.org/*

Data were cleaned to unify inconsistent categories. Attitudinal variables are measured on ordinal (Likert-type) scales; between-group comparisons therefore use the non-parametric Mann–Whitney U test, and associations use Spearman's rank correlation. Willingness to join combined training was modelled with a binary logistic regression, with the outcome coded 1 for "Yes, definitely" and 0 otherwise. Predictors were self-rated digital ability, AI interest, green-skills importance, sustainability-project interest, field of study (Engineering = 1) and level of study (Master = 1).

4. Results

4.1. Descriptive statistics

The overall profile shows students with relatively strong digital self-confidence and positive attitudes toward sustainability. About half rate their digital skills as medium and 47% as high or very high, while roughly 80% express interest in AI and 85% consider green skills important for their careers. Willingness to undertake combined training is high: 64.7% answered "Yes, definitely" and only one respondent was opposed. Table 1 summarises the main attitudinal distributions.

***Table 1** – Distribution of key attitudinal variables (N = 207)*

Variable	Most frequent response	n	%
Digital skills (self-rated)	Medium	105	50.7%
Interest in AI	Very interested	101	48.8%
Importance of green skills	Very important	118	57.0%
Sustainability project interest	Very interested	104	50.2%
Willingness (combined training)	Yes, definitely	134	64.7%

Beyond the modal responses, the shape of each distribution is strongly right-skewed toward positive attitudes, confirming broad receptiveness to both digital and green up-skilling across the sample.

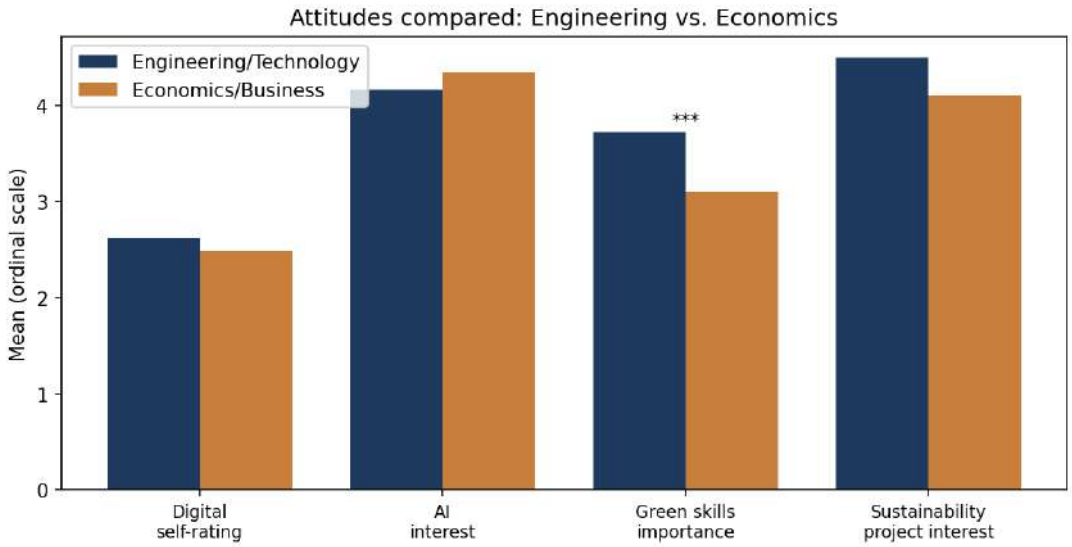
When asked which digital skills they most want to improve, students prioritised AI and machine learning (40.6%), data analysis (38.2%) and cybersecurity (33.8%). Among sustainability areas, renewable energy (46.9%), climate change and environmental protection (43.5%) and energy efficiency (42.0%) ranked highest. For support, the demand for practical training opportunities clearly dominates (74.4%), followed by career guidance and networking with companies (both around 44%). These priorities point toward applied, industry-linked provision.

Mann–Whitney U tests reveal a notable and somewhat counter-intuitive pattern (Table 2, Figure 1): Engineering students rate green skills as significantly more important and are more interested in sustainability projects than Economics students (both $p < 0.001$). For digital self-rating, AI interest and willingness to join training there is no statistically significant difference, indicating that a positive stance toward combining digital and green skills is widespread across fields.

Table 2 *– Field comparison of attitudes (Mann–Whitney U)*

Variable	Mean (Eng.)	Mean (Econ.)	p-value	Sig.
Digital self-rating	2.62	2.48	0.090	ns
AI interest	4.16	4.35	0.368	ns
Green skills importance	3.73	3.10	<0.001	***
Sustainability project interest	4.49	4.10	<0.001	***
Willingness (combined training)	2.68	2.62	0.374	ns

Figure 1 *– Comparison of mean attitudes (ordinal scale). *** p < 0.001.*



Spearman correlations (Table 3) show that the strongest association is between interest in AI and interest in sustainability projects (rho = 0.53), evidence of a digital–green "nexus" within the same student profile. Interest in sustainability projects is also strongly linked to concrete willingness to join training (rho = 0.59), while the importance attached to green skills correlates only weakly with digital self-rating, suggesting these are relatively independent dimensions.

Table 3 *– Spearman rank correlations among key attitudes*

Variable pair	rho	p-value	Sig.
Green importance ↔ Sustainability interest	0.45	<0.001	***
Digital self-rating ↔ AI interest	0.19	0.007	**
AI interest ↔ Sustainability interest	0.53	<0.001	***
Sustainability interest ↔ Willingness	0.59	<0.001	***
Green importance ↔ Willingness	0.31	<0.001	***

4.2. Logistic regression model

The logistic regression predicting full willingness ("Yes, definitely") fits the data well: N = 197, McFadden pseudo-R^2 = 0.300, classification accuracy = 81.2% and LR $\chi^2(6)$ = 76.2 ($p < 0.001$). As shown in Table 4 and Figure 2, interest in sustainability projects is the strongest predictor: each one-level increase almost quadruples the odds of full willingness (OR = 3.76). Self-rated digital ability also significantly raises the odds (OR = 2.19), whereas field and level of study have no independent significant effect.

Table 4 *– Binary logistic regression – predictors of willingness*

Predictor	B	SE	p-value	OR	95% CI
Constant	-9.38	1.61	<0.001	0.00	0.00–0.00
Digital self-rating	0.78	0.31	0.012	2.19	1.19–4.02
AI interest	0.42	0.24	0.074	1.53	0.96–2.44
Green skills importance	0.52	0.29	0.074	1.68	0.95–2.95
Sustainability project interest	1.32	0.29	<0.001	3.75	2.10–6.70
Field (Engineering=1)	-0.82	0.48	0.086	0.44	0.17–1.12
Level (Master=1)	-0.77	0.49	0.117	0.46	0.18–1.21

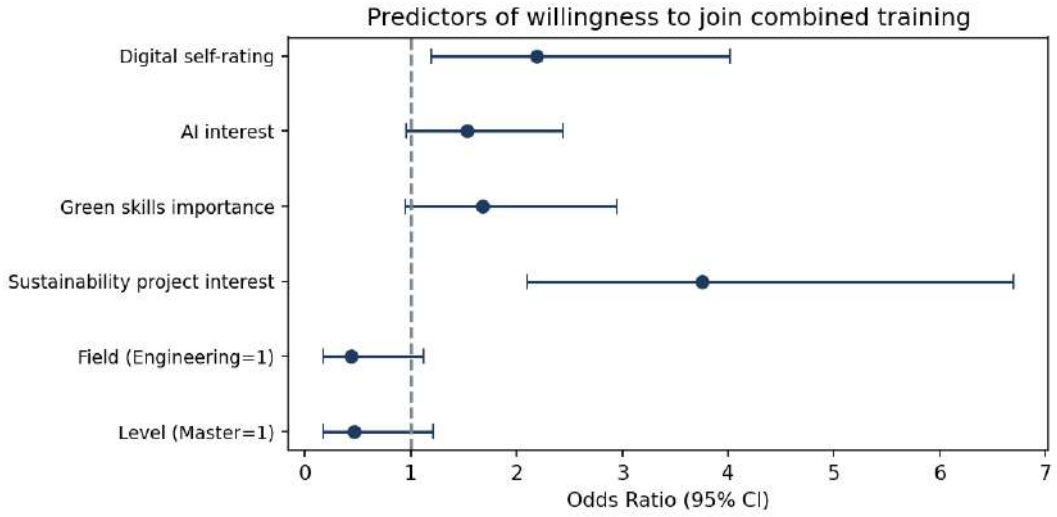


Figure 2 *– Odds ratios with 95% confidence intervals (reference line at 1).*

5. Discussion and conclusions

The results paint a consistent picture: students in Albania show high, simultaneous interest in AI and in sustainability, and a clear majority are willing to undertake training that combines the two. The positive correlation between digital and green inclinations supports the design of integrated rather than separate training programmes, since students drawn to one domain tend to be drawn to the other.

Two findings have direct practical value. First, willingness depends more on intrinsic interest, particularly in sustainability projects and digital skills , than on field or level of study, so recruitment for pilot initiatives should target motivation rather than discipline. Second, the

dominant demand for practical training (74%) indicates that hands-on components and university–industry collaboration should be prioritised. The higher sustainability engagement among Engineering students suggests they may serve as early adopters for interdisciplinary green–digital initiatives.

The study is limited by its two institution survey, self-reported and cross-sectional design, which precludes causal inference. Future work could extend the sample across faculties and countries, incorporate objective skill measures and track how expressed willingness translates into actual participation. Nonetheless, the evidence offers a useful basis for aligning curricula and student initiatives with the twin transition.

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Green and Digital Skills in Higher Education: The Case of Ss. Cyril and Methodius University in Skopje

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Abstract

The twin green and digital transition has become a strategic priority for the European Union, placing higher education institutions at the centre of developing the competencies required for sustainable economic growth, technological innovation, and climate resilience. Universities are increasingly expected to equip graduates with interdisciplinary knowledge and practical skills that support environmental sustainability while responding to rapidly evolving labour market demands. As a candidate country for European Union membership, North Macedonia has aligned its educational priorities with the Green Agenda for the Western Balkans and the Digital Education Action Plan.

This paper examines how Ss. Cyril and Methodius University in Skopje (UKIM), the largest public university in North Macedonia, contributes to the development of green and digital skills through its study programmes and institutional initiatives. The analysis combines a review of European and national policy frameworks with empirical evidence collected through the Erasmus+ SKILL2SUSTAIN project survey. The survey assessed study programmes, courses, research activities, and institutional practices related to sustainability and digital transformation.

The findings indicate that UKIM has successfully incorporated green and digital competencies across engineering, architecture, environmental sciences, and information technology programmes. However, opportunities remain for strengthening interdisciplinary curricula, expanding lifelong learning, increasing cooperation with industry, and aligning educational provision more closely with the European GreenComp and DigComp competence frameworks.

The study concludes that universities in North Macedonia can play a decisive role in supporting the country's green and digital transition by modernising curricula, fostering innovation, and preparing graduates capable of addressing contemporary environmental and technological challenges.

Keywords

Higher education, green skills, digital skills, sustainability, North Macedonia, UKIM, Green Agenda for the Western Balkans.

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1. Introduction

Climate change, environmental degradation, and rapid technological development have transformed the competencies required for sustainable economic and social development. Across Europe, the green and digital transitions have become mutually reinforcing priorities, reflected in strategic initiatives such as the European Green Deal, the Digital Education Action Plan (2021–2027), the European Skills Agenda, and the Green Agenda for the Western Balkans. These policies recognise that achieving climate neutrality and digital transformation depends largely on the availability of a workforce equipped with appropriate green and digital competencies.

Higher education institutions play a central role in this transformation. Beyond their traditional educational mission, universities increasingly contribute to innovation, knowledge transfer, and sustainable development by integrating environmental sustainability and digital technologies into teaching, research, and institutional governance. Consequently, universities are expected to prepare graduates capable of addressing complex environmental, technological, and societal challenges through interdisciplinary knowledge and practical problem-solving skills.

For the Western Balkan countries, these developments are closely linked to the European integration process. The Green Agenda for the Western Balkans identifies higher education as an important driver of sustainable economic development, emphasising curriculum modernisation, digitalisation, research capacity, and innovation. In North Macedonia, national higher education reforms have progressively promoted quality assurance, digital transformation, and sustainability while aligning university education with European policy priorities.

As the country's largest and most comprehensive public university, Ss. Cyril and Methodius University in Skopje (UKIM) occupies a leading position in this process. Through programmes in engineering, architecture, environmental sciences, information technologies, natural sciences, agriculture, and other disciplines, the university provides significant opportunities for developing competencies that support both the green and digital transitions.

Despite these developments, empirical evidence regarding the integration of green and digital competencies within North Macedonian higher education remains limited. This paper therefore investigates how UKIM contributes to the development of these competencies through its educational programmes and institutional activities.

The study pursues three objectives: to examine the current integration of green and digital skills within UKIM study programmes; to assess their alignment with European strategic priorities and competence frameworks; to identify opportunities for strengthening higher education's contribution to sustainable and digital transformation.

2. Higher Education and the Green-Digital Transition in North Macedonia

Higher education has become a strategic component of the green and digital transition throughout Europe. Universities are increasingly expected to educate graduates capable of supporting sustainable development while fostering innovation and technological progress. These expectations are particularly relevant for Western Balkan countries, where educational reforms accompany the broader process of European integration.

Within North Macedonia, reforms in higher education have focused on improving quality assurance, internationalisation, digitalisation, and alignment with the Bologna Process. At the same time, national development strategies increasingly emphasise

sustainability, renewable energy, environmental protection, smart specialisation, and digital transformation as key drivers of future competitiveness.

UKIM occupies a unique position within the national higher education system. As the largest public university, it encompasses a broad range of academic disciplines that collectively support sustainable development and technological innovation. Recent curriculum reforms, participation in European research and capacity-building projects, and growing institutional commitment to sustainability demonstrate the university's evolving role in preparing graduates for emerging labour market needs.

Against this policy background, evaluating the extent to which green and digital competencies are embedded within university education provides valuable evidence for future curriculum development and institutional planning.

3. Methodology

This research combines document analysis with empirical evidence collected through the Erasmus+ SKILL2SUSTAIN project. To provide a broader analytical context, the survey findings were complemented by European strategic documents [1-7], including the European Green Deal, the Green Agenda for the Western Balkans, the Digital Education Action Plan (2021–2027), the European Skills Agenda, and the GreenComp and DigComp competence frameworks.

The collected information was analysed using qualitative content analysis. Study programmes and institutional activities were examined to identify the extent to which they address sustainability, renewable energy, environmental protection, circular economy, climate resilience, artificial intelligence, Building Information Modelling (BIM), Geographic Information Systems (GIS), digital technologies, and other competencies supporting the twin transition.

The analysis was organised around four complementary dimensions of university contribution: education through curricula and competency development; research and innovation; institutional governance and strategic planning; and cooperation with external stakeholders.

Although the study focuses exclusively on UKIM, the university represents an appropriate case because of its size, disciplinary diversity, and leading role within the national higher education system. Consequently, the findings provide valuable insights into the current state of green and digital competence development in North Macedonia while identifying opportunities for future curriculum modernisation and stronger alignment with European educational priorities.

4. Analysis of educational process at UKIM

4.1. Educational capacity for green and digital skills

The SKILL2SUSTAIN survey demonstrates that Ss. Cyril and Methodius University in Skopje (UKIM) has established a substantial educational capacity to support the development of green and digital competencies [8,9]. Rather than concentrating sustainability-related education within a limited number of programmes, the university increasingly integrates these competencies across engineering, architecture, information technologies, environmental sciences, agriculture, and other disciplines (Figure 1).

This multidisciplinary approach reflects current European policy priorities, which encourage universities to embed sustainability and digitalisation throughout higher education rather than treating them as isolated fields of study.

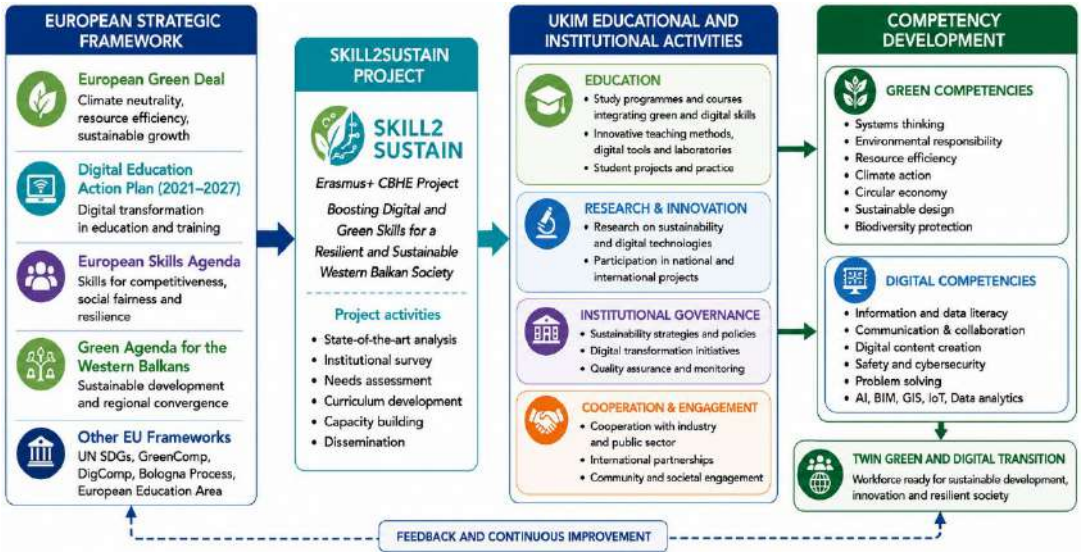


Figure 1 *– Conceptual framework linking European policies, the SKILL2SUSTAIN project, UKIM educational activities and competency development.*

4.2. Integration of green competencies

The analysis identified a broad range of study programmes addressing sustainability-related competencies. Green skills are particularly well represented within engineering, architecture, environmental sciences, agriculture, and natural sciences, where sustainability principles are integrated into both undergraduate and postgraduate education.

The identified educational content includes: renewable energy systems; sustainable construction; environmental protection; climate adaptation; circular economy; resource efficiency; waste and water management; biodiversity conservation; environmental legislation; disaster risk reduction.

These competency areas correspond closely to the GreenComp framework, particularly regarding systems thinking, environmental responsibility, and sustainable decision-making.

The survey also indicates that practical learning plays an important role in competency development. Laboratory exercises, design studios, fieldwork, and project-based learning enable students to apply sustainability principles to real-world engineering and environmental challenges.

4.3. Integration of digital competencies

Digital competencies are strongly embedded across technical and engineering programmes, particularly within the Faculties of Electrical Engineering and Information Technologies, Civil Engineering, Mechanical Engineering, and Architecture (Figure 2).

The survey identified educational content covering: software engineering; artificial intelligence; machine learning; Building Information Modelling (BIM); Geographic Information Systems (GIS); automation and robotics; cloud computing; Internet of Things (IoT); digital communication; data analytics.

These competencies closely reflect the DigComp framework while also supporting sustainable development objectives.

An important finding is that digital technologies are increasingly taught as tools for solving environmental and societal challenges. BIM supports resource-efficient construction, GIS facilitates spatial planning and environmental monitoring, while artificial intelligence and data analytics contribute to smart infrastructure, intelligent energy systems, and environmental management.

This convergence demonstrates that green and digital competencies are no longer developed independently but increasingly complement one another within contemporary engineering education.

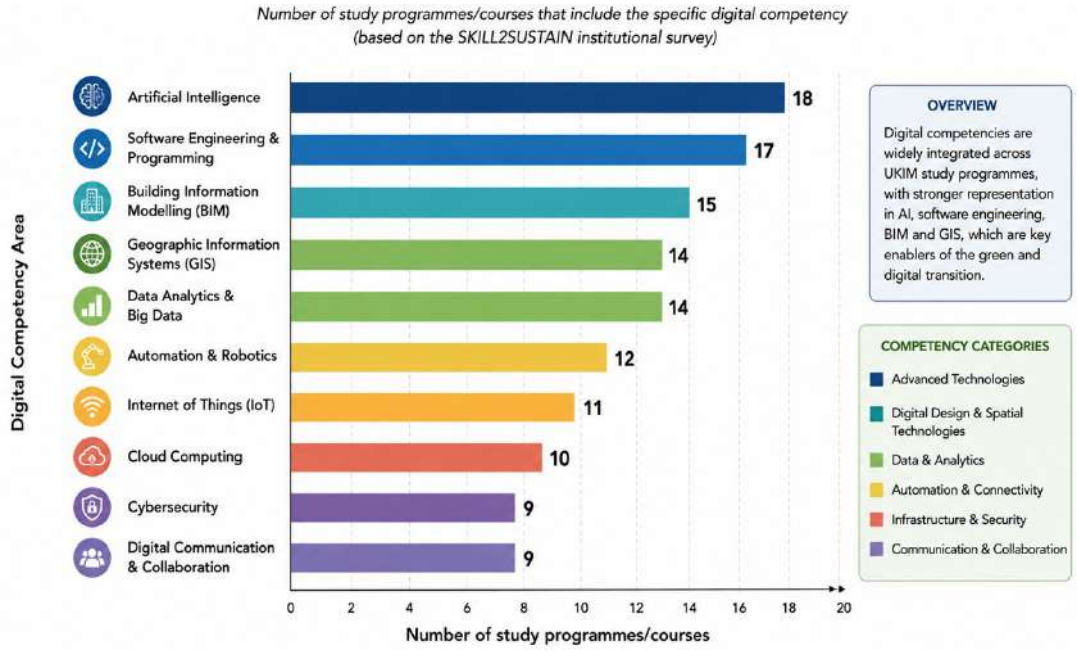


***Figure 2** – Distribution of digital competencies across UKIM study programmes*

4.4. Key findings

The survey confirms that UKIM has made substantial progress in integrating green and digital competencies into higher education (Figure 3). Engineering disciplines demonstrate the highest degree of integration, particularly in civil engineering, electrical engineering, mechanical engineering, architecture, and information technologies.

The analysis nevertheless identifies several opportunities for further development.

First, sustainability and digital competencies remain more strongly represented within technical disciplines than in social sciences, economics, education, law, and humanities. Expanding interdisciplinary approaches would strengthen the university's contribution to sustainable development.

Second, closer alignment with the GreenComp and DigComp competence frameworks would facilitate competency-based curriculum design and improve comparability with European higher education standards.

Third, greater cooperation with industry and public institutions could enhance practical learning opportunities through internships, challenge-based projects, and collaborative research.

Finally, expanding lifelong learning initiatives, including professional training and micro-credentials, would support continuous upskilling in response to rapidly evolving labour market demands.

Overall, the findings indicate that UKIM possesses a solid institutional foundation for supporting North Macedonia's green and digital transition while highlighting opportunities for further curriculum innovation and institutional development.

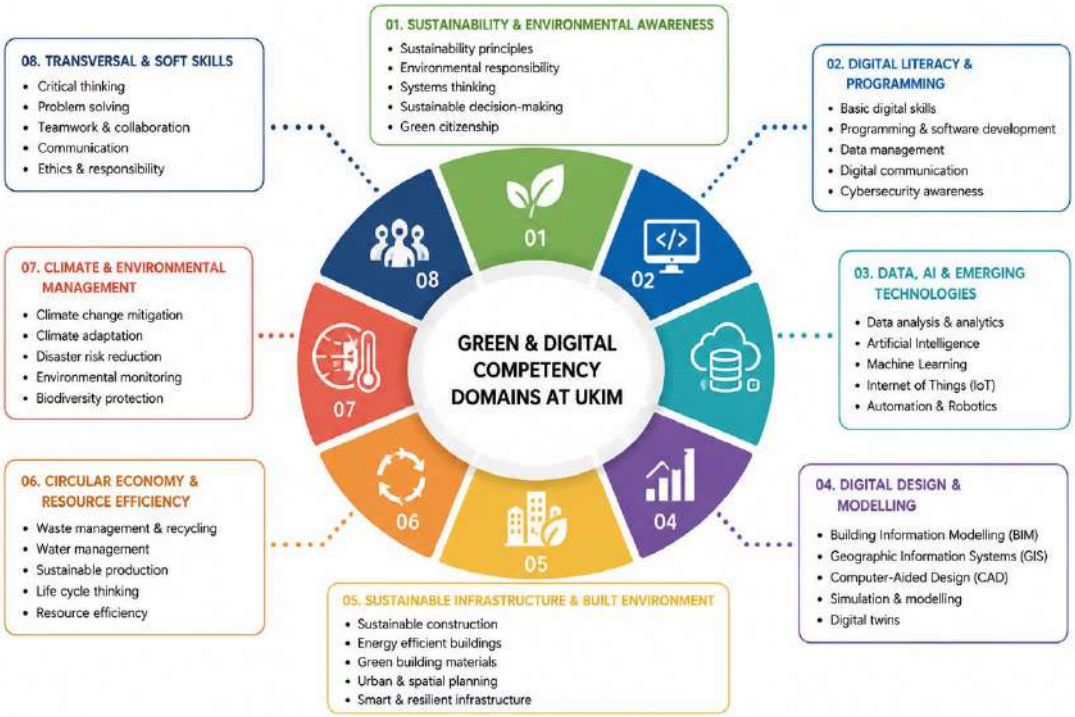


Figure 3 *– Key competency domains identified through the SKILL2SUSTAIN survey.*

5. Discussion

The findings demonstrate that Ss. Cyril and Methodius University in Skopje (UKIM) has established a solid foundation for integrating green and digital competencies within higher education. The identified study programmes indicate that sustainability and digitalisation are increasingly embedded across engineering, architecture, environmental sciences, and information technology, reflecting broader European priorities for the twin transition.

An important outcome of the analysis is the growing convergence between green and digital competencies. Rather than being developed independently, digital technologies such as artificial intelligence, Building Information Modelling (BIM), Geographic Information Systems (GIS), and data analytics are increasingly applied to address sustainability challenges, including energy efficiency, environmental monitoring, resilient infrastructure, and resource management. This integration corresponds closely with current European policy frameworks, which recognise digitalisation as an essential enabler of sustainable development.

The study also highlights the importance of interdisciplinary education. While engineering disciplines demonstrate the highest level of competency integration, expanding sustainability and digital learning across social sciences, economics, law, education, and other non-technical fields would further strengthen the university's contribution to national development. Contemporary environmental and technological challenges require collaboration across multiple disciplines and professional sectors.

Another important finding concerns the role of cooperation between universities and external stakeholders. Stronger partnerships with industry, public institutions, and international organisations would facilitate curriculum modernisation, increase opportunities for work-based learning, and ensure that graduates develop competencies aligned with labour market needs.

Finally, the analysis suggests that future curriculum development should increasingly adopt recognised European competence frameworks such as GreenComp and DigComp. Their systematic implementation would support competency-based curriculum design, facilitate programme evaluation, and improve the international comparability of higher education provision.

Overall, the findings confirm that UKIM is well positioned to contribute to North Macedonia's green and digital transition. Continued investment in interdisciplinary education, lifelong learning, international cooperation, and curriculum innovation will further strengthen its role in supporting sustainable development.

6. Conclusions

Higher education institutions have become key actors in supporting the green and digital transition by preparing graduates with the knowledge and competencies required for sustainable economic and social development. This study examined the contribution of Ss. Cyril and Methodius University in Skopje to this process through an analysis of study programmes and institutional initiatives conducted within the Erasmus+ SKILL2SUSTAIN project.

The results demonstrate that UKIM has made significant progress in integrating sustainability and digital technologies across a broad range of academic disciplines. Green competencies are particularly evident within engineering, architecture, environmental sciences, and agriculture, while digital competencies are strongly represented through programmes addressing artificial intelligence, software engineering, Building Information Modelling, Geographic Information Systems, automation, and related technologies. Importantly, many programmes combine environmental sustainability with advanced digital applications, illustrating the increasingly interconnected nature of the twin transition.

Despite these positive developments, the study identifies opportunities for further improvement (Figure 4). Greater interdisciplinarity, stronger alignment with the GreenComp and DigComp competence frameworks, enhanced cooperation with industry, and expanded lifelong learning opportunities would further strengthen the university's capacity to respond to emerging societal and labour market needs.

Although the research focuses on a single institution, the findings provide valuable insights into the current state of higher education in North Macedonia and demonstrate the important role universities can play in supporting sustainable development and digital transformation. Future research could extend this analysis to other higher education institutions in the country and explore the impact of competency-based education on graduate employability and long-term societal resilience.

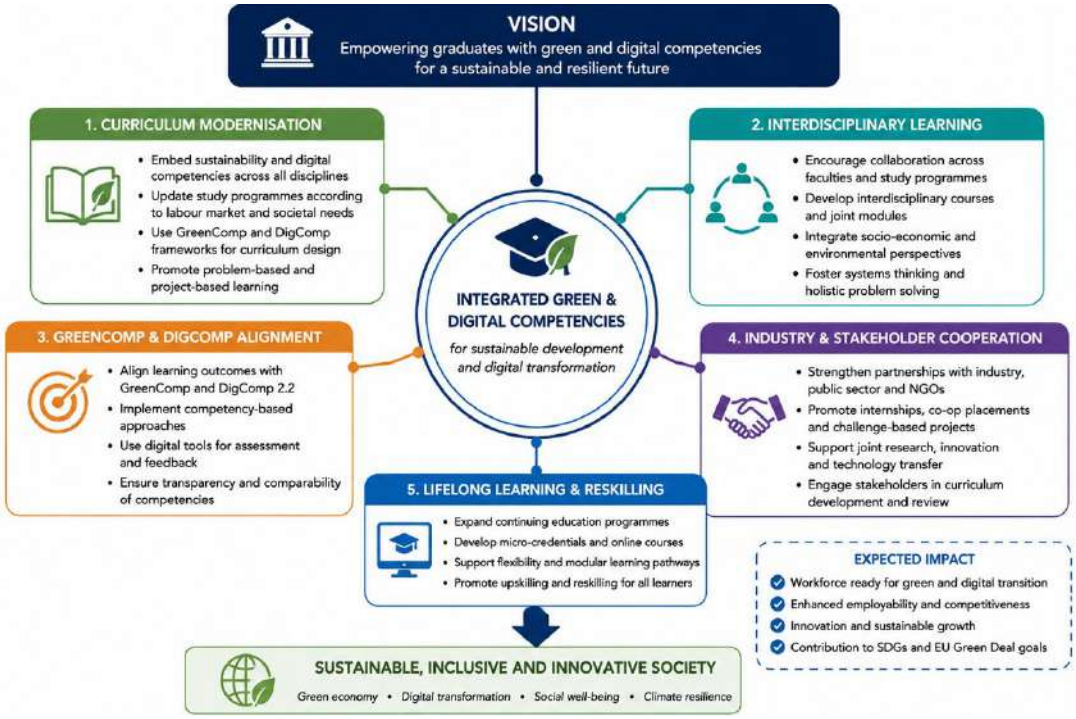


Figure 4 *– Recommendations for strengthening Green and Digital skills in Higher Education*

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Identification of Gaps Between Digital and Green Education in EU and Balkans HEIs

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Abstract

This paper identifies and analyses the gaps between digital and green education in higher education institutions (HEIs) of the European Union (EU) and the Western Balkans (WBC), drawing on a comparative desk research and stakeholder analysis conducted within the SKILL2SUSTAIN project. The analysis covers five key dimensions: strategic orientation, curriculum design and skills profiles, digitalisation of teaching and learning, green transition integration, and research, innovation and industry links. Data sources include institutional analyses of WBC HEIs, EU higher education mapping, and stakeholder survey results from SMEs, students, and public institutions in Bosnia and Herzegovina.

Findings reveal that WBC HEIs – including University College "CEPS-Center for Business Studies" Kiseljak, University of Banja Luka, University of Montenegro, University of Tirana, and Polytechnic University of Tirana – demonstrate growing strategic alignment with EU priorities, strong applied and regional relevance, and increasing integration of hybrid digital-green competencies, particularly at MSc and PhD level in technical disciplines. However, significant gaps persist compared to EU reference institutions such as the University of Novi Sad, University of Ljubljana, University of Zagreb, and Ss. Cyril and Methodius University in Skopje. These gaps span institutional governance, cross-faculty curriculum integration, advanced digital pedagogy, institution-wide green transition embedding, and research commercialisation capacity.

The analysis shows that the gap between WBC and EU HEIs is not one of vision, but of system maturity, institutional capacity and scale. WBC institutions operate in a project-driven mode, while EU institutions demonstrate systemic, governance-embedded transformation. Recommendations include transitioning from initiative-based to system-based reform, developing interoperable digital-green training frameworks, co-designing micro-credentials, strengthening research-innovation ecosystems, and embedding stakeholder-responsive governance. Bridging these gaps is a strategic priority for regional convergence, European integration, and sustainable higher education transformation across the Western Balkans.

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Keywords

Digital skills, green skills, higher education, Western Balkans, gap analysis, sustainability, SKILL2SUSTAIN.

1. Introduction

The twin digital and green transition represents one of the most urgent systemic challenges facing higher education institutions (HEIs) across Europe. While EU member states have developed robust policy frameworks – including the European Green Deal [1], the Digital Education Action Plan [2], and the EU Digital Decade [3] – higher education institutions in the Western Balkans (WBC) face the dual challenge of aligning with EU priorities while addressing persistent structural and resource constraints. This divergence has created measurable gaps in strategic governance, curriculum design, digital pedagogy, green competency integration, and research-innovation ecosystems [4].

This paper presents a systematic identification and analysis of these gaps, based on comparative desk research conducted as part of the SKILL2SUSTAIN project2. The analysis draws on three evidence sources: (i) institutional mapping of WBC HEIs, covering strategies, curricula, research projects and support centres; (ii) EU HEI practice mapping across equivalent dimensions; and (iii) stakeholder survey findings from SMEs, students and public institutions in Bosnia and Herzegovina. Together, these sources enable a supply-side and demand-side comparison across five analytical dimensions [5].

The paper is structured as follows: Section 2 describes the methodology; Section 3 analyses gaps across the five dimensions; Section 4 presents a synthesis and strategic recommendations; and Section 5 concludes with implications for EU-WBC cooperation and higher education transformation.

2. Methodology

The comparative analysis employs a structured desk research approach combined with qualitative content analysis and cross-dimensional benchmarking. EU HEIs – specifically the University of Novi Sad (UNS), University of Ljubljana (UL), University of Zagreb (UZ), and the Saints Cyril and Methodius University of Skopje (UKIM) – serve as a reference framework for identifying prevailing trends and good practices in digital and green education. WBC HEIs – CEPS Kiseljak, University of Banja Luka (UBL), University of Montenegro (UoM), University of Tirana (UT), and Polytechnic University of Tirana (PUT) – are analysed in terms of current implementation level and expressed institutional needs [5].

The analytical framework covers five dimensions: (i) strategic orientation and governance; (ii) curriculum design and skills profiles; (iii) digitalisation of teaching and learning; (iv) green transition integration; and (v) research, innovation and industry links. For each dimension, EU trends are contrasted with WBC realities, enabling systematic identification of gaps in skills provision, institutional frameworks, digital infrastructure and ecosystem cooperation. Stakeholder demand data from the SKILL2SUSTAIN questionnaires [6] provide additional validation of identified gaps from the perspective of SMEs, students and public entities.

3. Gap analysis

3.1. Strategic orientation gap

EU HEIs demonstrate a systemic, governance-driven approach to digital and green transition. Institutions such as UL, UZ, UNS and UKIM integrate sustainability and digitalisation into formal institutional policies, long-term roadmaps (2030–2040), quality assurance systems, materiality matrices, and publicly reported indicators. Dedicated structures – sustainability hubs, digital transformation offices, innovation ecosystems – ensure accountability and institutional continuity beyond individual projects [4].

WBC HEIs show increasing strategic awareness, with documents such as the CEPS Strategy 2024–2029, UPT Strategic Plan 2019–2024, UT Climate Action Plan, and UoM Development Strategy acknowledging sustainability, digitalisation and internationalisation as priorities. However, implementation remains fragmented and project-driven. Digitalization and sustainability are often confined to specific faculties, externally funded projects, or pilot actions, without full integration into cross-faculty governance, budgeting, or performance management systems [5].

The stakeholder surveys confirm this gap: WBC public institutions, SMEs and students all express strong and consistent demand for hybrid digital-green skill development, yet WBC institutional strategies are not yet consistently operationalised through university-wide governance mechanisms or permanent funding structures [6]. WBC transformation is initiative-based; EU transformation is system-based.

3.2. Curriculum design and skills profiles gap

Curriculum integration of hybrid digital-green skills is uneven across WBC institutions and program levels. At bachelor level, integration rates vary considerably: CEPS Kiseljak reaches 17–24% (except Information Technology at 78%), UBL achieves 10–33%, while UoM shows stronger coverage at 58–60%. MSc and PhD programs perform better, particularly in engineering: UoM MSc/PhD programs reach 60–71%, and PUT MSc/PhD programs in environmental and civil engineering reach 75–81%. Non-technical disciplines – economics, social sciences, natural sciences – show substantially lower integration across all WBC institutions [5].

EU HEIs, by contrast, integrate hybrid digital-green skills systematically across bachelor, master and doctoral levels. Curricula at UNS, UL, UZ and UKIM are modular, interdisciplinary, competence-based and project-oriented, with hybrid profiles such as AI combined with sustainability, BIM integrated with circular economy, and ESG linked to digital finance embedded early and across faculties [4]. Lifelong learning (LLL) and micro-credential ecosystems further support continuous upskilling in a manner not yet replicated at WBC scale.

The gap is characterised by limited interdisciplinary design, insufficient early bachelor exposure, weak inclusion of business and social science disciplines, and underdeveloped modular and project-based learning formats. WBC curricula are specialised but fragmented; EU curricula are systematic and transversal [7].

3.3. Digitalization of teaching and learning gap

WBC HEIs are advancing in the digitalisation of teaching but remain at a stage where digital tools are program-specific rather than institutionally embedded. CEPS, UBL, PUT and UT use blended learning, laboratory work, workshops, and Knowledge Hubs for Climate and Sustainability (KHCS) to support digital engagement. Tools such as BIM, GIS, simulation, and learning management systems are in use, but coverage is uneven and infrastructure varies significantly across institutions [5].

EU HEIs implement institution-wide digital ecosystems that transform pedagogy, assessment, and collaboration. Virtual labs, AI-supported teaching, digital twins, VR/AR environments, learning analytics, and integrated e-administration are increasingly standard at UNS, UL and UZ, enabling a systematic development of hybrid digital-green skill profiles across all disciplines [4]. Open-access research repositories and e-learning platforms further support lifelong and self-directed learning.

The gap is characterised by limited advanced tools (AI, VR/AR, digital twins) in WBC settings, absence of standardized digital pedagogy frameworks, and uneven institutional coverage. WBC digitalisation is functional; EU digitalisation is transformational [8].

3.4. Green transition integration gap

Green transition integration in WBC HEIs varies significantly by institution and discipline. PUT excels in engineering programs, reaching up to 81% integration at MSc/PhD level. CEPS and UBL integrate sustainability in energy, logistics, security and construction programs. UT shows limited integration in economics and natural sciences (3–11%). UoM integrates green topics mainly through civil engineering and infrastructure programs [5].

WBC HEIs demonstrate strong local relevance, applied focus and stakeholder engagement through KHCS and Knowledge Valorisation Centres (KVCs), but green transition is not yet institution-wide. EU HEIs embed green transition across curricula, research, governance and campus operations. Students work with advanced green tools (BIM, Life Cycle Assessment, digital twins, ESG modelling), and green competencies are standardized and harmonized across disciplines at UNS, UL, UZ and UKIM [4].

Key gaps include the absence of harmonized green competency frameworks, uneven coverage beyond engineering, and limited integration of green principles into campus operations and institutional governance. WBC green integration is adaptive and program-level; EU green integration is structural and institution-wide [9].

3.5. Research, innovation and industry links gap

WBC HEIs place strong emphasis on applied and regionally relevant research. CEPS implements initiatives such as SKILL2SUSTAIN, SEE-GL and GROWTH, addressing digital skills, green logistics and climate neutrality. UBL focuses on energy poverty, circular economy and sustainable infrastructure through projects like KLABS and ENPOWER. UT and PUT conduct research on energy efficiency, smart cities and digitalisation. Project budgets are moderate, typically ranging from €42,000 to €837,000, funded primarily through Erasmus+ CBHE and Horizon Europe capacity-building streams [5].

EU HEIs operate in high-intensity research and innovation ecosystems. UNS, UL and UZ pursue multi-million Horizon projects integrating AI, digital twins, smart water systems, green electronics and circular construction, with strong technology transfer, commercialization and spin-off development. Global partnerships and interdisciplinary

collaboration across faculties enable EU HEIs to shape policy, transfer technology and produce high-impact innovation outputs [4].

The gap is characterised by differences in research scale, commercialization capacity, IP management, and integration into global innovation networks. WBC innovation is capacity-building and employability-oriented; EU innovation is market-shaping and deep-tech driven [10].

4. Synthesis and recommendations

4.1. Overall gap synthesis

Table 1 presents a structured synthesis of the identified gaps across the five analytical dimensions, summarizing the current state of WBC and EU HEIs, the nature of the gap, and potential bridging pathways.

***Table 1** – Gap synthesis across analytical dimensions*

Dimension	WBC HEIs – Current State	EU HEIs – Current State	Nature of Gap	Bridging Pathways
Strategic Orientation	Project-driven; fragmented governance; limited cross-faculty integration	Systemic; long-term roadmaps; embedded in governance, budgeting, reporting	Institutional maturity and permanence	Establish RECs, interoperable platforms, cross-faculty governance structures
Curriculum Design	Uneven; strong in MSc/PhD engineering; weak at bachelor and social science level	Modular, interdisciplinary, competence-based across all levels and disciplines	Integration depth and disciplinary breadth	Introduce hybrid modules, interdisciplinary design, early bachelor exposure
Digital Learning	Tools and delivery focus; BIM, GIS, simulation; program-specific	Pedagogical transformation; AI, VR/AR, digital twins, learning analytics	Innovation level and pedagogy transformation	Invest in advanced digital tools, standardize digital pedagogy frameworks
Green Integration	Program-level; strong in engineering; limited in economics, social sciences	Institution-wide; harmonized green competencies; embedded in governance and campus	Structural embedding and institutional scope	Harmonize green competencies; extend beyond engineering; integrate campus operations
Research & Innovation	Applied, regional, capacity-building; moderate funding (€42k–€837k)	Deep-tech, global networks, multi-million Horizon projects, technology transfer	Innovation scale and commercialization	Strengthen R&I intensity, IP management, deep-tech partnerships
Lifelong Learning	Courses with ECTS credit (CEPS, UPT); limited scope and recognition	Micro-credentials ecosystem; widely recognized; industry-linked	Recognition, scalability, and stakeholder access	Develop micro-credentials, link to EU competency frameworks
Stakeholder Engagement	Operational; KHCS/KVC hubs; applied cooperation with SMEs and public sector	Strategic co-creation; embedded in R&I governance; policy and industry linkages	Governance integration and strategic scope	Integrate stakeholder needs into strategy, monitoring, and co-design processes

The analysis confirms that the gap between WBC and EU HEIs is not one of vision, but of system maturity, institutional capacity and scale. WBC HEIs demonstrate excellence in regional relevance, applied learning, stakeholder responsiveness and flexible adaptation, but transformation remains fragmented, project-based and resource-constrained. EU HEIs demonstrate institutionalised strategies, interdisciplinary curricula, advanced digital ecosystems, strong research-industry integration and scalable lifelong learning [7].

4.2. Strategic Recommendations

To bridge the identified gaps, WBC HEIs must transition from initiative-based reform to system-based transformation. This requires embedding digital and green transition into governance, funding, curriculum architecture, digital infrastructure, research commercialization and lifelong learning frameworks [8]. EU partnerships within SKILL2SUSTAIN and similar initiatives can accelerate this convergence by supporting institutional capacity building, interoperable platforms and regionally coordinated ecosystems aligned with European climate neutrality and digitalisation objectives [1,2].

***Table 2** – presents a structured set of recommendations organized by priority area and implementation horizon.*

Priority Area	**Short-Term Actions (6–18 months)**	**Medium-Term Actions (18–36 months)**
Governance & Strategy	Map existing digital-green strategies; establish cross-faculty coordination bodies	Embed sustainability into budgeting, QA and institutional reporting systems
Curriculum	Introduce hybrid modules at bachelor level; extend to non-technical disciplines	Develop modular, competence-based interdisciplinary curricula aligned with EU frameworks
Digital Pedagogy	Pilot advanced digital tools (AI, BIM, GIS); staff training in digital pedagogy	Standardize digital pedagogy frameworks; deploy virtual labs and learning analytics
Green Integration	Harmonize green competencies; develop green campus operational plans	Embed green transition across all faculties; link to EU Green Deal monitoring indicators
Research & Innovation	Strengthen KVC/KHCS networks; apply for larger Horizon consortia	Build deep-tech partnerships, IP capacity, and commercialization pathways
Lifelong Learning	Design and pilot micro-credentials in key hybrid skill areas	Build recognized LLL ecosystem linked to EU competency frameworks and industry
Stakeholder Engagement	Map stakeholder skills needs annually; include in curriculum review processes	Co-design training programmes with SMEs, public institutions and EU partners

Joint training delivery, co-designed micro-credentials, living labs, and public-private innovation workshops focusing on AI adoption, energy efficiency, and sustainability reporting are identified as the highest-impact cross-stakeholder interventions within the SKILL2SUSTAIN framework [6].

5. Conclusion

This paper presents a systematic gap analysis between digital and green education in EU and Western Balkans HEIs across five dimensions: strategic orientation, curriculum design, digital pedagogy, green transition integration, and research-innovation capacity. The analysis demonstrates that WBC HEIs are strategically aligned in vision but limited in institutional depth, while EU HEIs demonstrate systemic, governance-embedded transformation supported by advanced infrastructure, interdisciplinary curricula and global innovation ecosystems.

The identified gaps are structural rather than attitudinal: WBC institutions operate with strong motivation, regional relevance and growing stakeholder demand, but face persistent constraints in permanent funding, cross-faculty coordination, advanced digital tools, harmonized green competency frameworks, and research commercialization capacity. Closing these gaps requires a coordinated transition from project-driven to system-driven reform, supported by EU-WBC cooperation, interoperable institutional frameworks, and regionally scaled capacity-building mechanisms.

The SKILL2SUSTAIN project, and future collaborations building on its findings, represent a strategic opportunity to operationalise this transition. By co-designing training, embedding stakeholder needs into institutional governance, and scaling micro-credential and research-innovation ecosystems, WBC HEIs can accelerate convergence with EU benchmarks and contribute meaningfully to European climate neutrality and digital transformation objectives.

Acknowledgement

This research was conducted within the SKILL2SUSTAIN project – Boosting digital and green skills for a resilient and sustainable Western Balkan society – co-funded by the European Union under the Erasmus+ Programme (Grant Agreement No. 101127181). The views and opinions expressed are those of the authors only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA).

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Needs assessment for WBC Digital and Green Education in Academia

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Abstract

Higher Education Institutions (HEIs) are in continuous pressure to be the leaders on the twin transition, by adopting digital transition and green skills into their curricula, study programs, and research activities. The aim of this study was to identify the current situation with the adaptation of digital and green transition in five HEIs of the Western Balkan Countries (Albania, Bosnia and Herzegovina, and Montenegro). This research is done in the framework of SKILL2SUSTAIN project, where all these higher education institutions are partners. The results showed the commitment of these institutions to prepare institutional frameworks, initiatives or strategies focused on the digital and green transition. While, curricula review revealed a variation within and between HEIs of WBCs related to the percentage of digital and green skills offered from each program type (Bch, MSc, PhD). Moreover, it was reported the involvement of these universities in various projects with focus on digitalization, green skill, sustainability, as well as their specific course and centres offering knowledge and expertise in both digital and green skills.

Keywords

Digital Transition, Green Skills, Sustainability, Higher Education Institutions, Western Balkan Countries, Curricula.

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1. Introduction

The convergence of digitalization and sustainability agendas increasingly conceptualized as the "twin transition", has emerged as a central point in among academics and policy makers, defined as the synergistic deployment of digital technologies to advance environmental sustainability objectives [1]. While the European Commission has framed this intersection as a cornerstone of its strategic vision for a resilient and sustainable future, the articulation and operationalization of the twin transition within higher education institutions (HEIs) remains insufficiently understood [2-3]. As universities are positioned as knowledge producers, educators, and societal anchors, they are expected to integrate digital technologies and sustainability principles into their operations, educational offerings, and stakeholder engagement. However, emerging evidence indicates that HEIs often struggle to align digital investments with sustainability objectives due to fragmented strategies, limited integration, and underdeveloped governance arrangements [4]. A recent systematic review reveals that research on the convergence of digitalization and sustainability in higher education is organized around interconnected thematic domains centred on technology acceptance, innovation, sustainable learning, and institutional transformation [5]. Studies demonstrate that sustainability principles including green chemistry, circular economy, and resource efficiency are often confined to elective courses rather than being integrated into core curricula [4]. Similarly, digital competencies are frequently introduced at a basic level, with limited exposure to advanced technologies such as artificial intelligence and machine learning. The Western Balkan (WBC) region confronts these global challenges within a distinct institutional and developmental context. As HEIs across the region navigate their path toward EU integration, they face considerable systemic barriers related to: infrastructure, academic staff trainings, funding, and a significant competency gap wherein digital skills and green concepts remain weakly integrated or confined to specific disciplines [6].

In response to these challenges, a series of international cooperation projects particularly those funded under the Erasmus+ Capacity Building in Higher Education programme are actively orchestrating systemic transformation across the region. Initiatives such as SKILL2SUSTAIN exemplify the regional commitment to mainstreaming holistic approaches that treat digital and green skills as interconnected components of modern education [7]. The aim of this study is to get an overview of digital and green transition initiatives in each of HEI partners of the SKILS2SUSTAIN project in Albania, Bosnia and Herzegovina, and Montenegro.

2. Materials and methods

The research presented in this article is based on one of the findings of SKILL2SUSTAIN project. This project has been funded with support from European Commission, within ERASMUS + programme. This section presents the methodology used during the completion of the task about all practices related to digital and green transition in each Higher Education Institutions (HEI) in Albania, Montenegro and Bosnia and Hercegovina. For this purpose, from each HEI part of the SKILL2SUSTAIN project was collected the following information:

- The institutional framework/strategies/efforts for implementation of digital and green solutions within HEI services.
- Review of curricula related to green and digital skills.
- List of courses focused on green transition and digital skills
- List of projects (finished/on-going) related to green transition and digital skills.

- List of centres (HUBs) offering services or green and digital research for academics and stakeholders.

The purpose of collecting all practices related to digital and green transition was to create an overview of the current situation at WBC HEIs, and then to compare these findings with our EU and associated to EU HEIs partners. The detailed information was reported from five Higher Education Institutions:

- two HEIs in Albania: Polytechnic University of Tirana (PUT), and University of Tirana (UT);
- two HEIs in Bosnia and Herzegovina: University of Banja Luka (UBL), and University College CEPS Kiseljak;
- one HEI in Montenegro: University of Montenegro (UoM).

All datas were reported at the institutional level for each HEI of Albania, Montenegro and Bosnia and Hercegovina.

Regarding the information about the review of the curricula focused on digital and green transition was reported at the institutional level for all study programs offered from each HEI, as well as with the number of study programs in which some subjects are related to green and digital skills practices, and the percentage that this subjects has for each program type (Bachelor/Master/PhD).

3. Results and discussions

To address the twin transition, HEIs has to be committed first of all in developing specific strategies for implementation of digital and green solutions within HEI services. For this reason, the first part of this research was focused on the analysis of these institutional framework/strategies/efforts in each partner HEI of Albania, Bosnia and Herzegovina, and Montenegro. This analysis revealed the increasing efforts of university governing bodies in the preparation and approval of different internal regulations, initiatives or strategies with focus on digitalization and sustainability. Three of these HEIs (PUT, UT, CEPS) reported the “Plan for climate action” prepared under the 1Future project. The UOM reported an institutional unit established to coordinate and support digital transformation initiatives, digital services, innovation activities, and the use of advanced ICT solutions within university operations and HEI services.

Recognizing that in each higher education institutions in the Western Balkans digital and green transition can be different, depending on specific needs and capabilities of individual institutions, we were focused on the review of curricula related to digital and green skills. Below are given the statistics related to the total number of Bachelor/Master/PhD programs for each HEI in Albania, Bosnia and Herzegovina, and Montenegro, and the percentage of those programs focused on digital and green transition, as well as the information related to specific courses, projects and centres focused on green transition and digital skills at the faculty or University level for each WBC partner.

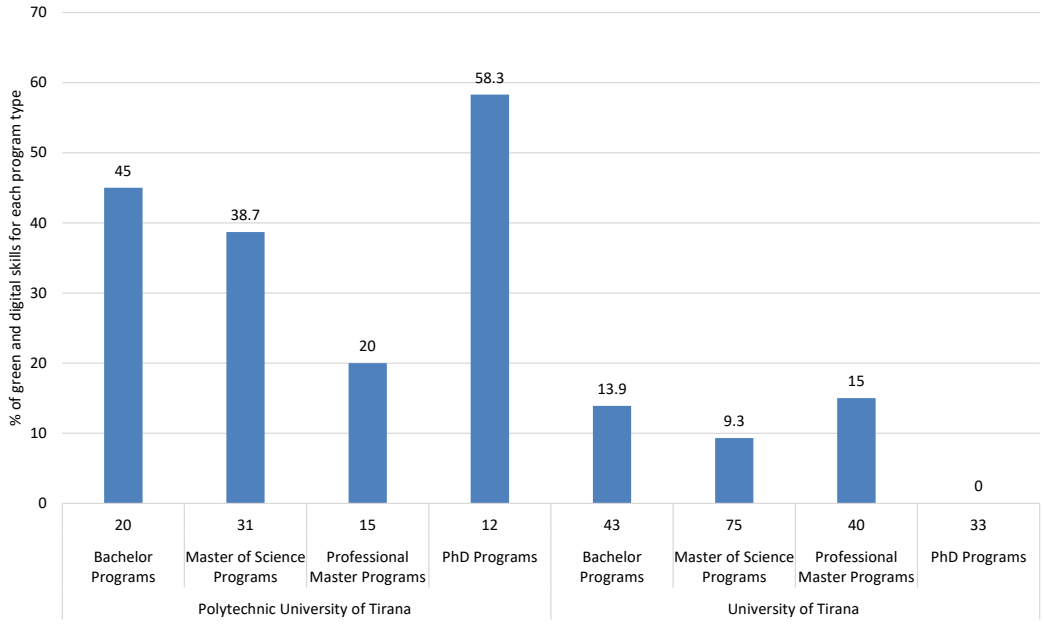


Figure 1 – *Study programs offered from each Higher Education Institution in Albania and the percentage of green and digital skills for each program type.*

As can be seen in Figure 1, Albanian HEIs offers different study programs at all three levels, both in terms of quantity and curriculum. It is evident that the percentage of those programs focused on green and digital skills varies from 0% to 15% at the University of Tirana for bachelor and master programs, and from 20% to 58.3% at the Polytechnic University of Tirana for bachelor, master and PhD programs. The PhD programs at the Polytechnic University of Tirana has the highest percentage of green and digital skills than any other program, due to the focus of the PhD projects on topics related to IT, AI, environment, sustainability, construction and not only.

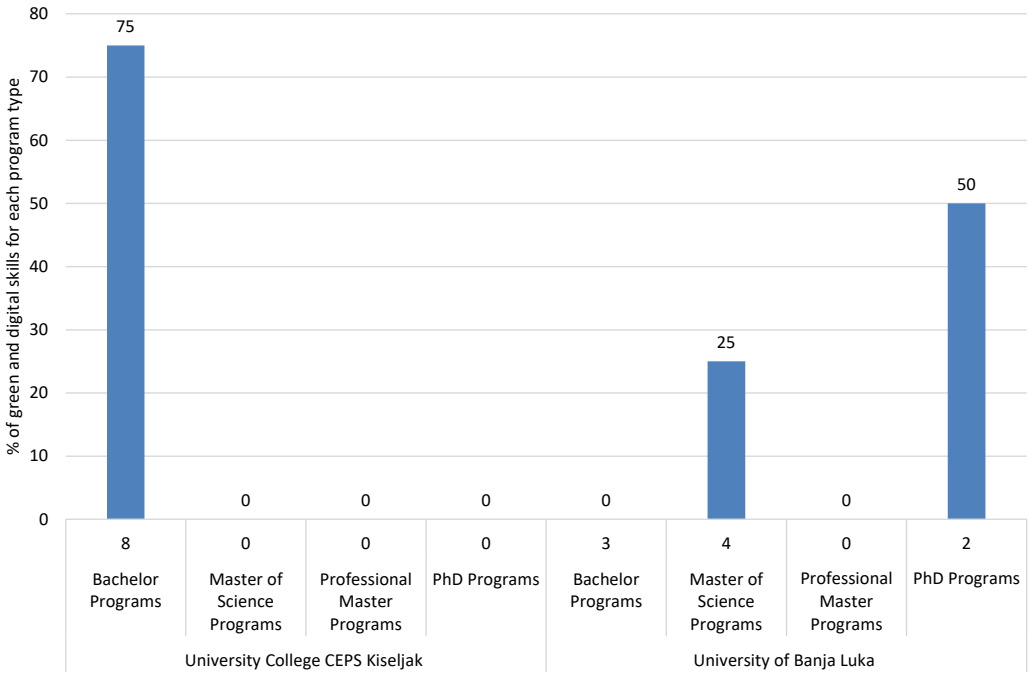


Figure 2 – *Study programs offered from each Higher Education Institution in Bosnia and Herzegovina, and the percentage of green and digital skills for each program type.*

The University College CEPS Kiseljak in Bosnia and Herzegovina offers only Bachelor programs, where 75% of them offers in their curricula topics or practices related green and digital skills. While, the University of Banja Luka offers bachelor, master of science and PhD study programs, where the percentage of green and digital skills for each program type is respectively 0%, 25% and 50%, as it is shown in figure 2.

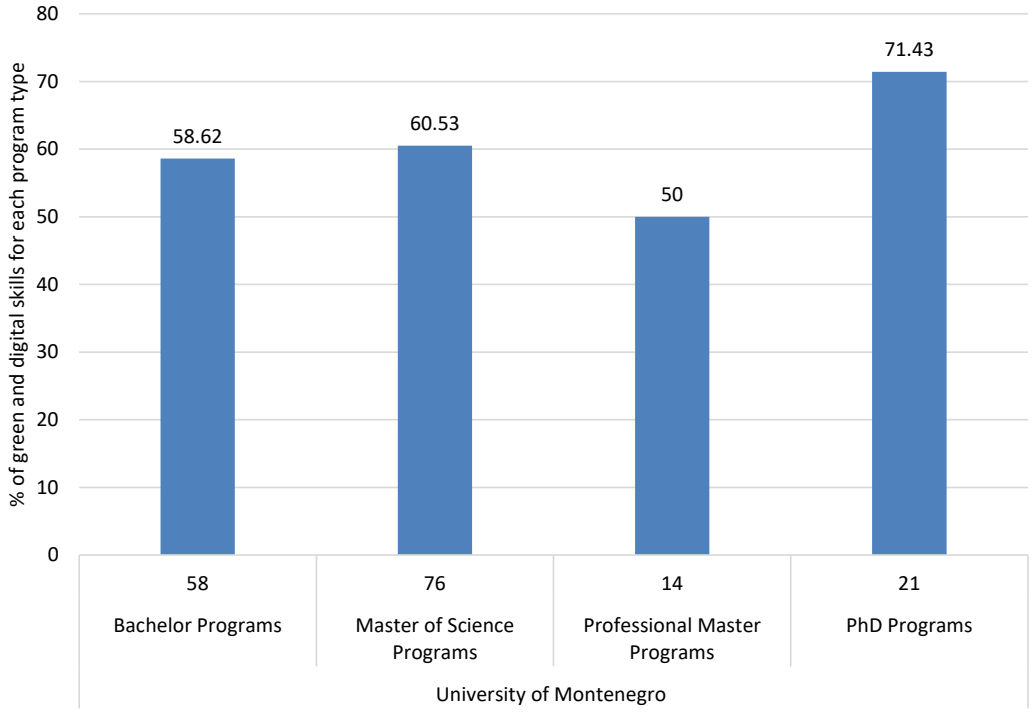


Figure 3 – *Study programs offered from the Higher Education Institution in Montenegro and the percentage of green and digital skills for each program type.*

The review of curricula at the University of Montenegro in Montenegro it is shown in figure 3, where the huge number of Bachelor and master of science programs stands out, as well as the percentage of green and digital skills at all study programs, varying from 50 to 72.

Another category taken into analysis within this research is the list of courses focused on digital and green transition offered by units within HEIs. In Albania, it is reported only one course delivered by the Faculty of Civil Engineering at the Polytechnic University of Tirana on “Real estate evaluation”. While, from Bosnia and Herzegovina, the University College CEPS Kiseljak offers a short course on “Sustainable Development, Circular Economy, and Societal Resilience (1FUTURE)”, and two Long Life Learning courses on “Analysis and Management of Operational Business Risks” and “Critical Infrastructure Risk Management”.

Another category taken into analysis within this research is the participation of HEIs in the WBCs in projects focused to green transition and digital skills, as can be seen in the table below. The majority of the projects are still on-going in all WBC HEI.

Table 1 – *Projects focused to green transition and digital skills in each Higher Education Institution in Albania, Bosnia and Herzegovina, and Montenegro.*

WBC	HEI	No of project focused to green transition and digital skills	ongoing
ALBANIA	Polytechnic University of Tirana	17	17
	University of Tirana	25	20
BOSNIA AND HERZEGOVINA	University College CEPS Kiseljak	9	9
	University of Banja Luka	5	2
MONTENEGRO	University of Montenegro	6	4

Finally, the analysis of the centers offering services on green and digital research for academics and stakeholders from each HEI, revealed that: The Faculty of Civil Engineering (PUT), Faculty of Economics (UT), and the University College CEPS Kiseljak have all the same center related to green and digital services “Knowledge Hub for Climate and Sustainability”. These centres was established in the framework of the 1FUTURE Project, as a working and research space for academics, students, professional and stakeholders. The University of Banja Luka has one center for “Materials and Constructions”, which supports the development and testing of materials applied in civil engineering and related fields, with a particular emphasis on research into the use of recycled materials. While at the University of Montenegro, several institutional centers support digital research infrastructure and services. These include the Centre of Information Systems (CIS), which provides digital networking, servers, and IT infrastructure; the Central University Library and digital repositories that support access to e-resources and open data; and the EURAXESS Centre, which supports researchers in accessing international digital research platforms. Additionally, the BIO-ICT Centre specifically integrates both digital technologies and green research approaches, offering multidisciplinary support relevant to sustainable and environmental research and technology development.

4. Conclusions

In summary, analysis of this study provided an overview of institutional frameworks, initiatives and strategies related to digital ang green skills, and it can be concluded that WBC higher education institutions are in the process of adopting the necessary regulations and strategies towards a smother twin transition.

HEIs in Albania, Bosnia and Herzegovina, and Montenegro performed the review of the curricula for all study programs offered at each HEI, by giving the information related to related to green and digital skills included in each study program. Curricula review revealed a variation within and between HEIs of WBCs related to the percentage of green and digital skills offered from each program type (Bch, MSc, PhD). Study programs offered in Albanian HEIs has already from 0 to 58% green and digital skills part of their curricula. The inclusion values of green and digital skills for each program type in the University of Montenegro has small differences between them, varying from 50 to 72%. While, in Bosnia and Herzegovina HEIs offers from 25 to 75% of green and digital skills in their study programs.

The higher education institutions have a good experience regarding the various projects with focus on digitalization, green skill, sustainability etc., in which they have been or are involved, since some of them are currently on-going. The large number of these projects shows the commitment of each country as well as the European Union or other organizations for financial support.

The curricula of each program type (Bch, MSc, PhD) in Albania, Bosnia and Herzegovina, and Montenegro's HEIs should include more topics or practices linked to the green skills and digitalization. Moreover, HEIs in these WBCs should prepare and implement specific plans or strategies in their institutional framework for a more digitalized and sustainable development.

Acknowledgement

This research was conducted within the "Boosting digital and green skills for a resilient and sustainable Western Balkan society"–SKILL2SUSTAIN Project 101178204-ERASMUS-EDU-2024-CBHE-STRAND-2, funded by the European Union. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

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Stakeholders' Needs for Green and Digital Skills in Bosnia and Herzegovina

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Abstract

This paper presents the results of a needs assessment conducted in Bosnia and Herzegovina within the Erasmus+ project SKILL2SUSTAIN – Boosting Digital and Green Skills for a Resilient and Sustainable Western Balkan Society. The study explored the digital and green skills needs of three stakeholder groups: SMEs, university students, and public institutions. Data were collected through tailored questionnaires completed by 123 SMEs, 477 students, and 22 public institutions.

The findings indicate strong demand for digital competencies, particularly in process automation, data analytics, artificial intelligence, and e-commerce, alongside clear sustainability priorities including energy management, circular economy practices, waste reduction, carbon footprint measurement, and compliance with EU sustainability standards. Students demonstrated high interest in sustainability-related projects and internships, while SMEs and public institutions expressed readiness to engage in training and capacity-building initiatives. These results highlight a growing need for integrated digital-green skill development and practical support for sustainability implementation, pointing to targeted training programmes, specialized green skills curricula, public-private collaboration initiatives, and structured internship opportunities as key recommendations. The findings provide a foundation for designing responsive training frameworks and strengthening stakeholder cooperation to support long-term sustainability and resilience in Bosnia and Herzegovina and the wider Western Balkans region.

Keywords

Digital skills, green skills, SMEs, public institutions, students, Bosnia and Herzegovina, SKILL2SUSTAIN, hybrid competencies, sustainability, training needs.

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1. Introduction

The global transition toward digital economies and green sustainability is reshaping labour markets and institutional competences worldwide. In the Western Balkans, this transition represents both an opportunity and a challenge: while regional stakeholders are aware of the urgency, structured frameworks for hybrid digital-green capacity building remain underdeveloped [1]. Recent evidence suggests that this digital-green skills gap is widening rather than closing. Cedefop's 2024 skills forecast digitalisation scenario shows that Europe's digital and green transitions are becoming increasingly intertwined, with up- and reskilling efforts still lagging behind the pace of technological and environmental change across EU labour markets [9]. At the regional level, the OECD's 2025 Economic Convergence Scoreboard for the Western Balkans identifies the skills cluster as the weakest-performing dimension relative to the EU, pointing to persistent shortfalls in employer-led digital skills training and continuing gaps in preparedness for the green transition across the region [11]. Comparable disconnects between educational outcomes and labour-market demand for green competencies have also been documented beyond the Western Balkans: a recent mixed-methods study of university students and companies found that, despite strong recognition of the importance of green skills on both sides, persistent barriers — limited practical learning opportunities, the cost of specialised certifications, and the absence of standardised recruitment criteria — continue to widen the gap between academic preparation and industry requirements [10]. Bosnia and Herzegovina, as a prospective EU member, faces particular pressure to align its educational, institutional, and business capacities with EU Green Deal objectives and digital transformation priorities [2].

This paper presents the results of a stakeholder needs assessment conducted under Task 2.4 of the SKILL2SUSTAIN project, coordinated by the University College “CEPS – Center for Business Studies”, Kiseljak, in partnership with the University of Banja Luka, the Chamber of Economy of the Federation of Bosnia and Herzegovina, and the Chamber of Commerce and Industry of the Banja Luka Region. The survey targeted three distinct groups: small and medium enterprises (SMEs), university students, and public institutions.

The purpose of this study is to identify existing skill gaps, training preferences, and readiness levels across stakeholder groups, providing an evidence base for designing relevant, demand-driven capacity-building actions. This paper is structured as follows: Section 2 presents the methodology; Section 3 discusses findings per stakeholder group; Section 4 synthesizes cross-stakeholder patterns; Section 5 presents recommendations; Section 6 discusses the limitations of the study; and Section 7 concludes with a summary of contributions.

2. Methodology

Three stakeholder surveys were implemented between October and November 2025. The questionnaires were developed in English and translated into Bosnian and Serbian to ensure clarity and accessibility. Distribution was conducted digitally through email outreach, institutional channels, and student networks, with responses collected via Google Forms. Data were stored in centralized folders per stakeholder group for consistency and traceability.

The targeted sample covered 22 public institutions, 123 SMEs, and 477 students across different academic years and disciplines. Each form opened with an informed consent statement ensuring anonymity, voluntary participation, and compliance with EU GDPR [3] and Bosnia and Herzegovina Law on Personal Data Protection [4]. The questionnaire design prioritized simplicity: questions were predominantly multiple-choice (single or multiple

answer), with an average completion time of 4–6 minutes, reducing respondent fatigue and improving response quality.

The near-complete response rate among public institutions reflects the coordinated distribution of the questionnaire through a small number of institutional contacts and chamber partners, whereas the comparatively lower response rates among SMEs and, particularly, students are consistent with typical patterns observed in voluntary, self-administered online surveys, where non-response is influenced by time constraints, competing priorities, and variable levels of engagement with the survey topics. Forms that were incomplete or did not meet the predefined data-quality criteria were excluded from the final dataset prior to analysis. Specifically, fewer than 20 responses were excluded due to incomplete questionnaires, missing key variables, and/or inconsistent or invalid responses. The survey methodology combined digital convenience, ethical safeguards, national collaboration, and a time-efficient design, ensuring alignment with the procedural requirements of the SKILL2SUSTAIN project framework while supporting the reliability and consistency of the collected data [5].

3. Findings

A stakeholder needs assessment was conducted among public institutions, university students, and SMEs in Bosnia and Herzegovina to identify priorities related to digital transformation and sustainability. The survey results provide insights into current skill needs, training interests, and opportunities for future digital-green capacity building and collaboration within the SKILL2SUSTAIN project.

3.1. Public institutions

A total of 22 valid responses were collected from public institution representatives, reflecting a diverse sample: educational institutions (~27%), public agencies (~18%), ministries (~14%), service organizations (~14%), municipalities (~9%), and public enterprises (~9%). Most respondents represent small institutions (1–49 employees), indicating that digitalization and sustainability initiatives are especially relevant for smaller public bodies.

Regarding openness to digital transformation, 74% of respondents described their institution as "very open," 13% as "partially open," and 13% as insufficiently open. Green skills were rated as "very important" by 48% and "somewhat important" by 43%, confirming broad sustainability awareness within the public sector.

Priority digital capacity-building areas included data management and analysis (72.7%), digital communication with citizens (59.1%), e-governance platforms (54.6%), and cybersecurity (45.5%). Sustainability support needs centred on energy management and circular economy (both 40.9%), energy efficiency in public buildings and sustainable urban mobility (both 36.4%), and waste management (27.3%). Interest in training on renewable energy was high: 61% very interested and 30% somewhat interested [5].

Preferred AI tools for public services included resource optimization (energy, water, transport), smart city applications, and predictive analytics for policy-making. For carbon footprint management, respondents favoured online monitoring platforms (~35%) and consultancy services for sustainability reporting (~35%). Technical assistance for environmental certifications (e.g., ISO 14001) was rated as very important by the majority, while awareness and use of digital partnership platforms for green initiatives remained limited, signalling a gap in cross-institutional networking capacity.

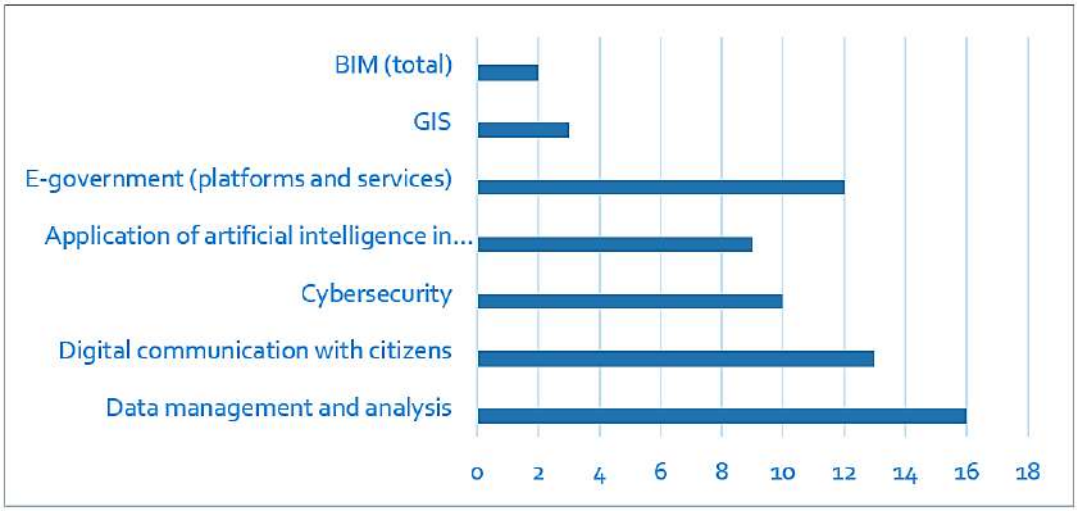


Figure 1 *– Areas of digital capacity-building most relevant for the staff (Source: Authors)*

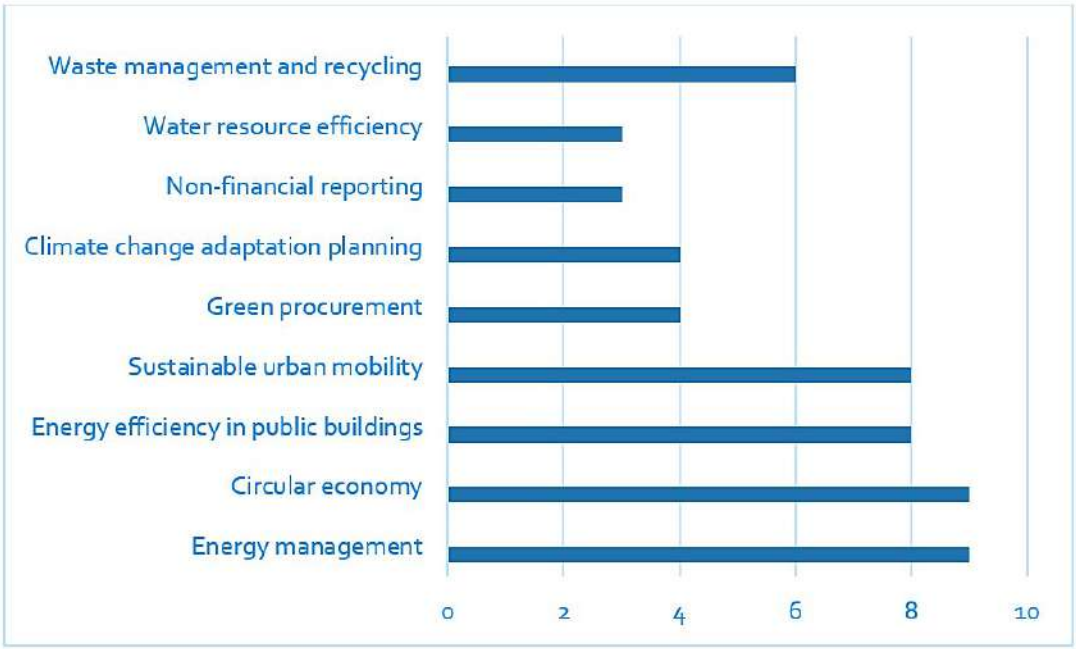


Figure 2 *– Sustainability areas the institutions like more support (Source: Authors)*

3.2. University students

The student survey gathered 477 valid responses from the University College CEPS (social and technical fields) and the University of Banja Luka (engineering and technology). The sample comprised 40.5% economy/business/social science students and 59.5% engineering/technology students, with 66% enrolled in first- or second-year programmes. Most respondents (99.6%) were in Bachelor or Master programmes.

Digital self-assessment showed a broadly confident cohort: approximately 40% rated their skills as High or Very High, 50% as Medium, and 10% as Low or Very Low. Priority improvement areas included Building Information Modelling – BIM (~42%), Artificial Intelligence and Machine Learning (~36%), data analysis (~30%), digital communication tools (~25%), and cybersecurity (~22%). Interest in AI training was particularly pronounced:

50% reported being very interested, and 31% somewhat interested, with highest engagement among engineering students.

On sustainability, 42% of students considered green skills "very important" for their future careers and 45% "moderately important," with 87% overall recognising sustainability competence as professionally relevant. Most frequently selected learning areas were energy efficiency (45%), climate change and environmental protection (39%), and renewable energy (34%). Regarding sustainability projects such as green campus initiatives, 22% were very interested and 35% moderately interested, suggesting strong potential for campus-level engagement [6].

For career support, students prioritized practical training opportunities (50%), networking with companies and organizations (38%), and online learning platforms (38%). These preferences confirm readiness for hybrid digital-green initiatives combining applied learning with professional networking.

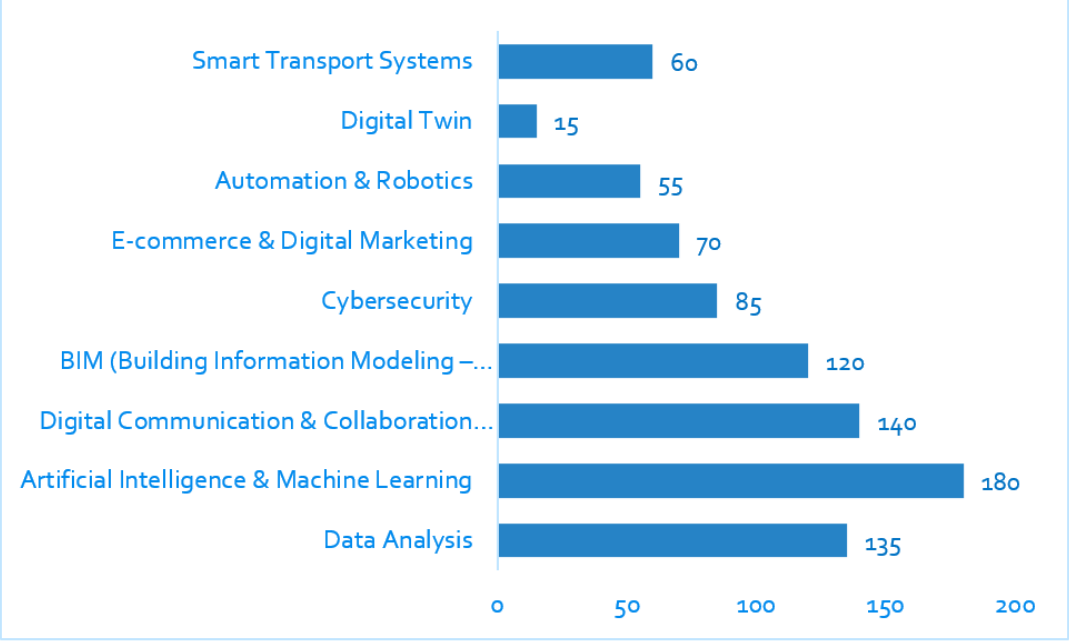


***Figure 3** – Digital skills to be improved (Source: Authors)*

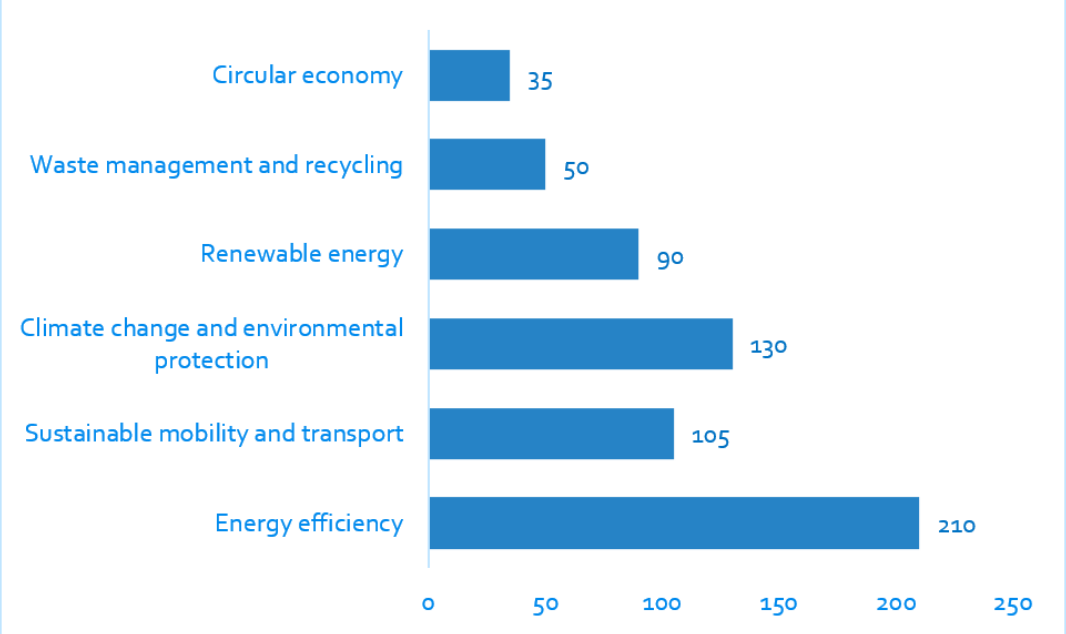


***Figure 4** – Sustainability areas to be developed (Source: Authors)*

3.3. SMEs

The SME survey captured 123 valid responses from companies across Bosnia and Herzegovina, predominantly micro and small enterprises (1–9 employees: 31%; 10–49 employees: 40%), with medium-sized firms (50–249 employees) at 28% and large enterprises at 2%. Openness to digital training was high: approximately 40–45% very open, 35–40% mostly open, and only 5–10% reporting limited openness.

Top digital training priorities were process automation (~55%), data analysis (~50%), BIM (~40%), e-commerce and online marketing (~30%), AI tools (~25%), and cybersecurity (~20%). Green skills were considered very important by 35% and partially important by 40%, with energy management emerging as the dominant sustainability support need (~60%), followed by waste reduction (~35%), sustainable transport (~28%), circular economy (~25%), and non-financial reporting (~20%).

Interest in renewable energy and energy efficiency training was strong (45% highly interested, 35% somewhat interested). Regarding sustainability reporting and EU green standards, approximately 18% would invest immediately, 22% within 1–2 years, and 42% conditionally depending on cost. Most valued AI-based products included market and consumer analytics (56%) and AI-powered customer support tools such as chatbots (53%). For carbon footprint measurement, SMEs preferred online self-assessment platforms (32%) and integration into existing management systems (24%). Awareness of digital platforms for green project partnerships remained low, with very few having used such tools in practice [5].

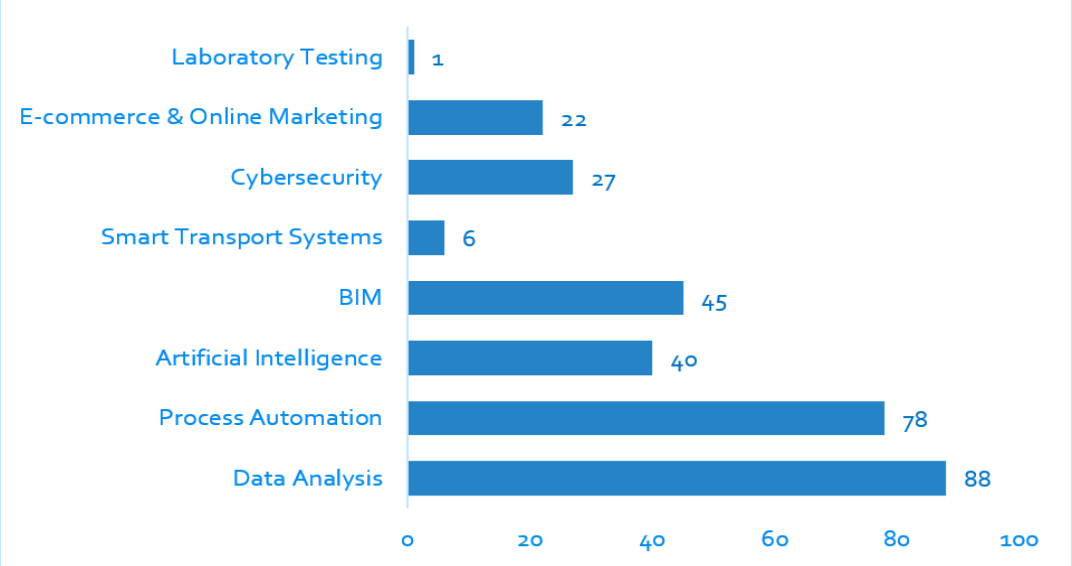


Figure 5 *– Areas of digital training (Source: Authors)*

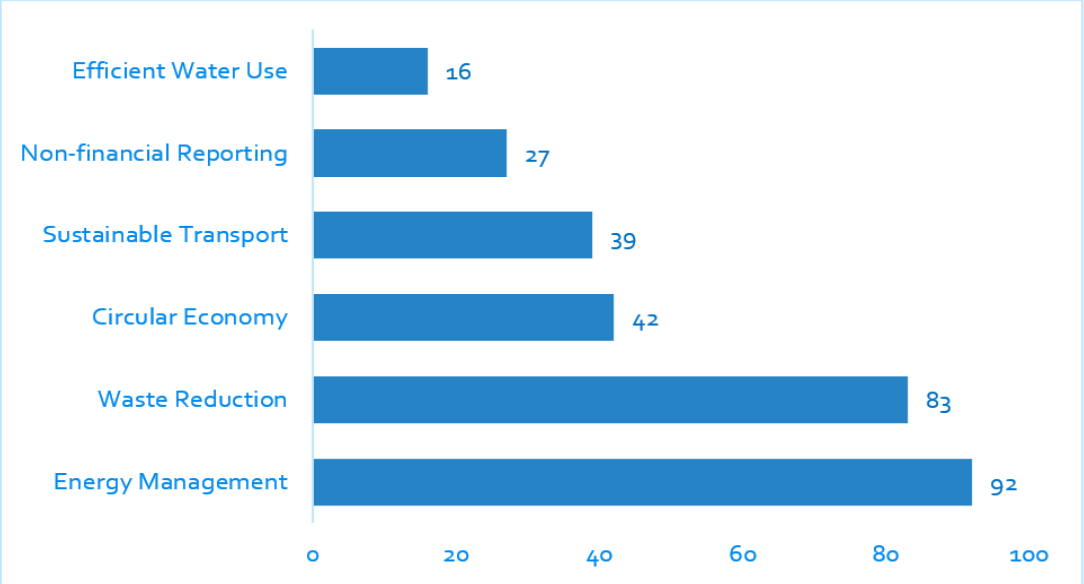


***Figure 6** – Areas of sustainability (Source: Authors)*

4. Cross-stakeholder synthesis

The three stakeholder surveys reveal a strong and consistent demand for hybrid competencies combining digital and green skills, with variations in priorities and readiness across groups. A shared recognition emerges that digital transformation and sustainability are integral to competitiveness, employability, and institutional development rather than optional priorities [7].

Across all groups, clear overlap exists in three domains: (1) digital skills linked to process automation, data handling, and AI-enabled tools; (2) green skills related to energy efficiency, renewable energy, and circular economy practices; and (3) strong interest in real-world engagement through internships, applied training, and project-based collaboration. These overlapping priorities provide a solid foundation for designing cross-stakeholder training actions.

Differences emerge primarily in maturity and expectations. SMEs prioritize immediately applicable tools and cost-effective compliance guidance. Public institutions focus on institutional participation in structured sustainability frameworks and long-term policy alignment. Students primarily seek skills development, employability enhancement, and hands-on experience. This differentiation supports a tiered training design: foundational modules for students, operational modules for SMEs, and partnership-oriented modules for public institutions [1].

***Table 1** – Cross-stakeholder comparison of priority skill areas*

Stakeholder	Top Digital Priorities	Top Green Priorities	Preferred Engagement
SMEs	Process automation, Data analysis, BIM, AI tools	Energy management, Waste reduction, Circular economy	Practical training, cost-efficient tools
Public Institutions	Data management, E-governance, Cybersecurity	Energy efficiency, Circular economy, Urban mobility	Structured partnerships, capacity building

Students	BIM, AI/ML, Data analysis, Cybersecurity	Energy efficiency, Climate change, Renewable energy	Internships, networking, online learning

5. Recommendations

Based on the findings, the following recommendations are proposed for the SKILL2SUSTAIN project and regional partners:

In the short term (6–12 months), priority actions should focus on: (i) developing introductory hybrid digital-green training modules for students integrating AI, BIM, and energy efficiency topics; (ii) launching practical SME training on process automation, data analysis, and AI-based market tools; and (iii) organizing public-private sustainability workshops as partnership pilots rather than general awareness events [5].

In the medium term (12–24 months), higher education institutions should develop modular and flexible curricula covering digital process automation, AI for market analytics, renewable energy for business applications, and EU green standards and sustainability reporting. These should be linked to structured internship frameworks, applied learning environments, and circular economy mentoring programmes. European experiences, including initiatives under the European Green Deal [2] and the EU Digital Decade [8], provide relevant models for curriculum adaptation.

Stakeholder roles should be clearly defined: universities lead curriculum co-design and training delivery; SMEs provide validation of real operational needs and host internships; public institutions pilot partnership engagement models and facilitate public-private initiatives supporting the digital-green transition. This alignment enables a coordinated and sustainable implementation of recommended actions across the region [7].

6. Limitations

Several methodological limitations should be considered when interpreting the findings reported above. First, the public institutions sample is small in absolute terms compared with the SME and student samples. This limits the statistical robustness of subgroup comparisons and means that the percentage-based estimates reported for public institutions in Section 3.1 should be interpreted as indicative of broad patterns rather than as precise, generalizable measures.

Second, reliance on digital distribution channels (email outreach, institutional networks, and Google Forms) and voluntary participation may have introduced selection bias. Respondents were more likely to be individuals or institutions already engaged with digital tools and receptive to sustainability topics, which may overstate the reported openness to digital transformation and demand for green skills relative to institutions, SMEs, or students with lower digital engagement or awareness who were less likely to respond.

Third, the cross-sectional and self-reported nature of the data limits causal inference and may be subject to social desirability bias, particularly regarding institutional and corporate commitment to sustainability. Finally, given that the survey was concentrated within specific academic, chamber, and administrative networks under the SKILL2SUSTAIN project framework, the generalizability of the findings to the wider Western Balkans region should be approached with caution. Future research should consider stratified sampling of public institutions and larger, more geographically diverse samples to strengthen the representativeness of subsequent needs assessments.

7. Conclusion

This paper contributes empirical evidence on the digital and green skills needs of SMEs, university students, and public institutions in Bosnia and Herzegovina. The combined survey results confirm a strong and consistent shift toward sustainability-driven skill demand and practical digital adoption across all three stakeholder groups. Despite differences in institutional roles and capacity, all groups demonstrate readiness to engage in hybrid digital-green initiatives when solutions are clearly linked to real needs, applied learning, and tangible outcomes.

SMEs require operationally oriented training, particularly in AI-supported processes, energy efficiency, and EU sustainability reporting. Public entities reflect institutional willingness to participate in sustainability-focused initiatives through structured partnerships. Students emerge as the strongest demand pool for training and project-based engagement, combining digital and green skills with career development aspirations.

Overall, the findings validate the need for incremental hybrid skill frameworks led by higher education institutions and implemented through SME engagement and public-private collaboration. The SKILL2SUSTAIN project is well-positioned to move decisively toward training delivery, internship linkages, and structured partnership development, contributing to long-term regional resilience and sustainability in the Western Balkans.

Acknowledgement

This research was conducted within the SKILL2SUSTAIN project – Boosting digital and green skills for a resilient and sustainable Western Balkan society – co-funded by the European Union under the Erasmus+ Programme (Grant Agreement No. 101127181). The views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA).

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T03

Innovative Curricula and Learning Methodologies for Sustainability

AI Based Avatars for Digital Skills Development and Sustainable Knowledge Transfer

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Abstract

Digital and green transition processes are reshaping contemporary societies, creating an increasing demand for digital competencies, lifelong learning, and effective knowledge transfer mechanisms. At the same time, the growing complexity of digital environments and information ecosystems presents challenges related to accessibility, engagement, and continuous skills development. Recent advances in artificial intelligence (AI) offer new opportunities to address these challenges through intelligent and personalized learning solutions. Among them, AI-based avatars have emerged as promising tools that combine natural language interaction, generative AI capabilities, and adaptive communication to support knowledge acquisition and user engagement. This paper explores the potential of AI-based avatars as enablers of digital skills development and sustainable knowledge transfer. Drawing upon concepts of digital literacy, lifelong learning, capacity building, and human-centered AI, the study discusses how AI avatars can facilitate personalized learning experiences and improve access to knowledge. A conceptual framework is proposed to explain the relationships between knowledge resources, AI technologies, learning processes, individual competence development, and broader societal outcomes. The framework highlights how AI avatars can contribute to digital literacy, user empowerment, sustainability awareness, and societal resilience through accessible and adaptive communication. The paper further discusses implications for higher education, professional training, and capacity-building initiatives, emphasizing the role of AI-enabled learning systems in supporting sustainable and resilient societal transformation. The proposed framework provides a foundation for future empirical research and practical applications of AI avatars in education and lifelong learning contexts.

Keywords

AI-Based Avatars, Digital Skills Development, Knowledge Transfer, Societal Resilience, Sustainable Development.

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1. Introduction

Contemporary societies are undergoing profound transformations driven by digitalization, technological innovation, and the growing need to address environmental and societal challenges. The concepts of digital and green transition have become central elements of international and regional development agendas, particularly within the European Union and the Western Balkan region [1,2]. Digital transformation is reshaping the ways individuals learn, communicate, work, and access services, while sustainability initiatives seek to ensure that technological progress contributes to long-term social, economic, and environmental well-being. As a result, the development of digital competencies and the ability to effectively access, understand, and apply knowledge have become essential prerequisites for active participation in modern society [3].

The rapid evolution of digital technologies has generated numerous opportunities for innovation but has simultaneously introduced new challenges. While access to information has never been greater, individuals often struggle to navigate increasingly complex digital environments. The continuous emergence of new technologies, platforms, and services requires ongoing learning and adaptation. Consequently, digital literacy is no longer limited to the ability to use digital devices; it encompasses a broad set of competencies related to information management, communication, critical thinking, problem-solving, and responsible use of technology. The growing complexity of digital ecosystems highlights the importance of lifelong learning and continuous skills development as key factors supporting employability, social inclusion, and resilience [4,5].

At the same time, organizations, educational institutions, and policymakers are increasingly recognizing the importance of effective knowledge transfer. The success of digital and green transition initiatives depends not only on the availability of technological solutions but also on the ability of individuals and communities to understand and utilize them. Knowledge dissemination therefore plays a critical role in supporting capacity building, fostering innovation, and enabling informed decision-making. However, traditional approaches to knowledge transfer often face limitations related to accessibility, personalization, engagement, and scalability. These challenges create opportunities for the adoption of innovative digital solutions capable of facilitating more efficient and inclusive learning experiences [1].

Recent advances in artificial intelligence (AI) have significantly expanded the possibilities for supporting learning, communication, and knowledge sharing. Technologies such as machine learning, natural language processing, generative AI, and intelligent virtual assistants are increasingly being integrated into educational and professional environments. AI-powered systems can provide personalized recommendations, adapt content to individual needs, automate information delivery, and support users in acquiring new knowledge and skills. As a result, AI is emerging as a powerful enabler of digital competence development and lifelong learning [5,6].

Among various AI-based solutions, AI avatars represent a particularly promising approach to enhancing user interaction and facilitating knowledge transfer. AI avatars combine conversational capabilities, natural language interaction, and visual representation to create engaging and accessible communication experiences. Unlike traditional static information resources, AI avatars can provide personalized guidance, explain complex concepts in understandable ways, and interact with users in real time. Their potential extends beyond customer support and service delivery applications, offering opportunities for broader use in education, professional training, public awareness campaigns, and capacity-building initiatives [6].

The growing relevance of AI-supported learning and communication technologies is particularly significant in the context of sustainable and resilient societal development. Digital

and green transition processes require citizens, professionals, and organizations to continuously acquire new knowledge and competencies. AI-based systems can contribute to this objective by making knowledge more accessible, supporting personalized learning pathways, and reducing barriers to information acquisition. Furthermore, such technologies can facilitate the dissemination of sustainability-related knowledge, support community engagement, and strengthen societal resilience through improved access to relevant information and learning opportunities [1,3].

This conceptual paper explores the role of AI-based avatars as tools for digital skills development and sustainable knowledge transfer. The study discusses the relationship between digital literacy, lifelong learning, and knowledge dissemination in the era of AI, while highlighting the potential of AI avatars as intelligent learning and communication tools. Particular attention is devoted to their contribution to sustainable and resilient societal transformation through enhanced accessibility, personalization, and democratization of knowledge. Finally, the paper proposes a conceptual framework that positions AI avatars as enablers of digital competence development, knowledge transfer, empowerment, and resilience, providing implications for higher education, professional training, and regional capacity-building initiatives.

1.1. Methodological Approach

This paper adopts a conceptual research approach based on a narrative and integrative review of relevant literature and subsequent conceptual modelling. The reviewed literature covers four intersecting areas: digital literacy and lifelong learning, AI-supported education, conversational agents and knowledge sharing, and the contribution of artificial intelligence to sustainable development and capacity building. The literature was used to identify recurring constructs, mechanisms, outcomes, and implementation conditions associated with AI-supported learning and knowledge transfer.

The study is therefore exploratory and conceptual rather than empirical. It does not test causal relationships or evaluate a deployed AI-avatar system. Instead, it integrates previously discussed elements into a structured framework that can guide future empirical research, system development, and context-specific implementation. Future studies should operationalize the proposed constructs and examine the framework through pilot applications, user studies, learning analytics, and comparative institutional research.

2. Digital Skills and Knowledge Transfer in the era of AI

Digital literacy has become a fundamental competency in contemporary society. As digital technologies increasingly shape education, work, communication, and everyday activities, individuals are expected to possess skills that enable them to effectively access, evaluate, and utilize digital information. Modern digital literacy extends beyond technical proficiency and includes information management, communication, critical thinking, problem-solving, and responsible use of technology [5,8]. These competencies are essential for participation in knowledge-based economies and digitally connected communities.

The growing complexity of digital environments has increased the importance of capacity building and lifelong learning. Rapid technological development continuously creates new demands for knowledge and skills, making continuous learning a necessity rather than an option. Educational institutions, organizations, and policymakers increasingly recognize that sustainable development depends not only on technological infrastructure but also on the ability of individuals to adapt to changing conditions and effectively use emerging technologies [1,2]. Digital platforms and online learning environments have expanded

opportunities for continuous skills development, making learning more accessible and flexible.

Despite the expansion of digital learning resources, the availability of information does not necessarily ensure effective knowledge acquisition. Learners differ in prior knowledge, digital competence, language, motivation, and access to expert support. They may therefore experience difficulties in identifying relevant information, evaluating its reliability, and translating it into practical knowledge. These limitations point to the need for learning solutions that can mediate between complex knowledge resources and heterogeneous user needs [7]. AI-supported conversational systems represent one possible response because they can organize information, contextualize explanations, and facilitate interactive access to knowledge. Their contribution, however, depends not only on technological functionality but also on pedagogical relevance, responsible design, and integration into broader learning and capacity-building processes.

3. AI-Based Avatars as Intelligent Learning and Communication Tools

Advances in artificial intelligence have enabled the development of increasingly sophisticated tools for communication and learning. Among these, AI-based avatars represent a promising solution that combines conversational capabilities, visual representation, and interactive communication. By integrating natural language processing, machine learning, and generative AI technologies, AI avatars create engaging user experiences and facilitate more intuitive access to information [9].

The emergence of generative AI has significantly expanded the capabilities of AI avatars. Unlike traditional scripted systems, modern AI avatars can dynamically generate content, adapt explanations to user needs, and provide personalized guidance in real time. This flexibility enables them to support users in understanding complex concepts, navigating digital environments, and acquiring new knowledge. As a result, AI avatars are increasingly viewed as intelligent intermediaries between knowledge sources and end users [6,10].

AI-based avatars differ from conventional digital repositories and scripted interfaces because they enable dialogic and multimodal interaction. Users can formulate questions in natural language, request clarification, receive examples, and progressively refine their understanding without navigating extensive documentation. When connected to appropriate knowledge sources, avatar systems may also adjust terminology, explanation depth, communication format, and feedback to the learner's level and immediate objective [10,11].

4. Supporting Sustainable and Resilient Societies Through AI

Digital and green transitions are interdependent processes. The adoption of digital technologies can support resource efficiency, data-informed decision-making, environmental monitoring, and new forms of education and work. At the same time, these changes create demands for new competencies related to digital participation, responsible technology use, sustainability literacy, and adaptation to changing occupational and societal conditions [1].

A central challenge is translating policy objectives, technical knowledge, and sustainability principles into information that different stakeholder groups can understand and apply. Citizens, students, employees, public-sector professionals, and small organizations do not have equal access to expertise or the same level of digital preparedness. AI-based avatars may support this translation process by providing interactive explanations of regulations, technologies, procedures, and sustainability practices, while adapting communication to the user's knowledge level and context [3].

Their potential contribution is therefore not limited to individual learning. When embedded in educational, organizational, or public-service environments, AI avatars can support institutional capacity building, dissemination of green-transition knowledge, and participation in digital transformation initiatives. Nevertheless, these benefits are conditional upon reliable knowledge sources, transparency, data protection, human oversight, accessibility, and sensitivity to local linguistic and institutional conditions. These requirements are particularly important in regions characterized by uneven digital development and limited institutional capacities [2,3].

5. Conceptual Framework for AI-Enabled Digital Skills Development

Existing studies provide important but relatively specialized perspectives on AI-supported learning and knowledge transfer. Factors influencing the sustainable use of AI-based educational chatbots have been examined primarily from knowledge-management and technology-adoption perspectives [7]. Knowledge and emotional scaffolding have been investigated within online learning environments [10], while conversational agents have also been considered as mechanisms for encouraging organizational knowledge-sharing practices [11]. Collectively, these studies establish the value of conversational interaction, scaffolding, and knowledge management, but they do not integrate these elements into a multilevel model connecting knowledge resources, enabling technologies, avatar-mediated learning processes, individual competence development, and wider digital and green transition outcomes.

The proposed conceptual framework in this paper is structured as a sequence of five connected components: knowledge resources, enabling AI technologies, the AI-avatar interface, learning and interaction processes, and individual and societal outcomes. Educational materials, expert knowledge, organizational resources, and sustainability-related information constitute the knowledge base. Natural language processing, generative AI, speech technologies, and multimodal communication enable the avatar to mediate between these resources and the user.

The central mechanism is an iterative learning process in which users formulate questions, receive contextualized explanations, request clarification, apply information, and obtain feedback. The avatar can adjust the form and depth of communication according to the user's prior knowledge, objectives, and interaction history. Through repeated interaction, this process may support digital literacy, knowledge evaluation, problem-solving, confidence in using digital technologies, and capacity for continuous learning [8,10].

Individual learning outcomes may subsequently contribute to broader effects, including workforce readiness, social inclusion, innovation capacity, sustainability awareness, and participation in digital and green transition initiatives [1–3]. The relationship is not presented as automatic or deterministic. Societal effects depend on institutional implementation, the quality of the underlying knowledge resources, responsible AI governance, user access, and the extent to which acquired competencies are applied in practice.

Figure 1 summarizes these relationships and presents the continuous learning loop through which user interaction and feedback may improve both learner outcomes and the relevance of avatar-supported communication.

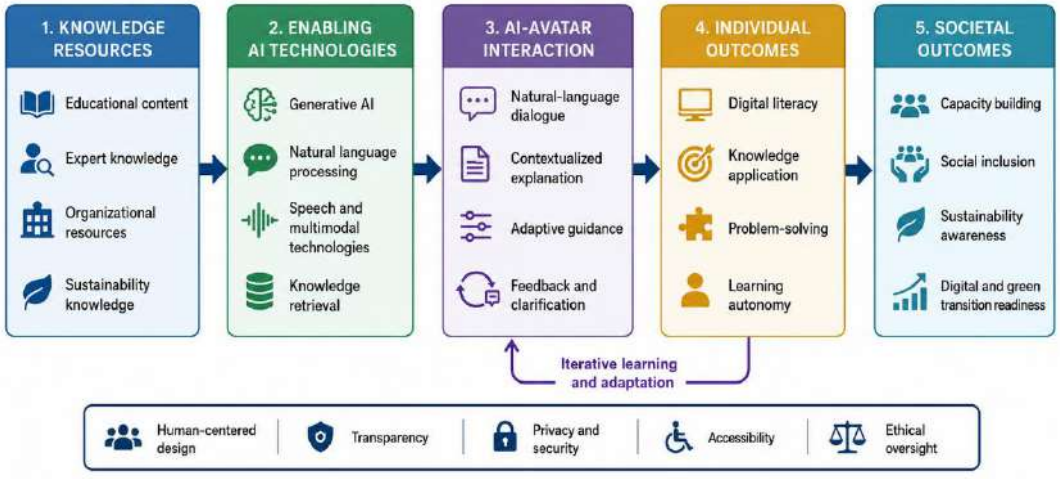


***Figure 1** – Proposed conceptual framework linking AI-avatar-enabled interaction with digital skills development and societal outcomes*

The originality of the proposed framework lies in this integrative and multilevel structure. Rather than treating an AI avatar only as a chatbot, learning assistant, or knowledge-sharing interface, the framework conceptualizes it as an intermediary within a broader knowledge-transfer ecosystem. It links technological capabilities with human-centered interaction mechanisms, distinguishes individual learning outcomes from longer-term societal effects, and explicitly incorporates a continuous feedback loop and responsible-AI principles as conditions for implementation.

A further contribution is the framework's orientation towards the Western Balkan context. The region's digital and green transitions take place under conditions of uneven digital readiness, differences in institutional capacity, multilingual communication needs, skills gaps, and variable access to specialized expertise. In this setting, AI avatars may be relevant not only to university teaching but also to vocational education, public administration, small and medium-sized enterprises, professional training, and citizen-oriented sustainability initiatives. The framework therefore emphasizes scalable access to contextualized knowledge, regional capacity building, multilingual adaptation, and the communication of digital and green transition requirements to heterogeneous stakeholder groups.

6. Implications for Higher Education and Capacity Building

The proposed framework has important implications for higher education and capacity-building initiatives. As digital and green transitions continue to reshape educational and professional environments, institutions increasingly require innovative approaches that support digital competence development, lifelong learning, and effective knowledge transfer. AI-based avatars can complement traditional educational methods by providing personalized, accessible, and scalable learning support [1,2,4].

In higher education, AI avatars can contribute to curriculum modernization by offering interactive access to learning resources, personalized explanations, and continuous guidance. Through natural language interaction and adaptive communication, they can support learner-centered educational experiences and enhance student engagement. Their ability to provide immediate feedback and contextualized explanations makes them particularly suitable for blended and online learning environments [6,12].

Beyond formal education, AI avatars can support professional training and workforce development by facilitating continuous upskilling and reskilling. They provide on-demand access to relevant knowledge and enable more flexible learning experiences, which are

increasingly important in sectors undergoing rapid technological change. In addition, AI-powered learning assistants may support regional and international capacity-building initiatives by improving access to expertise and promoting knowledge sharing among diverse stakeholder groups [1,3].

To realize these benefits, the implementation of AI avatars should be guided by principles of responsible AI use, including transparency, accessibility, privacy protection, and human-centered design. When appropriately integrated into educational and training ecosystems, AI avatars can become valuable tools for strengthening digital competencies, supporting lifelong learning, and contributing to sustainable societal development [4,5].

7. Conclusion

Digital and green transition processes are transforming how individuals learn, work, communicate, and participate in society. These changes have increased the importance of digital literacy, lifelong learning, and effective knowledge transfer as prerequisites for sustainable development and societal resilience. At the same time, increasingly complex information environments create challenges related to accessibility, engagement, and continuous competence development, highlighting the need for innovative learning and capacity-building approaches.

This paper explored the potential of AI-based avatars as intelligent learning and communication tools for digital skills development and sustainable knowledge transfer. Advances in artificial intelligence, natural language processing, and generative AI enable AI avatars to provide personalized, interactive, and user-centered learning experiences through adaptive guidance, natural language interaction, and contextualized explanations, thereby supporting diverse learners and continuous knowledge acquisition.

The paper's main contribution is an integrative conceptual framework linking knowledge resources and enabling AI technologies with avatar-mediated interaction, individual competence development, and broader societal outcomes. Unlike existing models focused on chatbot adoption, conversational scaffolding, or organizational knowledge sharing, the proposed framework integrates these perspectives into a continuous learning and knowledge-transfer process. It also distinguishes between immediate learning outcomes and longer-term societal effects while recognizing responsible AI, accessibility, and institutional implementation as enabling conditions.

The framework is particularly relevant to digital and green transition challenges in the Western Balkans, where differences in digital readiness, institutional capacity, language, and access to expertise may limit participation in transformation processes. AI-based avatars may improve access to specialized knowledge across higher education, professional training, public institutions, businesses, and citizen-oriented initiatives. However, these benefits remain conceptual rather than empirically validated. The framework therefore provides a foundation for future research by identifying relationships and implementation conditions for empirical testing.

Future research should validate the proposed framework through pilot implementations in higher education, vocational training, public services, and organizational learning. Studies should evaluate learning effectiveness, user acceptance, accessibility, trust, knowledge accuracy, and the effects of personalization. Comparative research across Western Balkan institutions could examine how language, infrastructure, digital readiness, and institutional capacity influence implementation, while longitudinal studies should investigate whether individual learning outcomes translate into sustained competence development and broader organizational and societal impacts.

Acknowledgement

This research was supported by the Provincial Secretariat for Higher Education and Scientific Research through the project **"Development and Application of AI-Based Avatars as a Service in Sales and Customer Support."**

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Digital and Green competencies through BIM and GIS Lifelong Learning Programs in Civil Engineering

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Abstract

The construction sector is undergoing intensive digital and green transformation driven by the implementation of Building Information Modeling (BIM), Geographic Information Systems (GIS), interoperability standards, and sustainability-oriented infrastructure management. Modern construction projects increasingly require interdisciplinary professionals capable of integrating technical, spatial, organizational, and managerial information within unified digital environments. In response to these challenges, the Faculty of Civil Engineering at the University of Montenegro developed four modular lifelong learning programs focused on BIM and GIS in civil engineering. The programs are designed as a progressive educational framework aimed at strengthening digital and green competences in accordance with European priorities related to digitalization and sustainable development. This paper presents the concept, structure, educational methodology, and expected impact of the programs, with particular emphasis on BIM–GIS integration, interdisciplinary learning, labor market relevance, and contribution to the modernization of engineering education and professional practice in Montenegro and the Western Balkans.

Keywords

BIM, GIS, lifelong learning, digital and green transformation, civil engineering, sustainability.

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1. Introduction

The construction industry is currently experiencing intensive technological transformation characterized by the digitalization of project processes, implementation of information modeling methodologies, development of geospatial information systems, and increasing requirements related to sustainable management of the built environment. Traditional approaches to planning, design, and project delivery are becoming insufficient for modern infrastructure systems that require high levels of interdisciplinary coordination, information management, and lifecycle-oriented decision-making.

Building Information Modeling (BIM) represents a methodology based on intelligent digital models integrating geometric, technical, time-related, cost-related, and managerial information about buildings and infrastructure systems. At the same time, Geographic Information Systems (GIS) enable spatial analysis, geodata management, territorial assessment, and location-based decision-making. The integration of BIM and GIS technologies has become one of the key directions in the digital transformation of the Architecture, Engineering and Construction (AEC) sector.

Contemporary labor markets increasingly require professionals who, in addition to traditional engineering knowledge, possess competencies related to digital modeling, data interoperability, geospatial analysis, collaborative digital workflows, and sustainability-oriented infrastructure management. Consequently, higher education institutions and lifelong learning systems are expected to adapt educational models to new technological and professional demands.

Despite the increasing implementation of BIM and GIS technologies within the European construction sector, higher education systems and professional training frameworks in many Western Balkan countries still face significant challenges related to digital transformation, interoperability-oriented education, and development of sustainability-driven engineering competences. Existing educational models are often insufficiently adapted to integrated digital workflows and multidisciplinary engineering environments increasingly required in contemporary infrastructure projects.

The paper also addresses the need for modernization of engineering education systems in the Western Balkans through integrated lifelong learning approaches aligned with digital and green transition priorities.

As a response to these challenges, the Faculty of Civil Engineering at the University of Montenegro developed four lifelong learning programs in the field of BIM and GIS in civil engineering. The proposed framework was developed with the objective of supporting digital and green transition processes within engineering education and improving alignment between academic competences and emerging labor market requirements in the construction sector. The programs were formally defined through the “Study on the Justification of Implementing Four Lifelong Learning Programs in BIM and GIS in Civil Engineering” and represent an interdisciplinary educational framework intended for engineers, technical professionals, and lifelong professional development within the fields of civil engineering, architecture, geodesy, mechanical engineering, electrical engineering, and related technical disciplines.

2. Program Structure and Educational Concept

The lifelong learning framework consists of four modular, progressive, and interconnected programs enabling participants to gradually acquire competencies related to project management, BIM methodologies, and GIS technologies.

The educational framework was structured according to principles of progressive competence development, interdisciplinary integration, and practical applicability within contemporary digital construction environments. The modular organization enables gradual transition from fundamental concepts toward advanced BIM–GIS integration and application-oriented engineering workflows.

Each program carries 15 ECTS credits and represents an independent educational unit within the overall framework. The programs are organized progressively, meaning that successful completion of the previous program represents a prerequisite for enrollment in the next level.

Program 1 – Fundamentals of Project Management, BIM and GIS introduces participants to project management principles, construction organization, BIM methodologies, GIS technologies, and digital transformation concepts within the construction sector. Special emphasis is placed on understanding the relationship between technical, organizational, and spatial information in modern project environments.

Program 2 – BIM and GIS Modeling focuses on the development of operational and technical competencies related to BIM model creation and coordination, geospatial database management, spatial analysis, and interoperability between software and information systems.

Program 3 – Integrated BIM–GIS for Construction Projects represents the integrative level of the framework and connects BIM and GIS technologies with construction project management processes. Particular attention is devoted to cost management, scheduling, risk management, sustainability, and legal and institutional aspects of digital transformation in construction.

Program 4 – Applied Practice and Final Project represents the final and application-oriented level of lifelong learning and is based on practical implementation of acquired knowledge through project studios, case study analysis, and development of a final practical project.

The structure of the programs is based on principles of vertical and horizontal integration of knowledge, combining theoretical foundations with practical implementation through software-based learning, laboratory work, project assignments, interdisciplinary collaboration, and problem-oriented engineering tasks. Particular emphasis is placed on integration of digital workflows, collaborative information management, and practical application of BIM–GIS methodologies in infrastructure and construction projects.

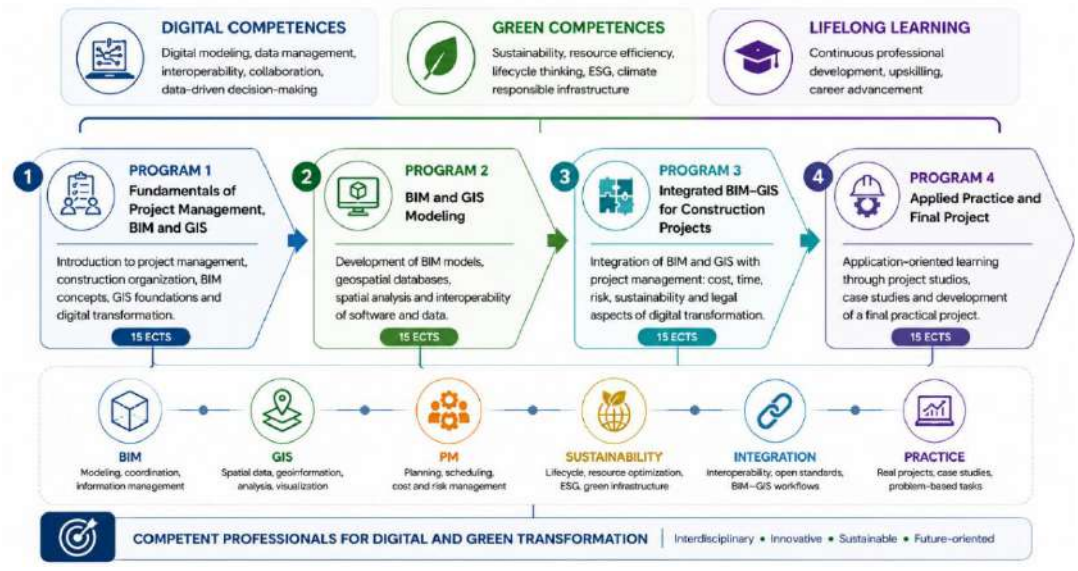


Figure 1 *– Conceptual framework and progressive structure of lifelong learning programs in BIM and GIS in civil engineering*

3. Digital and Green Competences

One of the primary objectives of the programs is the development of digital and green competences required in contemporary engineering practice. The programs were developed in accordance with modern European trends related to construction digitalization, interoperability, sustainability, and green transition.

The concept of digital and green competences within the programs is aligned with broader European priorities related to digital transition, sustainable infrastructure development, resource efficiency, and climate-oriented engineering practices. The programs therefore combine technological, managerial, spatial, and sustainability-related dimensions of contemporary engineering education.

The digital component of the programs focuses on:

- BIM modeling and coordination,
- geospatial data management,
- digital collaboration,
- information management,
- interoperability,
- integrated digital workflows,
- and data-driven decision-making.

Special importance is given to understanding international standards related to information management, particularly ISO 19650, as well as open data exchange formats and BIM–GIS interoperability principles.

The green dimension of the programs is reflected through:

- sustainability-oriented planning,
- lifecycle thinking,
- resource optimization,
- reduction of inefficiencies,
- ESG-oriented approaches,
- and sustainable infrastructure management.

Participants are expected to develop the ability to apply digital technologies and integrated BIM–GIS workflows in support of energy efficiency, risk reduction, optimization of resource management, and improvement of sustainability performance throughout the lifecycle of buildings and infrastructure systems. In this context, digital competences are viewed not only as technical skills, but also as strategic tools supporting sustainable and data-driven decision-making in the construction sector.

4. Teaching Methodology and Program Implementation

The programs are based on a modern educational approach focused on learning outcomes, active learning, and practical implementation of knowledge. Teaching activities are organized through a combination of:

- theoretical lectures,
- practical exercises,

- laboratory work,
- software-based learning,
- project assignments,
- case-study analysis,
- consultations,
- and mentoring activities.

The teaching methodology is based on outcome-oriented and participant-centered learning principles aimed at strengthening analytical, technical, collaborative, and problem-solving competences required in contemporary engineering practice.

Special emphasis is placed on project-oriented learning and development of problem-solving skills through realistic engineering scenarios and integrated BIM–GIS workflows. Participants work individually and in teams on simulations of real investment and infrastructure processes, thereby developing interdisciplinary competences and professional skills required in modern engineering practice.

The Faculty of Civil Engineering at the University of Montenegro provides the technical and organizational infrastructure necessary for implementation of the programs, including computer laboratories, software environments, and digital teaching resources. Additional support for strengthening digital capacities, educational modernization, and development of lifelong learning systems is provided through the Erasmus+ Skill2Sustain project.

5. Expected Impact and Market Relevance

The labor market continuously demonstrates increasing demand for professionals possessing BIM and GIS competencies. Digital transformation of the construction sector, development of smart infrastructure systems, and sustainability-related European policies are creating the need for new professional profiles capable of working within integrated digital environments.

Particular importance of the programs is reflected in their ability to address existing gaps between traditional engineering education models and rapidly evolving labor market requirements associated with digital construction processes, smart infrastructure systems, and sustainability-oriented project management.

The proposed lifelong learning programs directly respond to these demands through the development of:

- digital competencies,
- interdisciplinary knowledge,
- analytical skills,
- project management capacities,
- and practical engineering abilities.

The programs are particularly relevant for:

- design and consulting companies,
- construction and infrastructure firms,
- public institutions,
- facility management organizations,

- and international infrastructure projects.

From an institutional and regional perspective, the programs contribute to modernization of engineering education, strengthening cooperation between academia and industry, improvement of lifelong learning capacities, and increased participation in international educational, research, and digital transition initiatives within the Western Balkans.

Implementation of such educational frameworks may additionally require institutional adaptation, continuous software and hardware modernization, and strengthening of interdisciplinary cooperation between academia and industry.

6. Conclusion

The lifelong learning programs in BIM and GIS in civil engineering represent an important contribution to strengthening digital and green competences within engineering education and professional practice in Montenegro and the Western Balkans.

Through integration of project management principles, BIM methodologies, GIS technologies, interoperability concepts, and sustainability-oriented approaches, the programs provide participants with interdisciplinary knowledge and practical competences required in contemporary construction and infrastructure projects.

The modular and progressive structure of the programs, combined with practical implementation and alignment with European priorities related to digital and green transition, creates a flexible educational framework capable of supporting modernization of the construction sector and development of lifelong learning systems in engineering education.

The proposed framework also contributes to improving alignment between higher education systems and emerging labor market requirements associated with digital construction, integrated information management, and sustainable infrastructure development.

Acknowledgement

This work was developed within the framework of the Erasmus+ project SKILL2SUSTAIN – Digital and Green Skills for Sustainable Development, co-funded by the European Union. The authors acknowledge the support provided through the project activities aimed at strengthening digital and green competences, promoting lifelong learning, and advancing the modernization of engineering education in the Western Balkans.

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Graduate Engineers' Perspectives on the Study Programme in Disaster Risk Management and Fire Safety: A Survey-Based Analysis

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Abstract

This paper presents findings from a survey conducted among 62 graduates of the study program "Disaster Risk Management and Fire Safety Engineering (DRM&FSE)" at the Faculty of Technical Sciences, University of Novi Sad, Serbia. The survey was conducted as part of the new accreditation process and within the framework of the SKILL2SUSTAIN Erasmus+ Project. Graduates provided feedback on their motivations for enrolment, satisfaction with the curriculum, professional outcomes, and recommendations for improvement. Results reveal a highly motivated student body, primarily driven by a desire to contribute to society through a meaningful, human-oriented profession. The paper also highlights the program's strengths: dedicated academic staff, strong professional networks, and broad applicability to the labor market. The findings contribute to an evidence-based approach to higher education reform in disaster risk management across the Western Balkans.

Keywords

Disaster risk management, fire safety, higher education, graduate survey, Western Balkans, SKILL2SUSTAIN.

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1. Introduction

The increasing frequency and severity of natural and technological hazards across the Western Balkans and the wider European region underscores the urgent need for well-trained professionals in disaster risk management (DRM) and fire safety engineering. The Sendai Framework for Disaster Risk Reduction 2015–2030 explicitly identifies education and capacity building as strategic priorities for reducing disaster risk and strengthening societal resilience [1]. At the national level, Serbia faces significant exposure to a range of hazards, including floods, wildfires, landslides, earthquakes, and industrial accidents, while the integration of proactive disaster risk management into institutional practice remains a work in progress [2]. Building fires are happening every day, with severe loss of goods and human injuries, even deaths.

The study program "Disaster Risk Management and Fire Safety Engineering" (DRM&FSE) at the Faculty of Technical Sciences (FTN), University of Novi Sad, is one of the few dedicated academic pathways in the region producing engineers qualified in this domain. Research confirms that higher education institutions (HEIs) can play a transformative role not only in educating future professionals but also in shaping a culture of resilience within local and national communities [3, 4]. At the same time, aligning engineering curricula with evolving labor market demands and international frameworks - including the EU Digital Education Plan and the European Green Deal - requires continuous, evidence-based curriculum review [5, 6].

This paper presents the results of a structured graduate survey conducted in May 2025, as part of the DRM&FSE new accreditation process and within the framework of the Erasmus+ SKILL2SUSTAIN project (https://skill2sustain.uns.ac.rs/), which aims to boost digital and green competencies across higher education institutions in the Western Balkans. The survey gathered 62 responses from graduates across multiple cohorts and professional backgrounds. The objective is to provide an evidence base for curriculum development by capturing: (1) the motivational and informational factors guiding program choice; (2) graduate satisfaction and professional outcomes; (3) perceived strengths of the program; and (4) directions for improvement aligned with the needs of a modern, digitally and ecologically informed DRM profession.

2. Methodology

A web-based questionnaire was developed and distributed electronically to DRM&FSE alumni. The survey comprised 14 substantive questions covering:

- channels of programme discovery and enrolment motivation;
- ranking of the programme among application choices;
- retrospective satisfaction and re-enrolment intent;
- professional networking among graduates;
- perceived benefits of graduation;
- adequacy of acquired knowledge for professional practice;
- current field of employment;
- desired increases in course hours by subject area;
- suggestions for curriculum improvement; and
- advice for prospective students.

Data collection took place in May 2025, and 70 sent e-mails yielded 62 complete responses, representing a substantial share of the program's total graduate population, given its specialized nature. Responses were analyzed using descriptive statistics. For multiple-selection questions, individual items were extracted and frequency counts computed across all response combinations. Open-ended responses were reviewed qualitatively and coded thematically to identify recurring professional experiences and recommendations.

3. Results and Discussion

3.1. Program Discovery and Enrolment Motivation

Graduates were asked how they first heard about the DRM&FSEprogram. Results show that the faculty's official website and brochures were the primary information channel (~50%), followed by personal recommendations from friends, family, or professors (~32%). The combination of both sources accounted for an additional 6.5%, while social media, open days, and direct professional network referrals accounted for the remaining 11.5%. The prominence of personal recommendation as a discovery channel reflects the strong word-of-mouth reputation the program has cultivated among its graduates and professional community.

The primary motivation for enrolment is presented in Figure 1. An absolute majority of respondents (43.5%) were motivated chiefly by the desire to help people and to engage in a humane, socially responsible profession. This intrinsic motivation - oriented towards public service and professional responsibility - is a defining characteristic of the DRM&FSE student body and aligns closely with the values underpinning the Sendai Framework's vision of risk-aware, community-protective professionals. Recommendations from the professional or social environment were the second most common motivator (~16%), followed by combinations of recommendations and the desire to help others (~11.3%). Personal experience with catastrophic events (fires, floods, earthquakes) motivated approximately 8% of respondents, while career prospects and family traditions in the field were also cited as motivations.

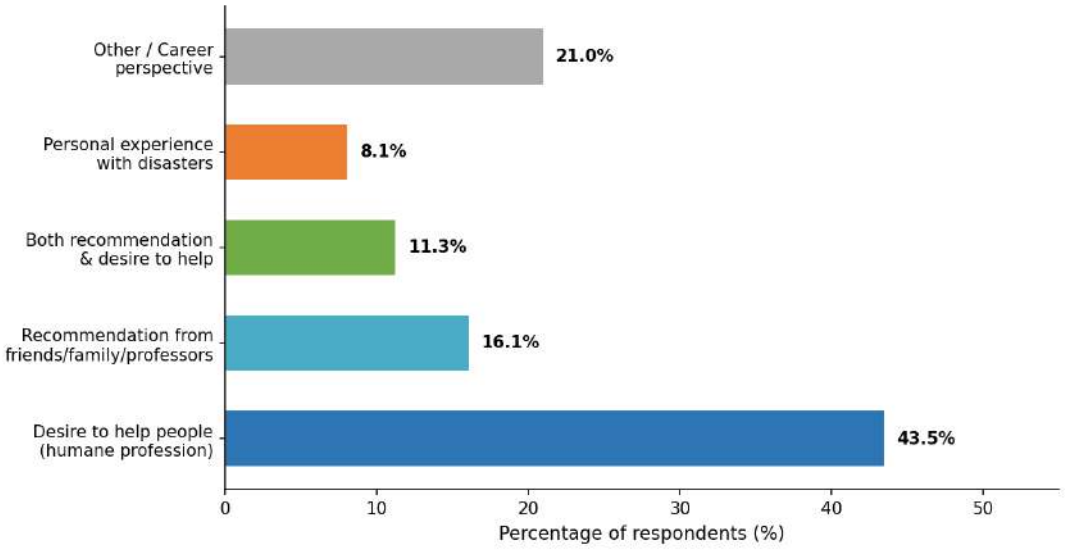


Figure 1 *– Primary motivation for enrolment in the DRM&FSE program (N=62)*

3.2. Enrolment Preferences and Retrospective Satisfaction

The program was the first choice for a strong majority of respondents: 72.6% ranked it first in their application list, 14.5% ranked it second, and only 11.3% ranked it third or lower. This finding contrasts favorably with general trends in technical higher education, where programs often attract students who were not admitted to their preferred programs.

When asked whether, with hindsight, they would enroll in DRM&FSE as their first choice today, 46.8% responded affirmatively, 29.0% answered "possibly", and 24.2% indicated either "no" or did not provide a clear answer (Figure 2) - among those who answered "yes" with elaboration, frequently cited reasons included: finding employment in the profession immediately after graduation, the broad and practically applicable knowledge base of the program, the quality and engagement of academic staff, and the social significance of the work. Representative positive testimonials include: "I easily found work in the field"; "The program gave me a secure job immediately upon graduation"; "Our program is always in step with changes in legislation, new knowledge, methods and technologies"; and "Our field is the link between all others - we are here to ensure a safe, secure and healthy environment from all risk perspectives".

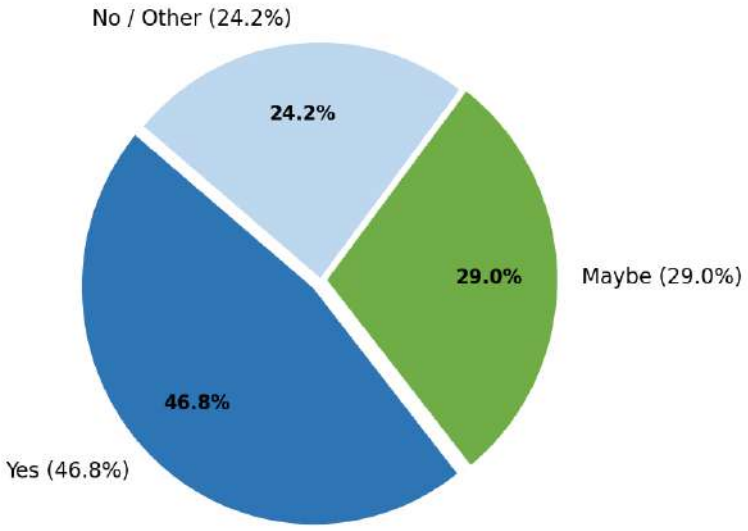


***Figure 2** – Retrospective enrolment preference ("Would you enroll as first choice today?", N=62)*

3.3. Professional Networking Among Graduates

The question on ongoing professional collaboration with fellow graduates yielded strongly positive results. A total of 29.0% of respondents collaborate regularly with former classmates, and 61.3% do so occasionally, depending on circumstances. Only 9.7% reported having no further contact. This high level of ongoing professional connection is particularly significant in a specialized field such as DRM&FSE, where informal knowledge exchange, project collaboration, and mutual support in navigating complex regulatory environments are highly valuable. The program effectively fosters not just individual competencies but a lasting professional community.

3.4. Employment Outcomes and Professional Benefits

Figure 3 presents the distribution of respondents' current professional fields (multiple selections were permitted). Fire safety and fire protection are the dominant areas of employment, reported in various combinations by approximately 53% of respondents. Occupational health and safety (OHS) ranks second (~32%), reflecting the strong legal and regulatory overlap between the two fields in Serbia and the accessibility of OHS-related professional licensing for DRM&FSE graduates. Disaster and catastrophe risk assessment is the third most common area (~27%), followed by general safety/security roles (~16%) and hazardous materials management (~13%). The diversity of employment fields confirms that the DRM&FSE degree provides a broad and flexible competence base applicable across multiple professional contexts.

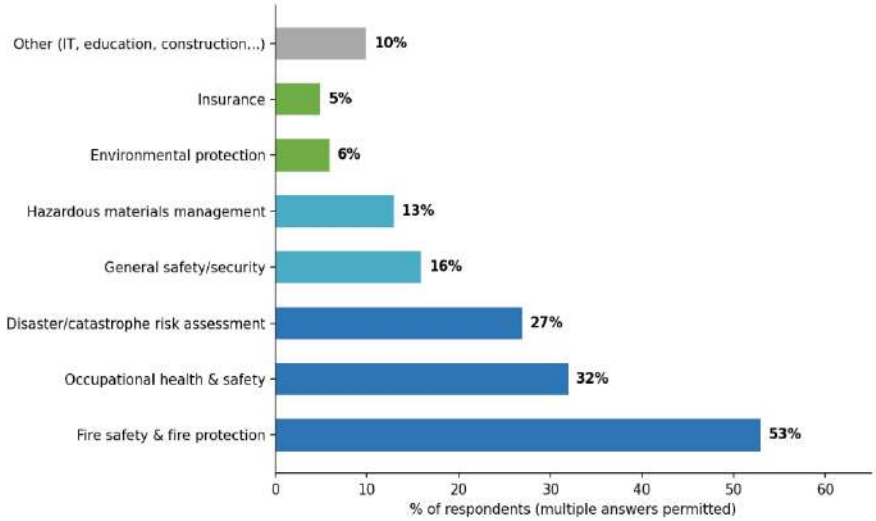


Figure 3 *– Current professional fields of employment among DRM&FSE graduates (multiple selections, N=62)*

Figure 4 shows the distribution of years of professional experience among respondents. The sample spans early-career graduates (1–2 years: 40.3%) through established professionals (7+ years: 19.4%), providing a cross-cohort perspective on the program's outcomes. The presence of graduates with greater experience enables the survey to capture both recent job-market conditions and longer-term career trajectories.

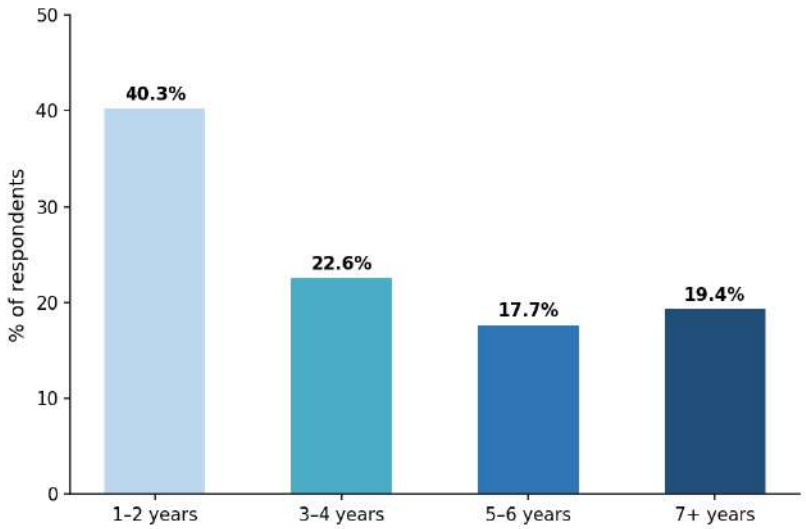


Figure 4 *– Years of professional experience among respondents (N=62)*

When asked about the greatest benefit derived from completing the degree, responses consistently centered on three themes: performing a socially responsible and meaningful job; work that aligns with personal interests and values; and opportunities for professional advancement. Composite responses combining multiple benefits were common and largely positive. One respondent captured the program's broad appeal: "I can truly say that my degree is always in step with changes in legislation, new knowledge, methods, and technologies across many fields - our work covers a remarkable scope".

3.5. Percieved Strengths of the Program

Advice from graduates to prospective students provides a direct, qualitative window into the program's perceived strengths. Recurring themes across open-ended responses include:

1. *Quality and commitment of academic staff.* Multiple respondents explicitly praised specific faculty members by name, citing their practical experience, teaching clarity, and genuine dedication to student success. One graduate noted: "Lecturers are outstanding experts with rich practical experience, and the knowledge is definitely applicable after graduation."
2. *Multidisciplinary and broad competence base.* The program's interdisciplinary character - spanning fire engineering, risk assessment, occupational safety, environmental protection, legal regulation, and GIS applications - was widely valued. Graduates emphasized that this study program prepared them to engage effectively with professionals from other engineering disciplines.
3. *Wide range of employment opportunities.* Graduates consistently highlighted the degree's labor-market versatility, noting that it opens doors in fire safety, OHS, risk assessment, environmental consulting, insurance, and hazardous materials management.
4. *Socially meaningful profession.* Many respondents emphasized the intrinsic value of working in disaster risk prevention and fire safety, describing the profession as "human", "dynamic", and "impactful".
5. *Strong cohort identity.* The small class sizes typical of the program were repeatedly cited as a factor enabling strong personal and professional bonds among graduates and the formation of lasting collaborative networks.

3.6. Adequacy of Knowledge and Recommendations for Curriculum Development

63% of introduced graduates indicated partial sufficiency, with room for improvement - a response pattern consistent with findings from similar graduate survey studies in DRM education, which note the inherent gap between the rapidly evolving regulatory and technological landscape and the cycles of academic curriculum revision [7]. The recommendations for improvement are overwhelmingly practical and forward-looking, summarised in Table 1.

***Table 1** – Most frequently recommended curriculum improvements*

(multiple selections permitted, N=62)

Improvement Area	Approx. % mentioning
More field visits/site activities	~77%
Access to modern technical tools and software	~65%
More laboratory exercises	~53%
Better availability and quality of literature	~48%
More computer-based exercises	~45%
More foreign language instruction	~29%

Among specific subject areas in which graduates recommend increasing course hours, information technologies - particularly AutoCAD, Pathfinder, and BIM - received the highest frequency of mentions, followed by technical regulations and standards, occupational health and safety, and disaster/catastrophe risk assessment. GIS was also consistently cited. Several respondents called for the inclusion of new thematic areas not yet formally represented in the curriculum: crisis management and business continuity (noted as increasingly demanded by large corporations since 2020), ESG (Environmental, Social and Governance) reporting, critical infrastructure protection, and insurance-related content. These suggestions directly reflect the evolving labor market, in which the DRM&FSE graduate's profile is expanding beyond traditional fire safety engineering towards a broader risk management advisory role.

This survey-based study provides a systematic, evidence-based account of graduate perspectives on the DRM&FSE study program at FTN Novi Sad. Five key conclusions emerge from the analysis:

1. The program attracts a strongly motivated student body. Nearly three-quarters enrolled as their first choice, primarily driven by intrinsic values of public service, social responsibility, and the desire to contribute to community safety and resilience. This motivational profile is a significant program asset that should be incorporated into promotional and pedagogical strategies.
2. Graduates demonstrate strong professional satisfaction and lasting peer networks. Close to 76% would re-enroll today ("yes" or "possibly"), and over 90% maintain professional contact with fellow graduates — an unusually high figure for a specialized engineering program that attests to the depth of professional identity formed during study.
3. The degree provides broad and versatile labor market applicability. Graduates work across fire safety, OHS, risk assessment, environmental protection, hazardous materials management, insurance, and international project management, reflecting the multidisciplinary scope of the program.
4. The quality and engagement of academic staff are consistently recognized as key program strengths, as is the interdisciplinary scope and the practical relevance of the curriculum's regulatory and technical content.
5. Targeted curriculum enhancements are recommended, with emphasis on greater practical training (field visits, industry workshops), deeper integration of digital tools (BIM, GIS, Pathfinder, AutoCAD), and the introduction of new thematic areas including crisis management, business continuity, critical infrastructure protection,

and ESG - all directly aligned with the EU's digital and green transition agenda and with the SKILL2SUSTAIN project's objectives.

4. Conclusion

Presented findings provide direct evidence for the re-accreditation of DRM&FSE and contribute to the wider SKILL2SUSTAIN project goal of modernizing higher education in disaster risk management and sustainability across the Western Balkans. Future work will extend this analysis through structured stakeholder consultations with employers and public-sector institutions, enabling a comprehensive labor market needs assessment to complement the graduate perspective presented here.

Acknowledgement

This research was conducted within the framework of the Erasmus+ project Boosting digital and green skills for a resilient and sustainable Western Balkan society - SKILL2SUSTAIN (2025-2028), co-funded by the European Union and within the project "Enhancement of teaching and scientific research capacities through the application of modern technologies in the fields of civil engineering, geodesy, and disaster risk management and fire safety", developed at the Department of Civil Engineering and Geodesy, Faculty of Technical Sciences, University of Novi Sad, Serbia. The views and opinions expressed are those of the authors only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them. The authors also wish to thank all DRM&FSE graduates who participated in the survey.

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Justification for the Introduction of the "Disaster Risk Management" Study Programmes (180 and 240 ECTS) in Bosnia and Herzegovina

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Abstract

Bosnia and Herzegovina, like the wider Western Balkans region, faces an increasing frequency and intensity of natural and technological hazards driven by climate change, unplanned urbanisation and ageing critical infrastructure, while higher education institutions continue to train safety professionals primarily within reactive, response-oriented frameworks. This paper examines the justification for introducing a dedicated study programmes in Disaster Risk Management (DRM) at a higher education institution in Bosnia and Herzegovina, developed within the Erasmus+ project "Boosting digital and green skills for a resilient and sustainable Western Balkan society" (Skill2Sustain, 2025–2028). The analysis combines four complementary evidence sources: a regional Needs Assessment for West Balkan Countries' Digital and Green Education in Academia; a Comparative Analysis between Western Balkans (WBC) partner needs and EU trends; a Report on Stakeholders' Needs for Green and Digital Skills in Bosnia and Herzegovina; and the curriculum architecture and learning outcomes adopted for the proposed 180 and 240 ECTS DRM programmes. The comparative evidence shows that while EU higher education institutions benefit from mature, long-term policy alignment and embedded digital-green strategies, WBC institutions remain more project-driven, dependent on Erasmus+ and Horizon Europe support, yet strongly motivated and regionally relevant. The stakeholder survey confirms convergent demand among students, SMEs and public entities in Bosnia and Herzegovina for applied digital-green competences, including GIS, AI-supported analysis and sustainability-oriented risk management. Building on this evidence, the paper argues that the proposed DRM curriculum, structured around the Sendai Framework for Disaster Risk Reduction (2015–2030) and the "Build Back Better" principle, directly addresses identified regional risk priorities such as hydrological hazards, geological hazards, wildfires and drought, and technological and industrial risk. The DRM programmes are shown to be complementary to the existing Occupational Safety and Fire Protection programme, with the former addressing external, system-level threats and the latter addressing internal organisational safety. The paper concludes that introducing this study programmes are justified on educational, labour-market and regional resilience grounds, and outlines comparable international precedents and implementation considerations.

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Keywords

Disaster risk management, higher education curriculum, Sendai Framework, Western Balkans, Skill2Sustain, Bosnia and Herzegovina.

1. Introduction

Contemporary society is confronted with a growing intensity and frequency of natural disasters and technological accidents, driven by climate change, urbanisation and the increasing complexity of critical infrastructure [1]. Traditional approaches that rely exclusively on post-event response are no longer sufficient. There is an urgent need for engineers and professionals who combine technical knowledge with analytical skills for identifying, assessing and mitigating risk before a disaster occurs. This paper investigates the justification for introducing a new study programmes, Disaster Risk Management (DRM) 180 and 240 ECTS, within the existing higher education portfolio of a Bosnian and Herzegovinian institution, and situates this curricular development within the broader regional context of digital and green skills modernisation supported by the Erasmus+ Skill2Sustain project (2025–2028).

The analysis draws on four bodies of evidence produced or reviewed in the course of curriculum design: (i) the regional Needs Assessment for West Balkan Countries' Digital and Green Education in Academia; (ii) the Comparative Analysis between WBC partner needs and EU trends, including the identification of gaps between digital and green education in EU and Balkan higher education institutions (HEIs); (iii) the Report on Stakeholders' Needs for Green and Digital Skills in Bosnia and Herzegovina; and (iv) the curriculum structure, workload allocation and intended learning outcomes adopted for the proposed DRM programmes at 180 and 240 ECTS. Together, these sources allow the justification for the new programmes to rest not only on disciplinary reasoning but also on empirically observed regional demand.

2. Methodology

The study applies a mixed-method research approach combining empirical data collection, comparative analysis, and curriculum development methods to justify the introduction of the Disaster Risk Management (DRM) study programmes within the higher education framework of Bosnia and Herzegovina. The methodology integrates both demand-side and supply-side perspectives by analysing stakeholder needs, institutional capacities, and European higher education trends related to digital transformation, green transition, and disaster resilience education. The research was conducted within the framework of the Erasmus+ Skill2Sustain project activities and involved the analysis of existing regional reports, stakeholder evidence, and the proposed DRM curriculum structure.

Empirical data were collected through three stakeholder surveys implemented between October and November 2025, targeting public institutions, small and medium-sized enterprises (SMEs), and students. The targeted sample included 22 public institutions, 123 SMEs, and 477 students from different academic years and disciplines. Questionnaires were developed in English and translated into Bosnian and Serbian to ensure accessibility and clarity. Data collection was performed digitally through institutional communication channels, email distribution, and student networks using Google Forms. Participation was voluntary and anonymous, with informed consent provided at the beginning of each questionnaire in accordance with EU GDPR principles and the Bosnia and Herzegovina Law on Personal

Data Protection. The questionnaire design focused on concise and accessible questions, primarily using multiple-choice formats, with an average completion time of 4–6 minutes to improve response quality and reduce respondent burden.

In addition to stakeholder data, the study employed a structured desk research and comparative benchmarking approach. The analysis synthesised three main evidence sources: (i) institutional assessments of digitalisation and green transition practices within Western Balkan higher education institutions, including strategies, curricula, projects, and institutional support structures; (ii) stakeholder needs assessments identifying current and future requirements for digital and green skills; and (iii) mapping of EU higher education practices, including study programmes, courses, research activities, and management approaches related to digital and green transformation. Qualitative content analysis and cross-dimensional benchmarking were applied to compare institutional capacities and educational trends between Western Balkan and EU higher education contexts. Finally, the collected evidence was integrated with the proposed DRM curriculum architecture, including workload allocation and intended learning outcomes for 180 and 240 ECTS study programmes, providing an evidence-based foundation for the development of a new interdisciplinary educational offer.

3. Regional and Policy Rationale

The proposed DRM programmes are fully aligned with the objectives of the Sendai Framework for Disaster Risk Reduction (2015–2030), adopted by the United Nations. The curriculum places primary emphasis on understanding risk and strengthening risk governance, with particular attention to the “Build Back Better” principle, which holds that post-disaster reconstruction of infrastructure and society should increase resilience to future threats rather than simply restore prior conditions. Given the specific vulnerability of the wider geographic area in which the institution operates, the programme is designed to respond to the risk categories that dominate the region: hydrological risk, geological risk, wildfire and drought risk, and technological and industrial risk.

By linking global civil protection standards to local field conditions, the proposed study trains engineers who are not purely theoretical specialists but operational practitioners capable of applying Geographic Information Systems (GIS) and remote sensing in real time. This ensures that every investment in infrastructure is simultaneously an investment in safety, contributing directly to economic stability and the protection of human life.

3.1. Comparative Evidence from EU and Western Balkans HEIs

The Comparative Analysis between WBC partner needs and EU trends indicates that both EU and Western Balkans higher education institutions are strategically committed to digitalisation and the green transition, but operate at markedly different levels of maturity and systemic integration. EU HEIs benefit from long-term policy alignment, stable funding frameworks and institutional strategies that embed sustainability and digital transformation across governance, curricula and research. WBC HEIs, by contrast, show strong motivation and clear regional relevance, yet their strategic orientation remains comparatively more project-driven and externally supported, frequently depending on Erasmus+ and Horizon Europe initiatives to sustain modernisation efforts.

In curriculum design and teaching practice, EU HEIs demonstrate advanced integration of interdisciplinary green and digital skills, supported by modern pedagogies, digital platforms, micro-credentials and lifelong learning systems, with digital twins, artificial intelligence tools, Building Information Modelling (BIM) and blended learning increasingly

standard. WBC HEIs instead concentrate on curricular modernisation and applied skills development linked to regional labour markets, particularly in logistics, transport, management and environmental protection, while facing persistent limitations in digital infrastructure, staff training and systematic lifelong learning frameworks. The comparative evidence therefore indicates that the gap between EU and WBC institutions lies not in intent but in capacity, scalability and institutional embedding of innovation.

Regarding research, innovation and industry cooperation, EU HEIs operate within mature ecosystems connecting academia, industry, policy and technology transfer, enabling large-scale and high-impact research, whereas WBC institutions emphasise knowledge valorisation, employability and regional partnerships while facing constraints in funding scale and research infrastructure. WBC institutions nonetheless provide valuable testbeds for applied innovation and regional pilots. This complementarity supports the rationale for a DRM programmes that are internationally benchmarked yet locally grounded: it allows the receiving institution to absorb advanced EU methodologies (GIS-based hazard modelling, structured risk governance) while contributing contextual relevance specific to the hazard profile of Bosnia and Herzegovina.

3.2. Stakeholder demand in Bosnia and Herzegovina

The Report on Stakeholders' Needs for Green and Digital Skills in Bosnia and Herzegovina confirms a consistent shift toward sustainability-driven skill demand and practical digital adoption among students, small and medium-sized enterprises (SMEs) and public entities. Despite differing institutional roles and capacities, all three stakeholder groups expressed readiness to engage in hybrid digital-green initiatives when these are clearly linked to real needs, applied learning and tangible outcomes.

SMEs reported a clear need for operationally oriented training, particularly in AI-supported processes, process automation, data analysis, energy efficiency and sustainability reporting aligned with EU green frameworks. Public entities expressed institutional willingness to participate in sustainability-focused initiatives, especially through structured partnerships, compliance-oriented activities and collaborative pilots rather than isolated actions. Students constituted the strongest demand pool for future training, internships and project-based engagement combining digital and green skills, expressing particular interest in AI, BIM, sustainable mobility, energy efficiency and hands-on career support. Taken together, these findings validate the need for incremental hybrid skill frameworks led by higher education institutions and delivered through SME engagement and public-private collaboration, a model directly consistent with the operational orientation of the proposed DRM curriculum.

4. Disaster Risk Profile of Bosnia and Herzegovina: Evidence from the Literature

Beyond the Skill2Sustain evidence base, an independent body of national and international literature documents the hazard profile that the proposed DRM programmes are intended to address. This literature spans humanitarian situation reporting, World Bank and United Nations risk assessments, and peer-reviewed engineering and climate research, and is reviewed below across the five hazard categories most relevant to Bosnia and Herzegovina: floods, landslides, wildfires, climate change, and earthquakes.

4.1. Floods and Landslides

The May 2014 floods remain the principal historical reference event for flood and landslide risk in Bosnia and Herzegovina. Triggered by the heaviest rainfall recorded in the country since observations began in 1894 [9], the floods affected an estimated 1.5 million people, around 39% of the population, across roughly 60 municipalities, and caused at least 53 fatalities together with widespread landslide activity [9]. The Recovery Needs Assessment conducted after the floods found that 81 local governments were affected, with three-quarters of the documented damage and losses borne directly by households, businesses and agricultural producers [11]. Subsequent reporting confirmed the recurrence of the hazard, with renewed flooding in 2014 alone triggering dozens of new landslides in the Tuzla and Banja Luka areas [10]. According to the 2017 World Risk Report cited in regional disaster risk reduction programming, 91 of the country's 145 local governments are classified as being at very significant risk from floods and landslides, with a further 27 at high risk [11], underscoring that this is not an isolated historical episode but a structural feature of the national risk landscape.

This structural vulnerability was confirmed again a decade later. On the night of 3–4 October 2024, intense rainfall over central and southern Bosnia and Herzegovina triggered flash floods and landslides that severely affected the municipalities of Jablanica, Konjic, Fojnica, Kiseljak and Kreševo, displacing boulders weighing over ten tonnes and destroying housing in Donja Jablanica and Buturović Polje [22]. By 17 October 2024, the disaster had been confirmed to have caused 27 fatalities, with several hundred households affected and prolonged isolation of communities due to destroyed road and communication infrastructure [22]. The United Nations' Multi-Cluster Initial Rapid Assessment, conducted with the Federal Civil Protection of Bosnia and Herzegovina and the national Red Cross Society, confirmed widespread damage to housing, infrastructure and essential services [23], while the EU activated its Civil Protection Mechanism to deploy international rescue teams [23]. The 2024 event, described locally as the worst flooding since 2014, shows that the hazard identified in the 2017 World Risk Report continues to materialise, reinforcing the case for dedicated training in flood and landslide risk governance.

4.2. Wildfires

Independent hazard screening classifies wildfire hazard in Bosnia and Herzegovina as high, reflecting a greater than 50% annual likelihood of fire weather capable of causing both life and property loss [12]. Climate projections reviewed by the same source indicate a likely increase in the frequency of fire-prone weather, a longer fire season, and an increase in fire severity, driven by rising temperature and greater rainfall variability [12]. Regional wildfire-susceptibility research situates Bosnia and Herzegovina within the broader Mediterranean climatic zone affecting the Western Balkans, where recurring drought and elevated air temperature have been identified as principal drivers of wildfire occurrence, with national drought and heat-wave episodes recorded repeatedly between 2000 and 2021 [17]. The World Bank's Country Climate and Development Report for Bosnia and Herzegovina similarly identifies wildfires, alongside floods and severe air pollution, as one of the country's most significant climate-related hazards, with associated economic and social impacts. [13].

4.3. Climate Change

Bosnia and Herzegovina is classified as vulnerable to climate change impacts, ranking 79th of 181 countries in the 2020 ND-GAIN Index [14]. National climate-trend research covering the period 1961–2023 shows that temperature increases in urban centres have

already exceeded 2°C. The analysis also indicates a clear shift in precipitation patterns, characterised by an increase in dry days alongside more frequent intense precipitation events, creating conditions that contribute to both severe droughts and flooding within the same years [15]. The sectors identified as most exposed are agriculture, water management, forestry, human health, tourism and biodiversity, with floods, droughts, forest fires and severe storm winds named as the principal climate-related risks [15]. The World Bank Climate Change Knowledge Portal similarly concludes that climate-driven hydrometeorological hazards, including droughts, heat waves, heavy precipitation, landslides and floods, are expected to intensify, primarily affecting agriculture and human health [16], while UNICEF programming documents project a further increase in the frequency, unpredictability and intensity of flooding, drought, heat waves and wildfires across the Western Balkans by the end of the century [11].

4.4. Earthquakes

Bosnia and Herzegovina lies within the Dinarides, part of the Mediterranean orogenic system, and its seismic activity has been documented for more than two thousand years [18]. Large earthquakes are infrequent but historically associated with far-reaching, costly damage; the country's first generation of probabilistic seismic hazard maps, expressed in terms of peak ground acceleration for 95- and 475-year return periods, was only completed in 2018 [18]. Engineering assessments of the existing building stock, for example in two municipalities of Sarajevo, highlight the vulnerability of structures built between 1918 and 2014 under varying seismic codes [19], while a magnitude 6.1 earthquake near Stolac in April 2022 demonstrated that seismic effects, including disturbance of karst groundwater systems, can be felt over 150 km from the epicentre [20]. Authors working on seismic hazard mapping note that revisions to NATO-era hazard maps have in some cases reclassified higher-risk urban areas, such as Banja Luka, as zones of lower hazard, a development flagged as a potential concern for spatial planning and population safety [21].

4.5. Synthesis

Read together, this literature corroborates, with independent national and international evidence, the same risk priorities that the Skill2Sustain curriculum documents identify qualitatively: recurrent and geographically widespread flood and landslide exposure, high and climate-amplified wildfire hazard, a measurable and accelerating climate trend affecting multiple economic sectors, and a historically significant but only recently systematically mapped seismic hazard. This convergence between project-based needs assessment and the broader scientific and humanitarian literature strengthens the empirical justification for the DRM programmes structured explicitly around hydrological, geological, wildfire/drought and technological risk categories, as proposed in Section 2.

5. Curriculum Architecture of the Proposed DRM Programmes

The DRM curriculum was developed by the Commission for Curriculum Development within the Skill2Sustain project, comprising academic experts from five partner countries. It is offered in two study programmes: a 180 ECTS three-year track and a 240 ECTS four-year track, both leading to the title of Bachelor / Bachelor Engineer in Disaster Risk Management within the existing study program of Occupational Safety and Fire Protection. One ECTS credit corresponds to 30 hours of student workload. The programmes can be delivered in full-time, part-time or distance-learning mode.

The first two semesters establish a common technical and scientific foundation (mathematics, physics, graphic communication, informatics, basic safety principles, environmental and health protection, programming, electrical and mechanical engineering fundamentals). From the third semester onward, the curriculum progressively introduces specialised DRM content: transport safety, hazardous materials risk, national security, thermodynamics, safety management, toxicology, fire and explosion hazards, civil protection, disaster simulation and GIS applications, crisis management, hydrology, information system reliability and security, and risk assessment. Elective modules allow further specialisation in areas such as electromagnetic radiation protection, engineering measurement, critical infrastructure, fire-prevention significance, technological process safety, stress psychology and alarm systems.

The 240 ECTS programme extends the 180 ECTS core with two additional semesters dedicated to applied operational competences: electrical safety on construction sites and public spaces, early-warning systems, intervention and rescue equipment, a capstone project, interventional epidemiology, post-disaster recovery management, fire protection of buildings, and a supervised practicum, complemented by electives in tactical intervention and rescue, peace and humanitarian operations, or terrorism. Table 1 summarises the principal structural differences between the proposed DRM programmes and the existing Occupational Safety and Fire Protection (OSH) programme offered by the same institution.

***Table 1** – Structural comparison between the OSH/Fire Protection programme and the proposed DRM programmes*

Programme feature	**OSH and Fire Protection**	**DRM (180 ECTS)**	**DRM (240 ECTS)**
Duration	3 and 4 years	3 years	4 years
ECTS credits	180 and 240	180	240
Award	Bachelor in OSH and Fire Protection	Bachelor engineer in Disaster Risk Management	Bachelor engineer in Disaster Risk Management
Core risk focus	Workplace safety, fire protection	Hydrological, geological, wildfire/drought, technological risk, security risk	As 180 ECTS, plus extended incident management, recovery and tactical response modules
Distinct methodological tools	Risk assessment, OSH legislation	GIS, remote sensing, hydrology, disaster simulation, emergency preparedness	GIS, remote sensing, hydrology, disaster simulation, early-warning systems, intervention equipment, Crisis preparedness and response

The two programmes are deliberately complementary rather than overlapping. The OSH and Fire Protection programme ensures stability and safety within the organisational boundary, while the DRM programmes ensure the resilience of that same organisation, and of the wider community, against extreme external threats. Both areas rest on the same underlying methodology of risk assessment and risk reduction in the interest of preserving human life and material assets, which justifies their coexistence within a single institutional portfolio rather than treating DRM as a redundant addition. In the proposed DRM curriculum structure, the 180 ECTS study program comprises a total of 36 courses, while the 240 ECTS study program comprises a total of 47 courses, including compulsory academic obligations such as internships, practical training, and final thesis components.

6. Learning Outcomes and Labour-Market Alignment

Upon completion of the first cycle of the 180 ECTS programme, graduates are expected to be able to describe and interpret core concepts in occupational safety, fire protection and disaster risk management; recognise the impact of human activity and technological systems on the environment; understand the legal and institutional framework of protection and rescue, including the role of civil protection; apply safety measures in transport, industry and other risk-bearing systems; identify the characteristics of hazardous substances; apply basic technical and engineering safety principles; analyse the impact of working and emergency conditions on human psychophysical states, including stress; participate in the preparation of protection and rescue plans, risk assessments and intervention plans; apply data collection and analysis methods, including statistics, informatics and GIS, in risk management; apply basic risk-assessment methods covering identification, analysis and evaluation; analyse environmental impacts such as pollution, radiation, noise and vibration on human health and system safety; apply crisis-management and post-disaster recovery principles; participate in the organisation of operational centres and coordination of emergency activities; and apply reliability and security principles for technical and information systems in support of risk reduction.

The 240 ECTS programme retains all of the above outcomes and adds the capacity to apply safety measures when working with electrical energy on construction sites and public spaces, to operate intervention and rescue equipment and execute tactical procedures in emergency situations, to manage and respond using early-warning systems for disaster prevention and mitigation, to apply fire protection and prevention measures in buildings and critical infrastructure, and to apply knowledge and skills from tactical intervention, humanitarian and peacekeeping operations in crisis and post-disaster situations. This extended outcome set corresponds closely to the operational competences that stakeholder consultations identified as being in short supply among SMEs and public entities in Bosnia and Herzegovina, particularly in relation to compliance-oriented activity, structured emergency partnerships and applied digital tools such as GIS.

7. International Benchmarking

The proposed DRM programmes have clear analogues among established international and regional programmes, supporting its academic legitimacy and labour-market recognisability. Comparable programmes include Disaster Risk Management and Climate Change Adaptation at Lund University (Sweden); “Disaster Risk Management and Fire Protection” at the University of Novi Sad (Serbia); Disaster Risk Management and Fire Engineering at the University of Tuzla (Bosnia and Herzegovina); and Fire Protection Engineering programmes at the University of Maryland and Oklahoma State University (United States). The existing Tuzla programme indicates that demand and academic precedent for DRM education in Bosnia and Herzegovina are already partially validated domestically; the proposed programmes extend comparable provision to a different region of the country, within a curricular design developed under the Skill2Sustain consortium.

8. Discussion

The evidence reviewed converges on a consistent justification for the DRM programmes. First, the regional risk profile, dominated by hydrological, geological, wildfire/drought and technological hazards and corroborated by independent national and

international literature in Section 3, creates an objective need for specialists trained across the full risk cycle rather than solely in post-event response. Second, the comparative EU–WBC analysis shows that Bosnian and Herzegovinian higher education is well positioned to adopt advanced tools such as GIS-based hazard modelling and structured risk governance, provided institutional capacity and external support, such as Skill2Sustain, are leveraged to close gaps in infrastructure and staff training. Third, the stakeholder needs assessment demonstrates active demand from students, SMEs and public entities for precisely the applied, digitally enabled competences embedded in the DRM curriculum.

9. Conclusion

The introduction of the Disaster Risk Management study programmes in Bosnia and Herzegovina is justified on three converging grounds: alignment with international policy commitments under the Sendai Framework and the "Build Back Better" principle; demonstrated regional and stakeholder demand for applied digital-green competences established through the Skill2Sustain needs assessment, comparative analysis and stakeholder survey, and corroborated by the independent hazard literature reviewed in Section 3; and a curriculum architecture, at both 180 and 240 ECTS, that is internationally benchmarked while remaining grounded in the specific hazard profile of the country. The proposed programmes offer a credible pathway for producing graduates capable of operating across the full disaster risk cycle, from prevention and risk governance to operational response and post-disaster recovery. Future work should monitor graduate employment outcomes and refine elective offerings in line with evolving regional risk patterns and continued EU–Western Balkans cooperation.

This paper was prepared with reference to the findings of the Needs Assessment for West Balkan Countries' Digital and Green Education in Academia, the Comparative Analysis between WBC partner needs and EU trends, and the Report on Stakeholders' Needs for Green and Digital Skills in Bosnia and Herzegovina, all produced within the Erasmus+ project Skill2Sustain.

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Navigating the Twin Transition: The Imperative for Modernized Education in Climate-Resilient Resource Management in Bosnia and Herzegovina

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Abstract

Bosnia and Herzegovina (BiH) sits at the intersection of post-conflict economic recovery, European Union integration, and the global green and digital energy transition. Its historical mining and metallurgical waste, long viewed as an environmental burden, represents an untapped source of Critical Raw Materials (CRMs) and Coal Bed Methane (CBM) under the contemporary circular economy paradigm. Progress, however, is hampered by archaic regulatory frameworks, systemic geospatial data opacity, escalating climate change risks, and a severe deficit in modernized engineering and geo-data skills. This paper synthesizes these institutional and environmental challenges to argue for an urgent paradigm shift in the region's higher education system. By prioritizing reskilling in geospatial data organization, advanced 3D deposit modeling, and innovative green extraction methods, BiH can bridge the gap between traditional industrial curricula and modern regulatory demands, securing an economically viable and socially just Twin Transition.

Keywords

Twin Transition, Critical Raw Materials (CRM), Circular Economy, Climate Resilience, Interdisciplinary Education.

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1. Introduction: The Resource Context and the Circular Economy

Bosnia and Herzegovina (BiH) possesses a deep-rooted mining tradition, with mineral exploration and extraction history persisting over centuries [1]. Despite this historical wealth, current extractive industries account for only 1.3% of the nation's GDP [2]. Historically, the massive accumulation of mining and metallurgical waste—such as tailings and slag from iron, lead, zinc, and aluminum extraction—has been viewed domestically in public and legislative discourse as a permanent environmental burden [3].

However, the contemporary "circular economy" paradigm reframes these techno-anthropogenic waste sites as untapped reservoirs of Critical Raw Materials (CRMs). Metals such as copper, zinc, lead, cobalt, and rare earth elements are essential for the global shift toward renewable energy systems, including photovoltaics and high-capacity battery storage [4, 5]. Furthermore, unquantified methane emissions from coal beds (CBM) present a viable transitional energy source [6]. Unconventional gas extraction technologies are significantly altering the global energy landscape, where capturing CBM serves a dual purpose: acting as a baseload fuel to stabilize intermittent renewable grids, and mitigating fugitive emissions of a highly potent greenhouse gas [7, 8].

Unlocking this vast potential requires navigating a "Twin Transition"—simultaneously adopting green sustainability and digital technologies. Currently, this transition is paralyzed by a workforce heavily reliant on traditional, linear methods of primary resource extraction, lacking the interdisciplinary competencies required for modern secondary resource management [9].

2. Institutional Hurdles and the Geospatial Data Deficit

The successful modernization of the mining sector is severely constrained by BiH's complex, decentralized political structure and an archaic regulatory framework largely inherited from the Yugoslav era [10]. The nation faces profound institutional inertia, overlapping jurisdictions among its administrative entities (the Federation of Bosnia and Herzegovina, Republika Srpska, and Brčko District), and an entrenched system of political patronage that breeds corruption and delays the permitting process [10, 11].

A glaring vulnerability within this institutional framework is the management of spatial and geological information. Currently, vital geospatial data—such as digital elevation models, land boundaries, and geological vector layers—is fragmented, rarely updated, and not freely shared among governmental entities [11]. Furthermore, digital cadastral systems are highly unsynchronized with atavistic land-book records, meaning that documented possession rarely corresponds with legal ownership [11]. This data opacity and lack of a unified spatial data infrastructure (SDI) not only stifles foreign investment in CRM exploration but makes responsible environmental planning and risk assessment nearly impossible.

3. Climate Change Vulnerabilities and Infrastructure Risks

The urgency for updated modeling, planning, and infrastructure development is compounded by the escalating realities of climate change. Existing models indicate that the central and western portions of the Balkan Peninsula are highly susceptible to shifting rainfall patterns, prolonged droughts, and extreme weather phenomena [12]. Recent events, such as the massive "atmospheric rivers" of October 2024, precipitated hundreds of liters of water

per square meter within a narrow geographic area in under six hours, resulting in devastating flash floods and landslides [13, 14].

Because BiH's primary metallogenetic provinces are located in rugged, mountainous terrains and rely on an aging, substandard transportation infrastructure built primarily between 1968 and 1975, climate-induced natural disasters pose catastrophic risks [15]. A single flash flood can instantaneously sever logistics chains, destroy retention dams at historical tailings sites, and cause significant loss of life [16]. Responsible resource extraction in this new climatic framework strictly requires blending environmental compliance with advanced predictive modeling to create resilient, adaptive operational strategies. Figure 1 synthesizes these converging institutional, geospatial, and climatic urgency factors into a unified rationale for modernized planning and education.

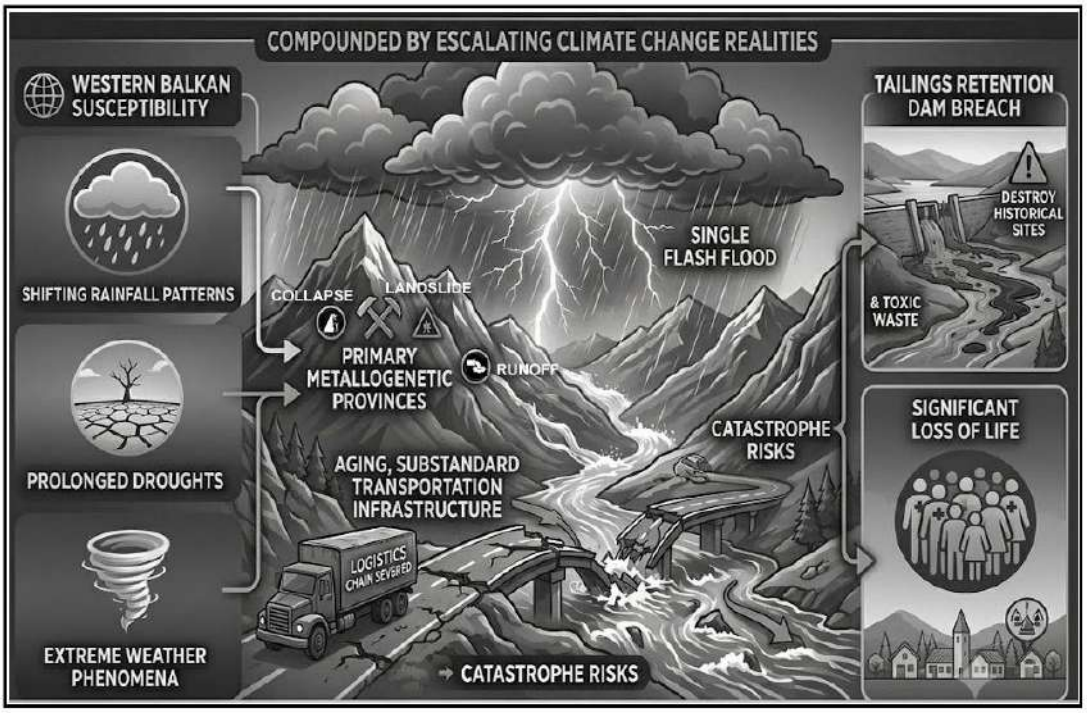


Figure 1 *– Urgency concepts for updated modeling, planning and education. Source: Authors, based on [10-17], illustrated with the assistance of AI.*

4. The Educational Imperative: Reskilling for the Future

To reconcile the promise of CRM wealth with the harsh realities of climate hazards and administrative bottlenecks, a profound transformation of the Western Balkans' educational system is mandatory [9, 17]. A critical gap exists between traditional academic curricula—which remain heavily focused on legacy extraction techniques—and modern industrial, environmental, and regulatory demands [9]. Universities must pivot toward interdisciplinary programs that merge geosciences, data science, and environmental protection.

4.1. Geospatial Data Organization and Infrastructure

Because the dearth of synchronized, accessible spatial data paralyzes development and emergency response, curricula must train a new generation to build and manage modern, open-source geospatial frameworks. Professionals trained in advanced Geographic Information Systems (GIS), drone-assisted remote sensing, and 3D mapping are urgently

needed. These skills are vital to untangle the bureaucratic legacy of land rights, digitize terrain constraints, and provide the transparent data necessary for sustainable exploration and participatory community mapping [18].

4.2. Advanced Deposit Modeling and Predictive Forecasting

Traditional exploration methods are insufficient for assessing the complex geochemistry of historical tailings or preparing for climate risks. Education must emphasize 3D deposit modeling, geostatistics, and resource estimation aligned with international reporting standards. Furthermore, geoscientists and engineers must be trained in predictive forecasting—such as modeling hydrological runoff from atmospheric rivers and utilizing Digital Twins—to simulate potential infrastructure vulnerabilities in a controlled environment before a disaster strikes [16, 18].

4.3. New Extraction and Exploitation Methods

Universities must move beyond environmentally destructive methodologies. Engineering programs should prioritize green extraction techniques, focusing on the hydrometallurgical recovery of CRMs from waste, bioleaching, and the safe, controlled capture of CBM (drawing on successful global analogs like the San Juan Basin) [8, 19]. This training must also be deeply intertwined with the principles of the Just Transition, offering lifelong learning, reskilling, and upskilling opportunities for the current coal-mining workforce to secure their livelihoods in the new green economy [20]. Figure 2 illustrates the resulting paradigm shift in engineering and geoscience education required to reconcile these three reskilling priorities within a coherent institutional strategy.

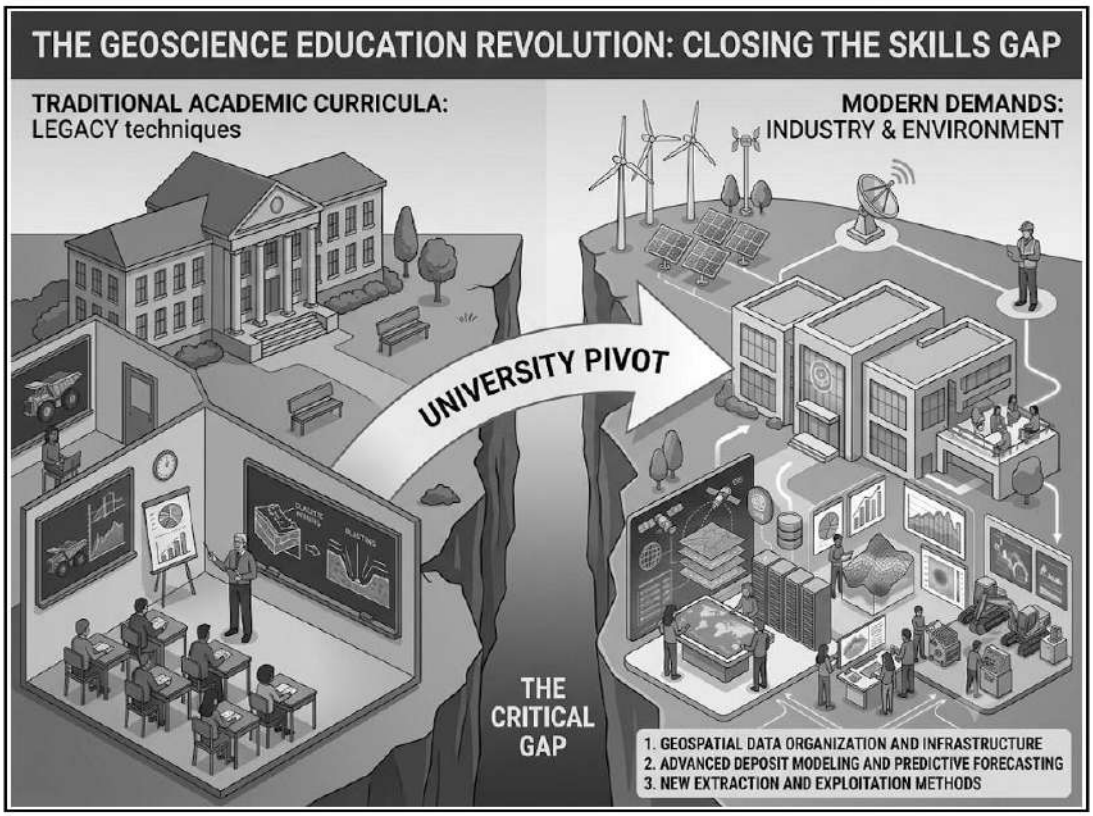


Figure 2 *– Education paradigm shift required for Bosnia and Herzegovina.*
Source: Authors, based on [8, 9, 16, 18-20], illustrated with the assistance of AI.

The rationale for this modernization extends beyond a narrow technical skills gap; it reflects a broader European recognition that education systems must be restructured to remain relevant to fast-changing labour markets and civilizational challenges. The European Commission's Skills Agenda for sustainable competitiveness, social fairness and resilience explicitly identifies the twin green and digital transition as the central driver of future skills demand, calling on Member States and candidate countries alike to embed reskilling and upskilling pathways within higher education [25]. Within the European Higher Education Area, the Rome Ministerial Communiqué similarly commits signatory countries, including Bosnia and Herzegovina as a Bologna Process participant, to align study programs with labour-market needs while safeguarding academic quality and mobility [26]. At a global level, UNESCO's 2021 report on the futures of education frames curriculum renewal as part of a wider social contract for education, in which higher education institutions are expected to anticipate societal and environmental transformation rather than merely respond to it once skills shortages become acute [27]. For BiH's mining and energy engineering programs specifically, this rationale is amplified by the country's EU accession trajectory, which requires progressive harmonization of vocational and higher education standards with EU policy frameworks, and by the immediate operational urgency created by the institutional and climate vulnerabilities described in Sections 2 and 3.

Operationalizing this pivot requires a structured, iterative procedure rather than an isolated curricular update. Modernization should begin with a systematic labour-market and skills-needs assessment, since skills anticipation exercises in the Western Balkans have historically been poorly integrated into education and training policy, producing persistent mismatches between graduate competencies and industry demand [21]. Curriculum revision must therefore proceed through structured consultation with a broad stakeholder base, mining and energy sector employers, professional associations, regulatory bodies, and international donor programs, so that new course content reflects operational realities rather than purely academic priorities. Newly designed programs should be explicitly benchmarked against the European Qualifications Framework and the corresponding national qualifications framework to ensure comparability, mobility, and recognition of graduate competencies across the region and the wider European Higher Education Area [22]. The design and revision process itself should follow defined institutional procedures, faculty council review, external expert evaluation, and formal approval by university senates or accreditation agencies, in line with the Standards and Guidelines for Quality Assurance in the European Higher Education Area, which require that study programs be periodically and systematically reviewed to confirm their continued relevance [23]. Emerging digital competencies, including GIS, remote sensing, and predictive modeling, and green competencies aligned with recognized sustainability competence frameworks should be embedded as core learning outcomes rather than elective additions [24]. Sustained institutional commitment to continuous monitoring, employer feedback loops, and periodic curriculum review is ultimately essential to prevent the recurrence of the obsolescence that currently characterizes the region's engineering and geosciences education.

Beyond these procedural safeguards, the substantive content of learning outcomes requires equally deliberate revision. Programme- and course-level learning outcomes should be rewritten according to constructive alignment principles, explicitly specifying the competencies graduates must demonstrate rather than the topics instructors intend to cover, and mapped transparently onto assessment methods so that achievement of each outcome can be verified [22, 23]. In practice, this means restructuring modules such as mine planning, geostatistics, and environmental permitting around demonstrable competency statements, for example the ability to construct a 3D block model from sparse drillhole data or to conduct a climate-risk screening of a tailings facility, rather than around lecture-hour allocations. The integration of digital and green competences should likewise be systematized using recognized reference frameworks: the European Commission's DigComp 2.2 framework offers a structured taxonomy for embedding data literacy, digital content creation, and problem-solving competencies across engineering and geoscience modules [28], while GreenComp provides an analogous structure for sustainability competencies, including systems thinking and futures literacy, both directly applicable to circular-economy-oriented mining curricula [24]. Practical implementation examples already exist within the wider European raw materials sector: the European Raw Materials Academy, coordinated by EIT RawMaterials, is building a pan-European, modular, and certified training portfolio spanning the entire raw materials value chain, from primary mining to recycling and the circular economy, explicitly designed to connect curricula with real-time industry needs, and thereby

offers a transferable template for BiH's own reskilling architecture [29]. Complementary good practice can be drawn from OECD analyses of skills systems undergoing green and digital transition, which emphasize that resilient reskilling architectures depend on continuous labour-market intelligence rather than one-off curriculum reviews [30]. Finally, monitoring and evaluation mechanisms must be built into the curriculum lifecycle from the outset: graduate employment tracking, employer satisfaction surveys, and periodic competency audits should feed back systematically into subsequent review cycles, converting curriculum modernization from a single discrete event into a continuous improvement process capable of anticipating, rather than merely reacting to, the accelerating pace of technological and climatic change facing the region's extractive and environmental sectors.

5. Conclusion

Bosnia and Herzegovina possesses the geological resources required to meaningfully contribute to the global green energy transition while simultaneously remediating its legacy environmental burdens. However, navigating the legacy of a decentralized bureaucracy, opaque geospatial data systems, and escalating climate hazards requires moving decisively beyond traditional practices. The ultimate solution lies in human capital. By investing aggressively in interdisciplinary education, reskilling the existing workforce, and upskilling new professionals in geospatial data organization, advanced deposit modeling, and innovative green extraction methods, BiH can ensure its energy transition is economically robust, ecologically resilient, and socially just.

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T04

Digital Tools & Technologies (BIM, GIS...) for the Built Environment

A Proposed Closed-Loop Method for Carbon-Aware Prioritization and Ai-Based Energy Optimization of Active Software Components

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Abstract

Software components located within the same software application may differ substantially in terms of energy consumption and their associated operational emissions. For this reason, treating them equally during optimization is not methodologically justified. In this paper, the authors propose a closed-loop method for environmentally oriented and practically useful ranking of active software components and the application of AI-assisted optimization to software components assessed as having the greatest environmental impact. The proposed method combines the Stubbed Energy Profiling Method, data on the execution frequency of specific components, and elements of the Software Carbon Intensity methodology with the aim of estimating their annual operational emissions. All included software components are ranked according to the calculated values, after which a large language model generates candidate optimized versions of the code, starting with the components assigned the highest calculated priority. Each candidate version must also undergo functional and regression validation and renewed energy-consumption measurement. The reason for this is that the functionality of the software component must not be compromised after energy optimization. The proposed method additionally includes the energy consumed during AI-assisted optimization and code testing, thereby enabling the estimation of the net energy benefit and the energy break-even point. The main contribution of the paper is the integration of previously separate procedures for energy profiling, environmental ranking, AI-assisted optimization, and energy validation into a unified and formalized methodological framework. The method described by the authors in this paper has not been empirically validated, and therefore future research should examine its applicability, reproducibility, and practical value in real-world software applications.

Keywords

Software energy efficiency, software components, operational emissions, large language models, AI optimization.

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1. Introduction

Software applications achieve their functionalities and objectives by using processing, memory, network, and other infrastructure resources, which means that their operation is associated with electricity consumption and, consequently, corresponding carbon emissions. However, individual functional units within the same software application do not contribute equally to its total energy consumption. Identifying the components that make the greatest contribution to energy consumption therefore represents a highly significant prerequisite for any targeted software optimization. The StEP method enables the estimation of the energy contribution of individual software components by comparing the original application with its variants in which the observed components are replaced by stubs [1], while the Software Carbon Intensity standard provides a methodological basis for expressing the carbon intensity of a particular software system [2].

Alongside the development of methods for energy profiling and software ranking, some recent studies have examined the possibility of applying large language models to energy-oriented source code optimization. Peng et al. presented an automated approach to this problem in which the model is used to refactor code in order to reduce energy consumption while preserving the overall functional correctness of the software [3]. However, the results of some other experimental studies show that instructing a model to generate energy-efficient code does not always lead to an actual reduction in energy consumption and that the outcome depends on the programming language in which the software is written, the problem being analysed, and the generated implementation [4]. Therefore, the energy benefit of AI optimization cannot be assumed solely on the basis of changes to the software code or a shorter execution time, but must be confirmed through repeatable measurements both before and after optimization.

The mentioned approaches consider individual steps of the problem separately. The StEP method is focused on identifying the software components that contribute most to energy consumption [1], while approaches based on large language models examine the possibility of generating or refactoring more energy-efficient code [3,4]. However, the analyzed sources do not describe a unified procedure in which active software components would first be ranked according to their annual environmental impact, after which AI optimization would be applied only to such priority components, with the proposed changes accepted exclusively after functional and energy validation. Additionally, it is necessary to determine whether the energy saved during the future execution of the optimized code ultimately exceeds the energy consumed by AI optimization and repeated testing.

The aim of this paper is to develop and formally describe a closed-loop method for environmentally targeted ranking and AI optimization of active software components. The proposed method first estimates the energy contribution of software components and then relates it to the frequency of their actual execution within the program and the carbon intensity of the electricity used in order to determine their annual environmental impact. The components with the highest estimated impact are ultimately subjected to AI-assisted code optimization. Each proposed modification is accepted only if it passes functional and regression tests and if repeated measurements confirm an actual reduction in energy consumption. An additional contribution of the paper lies in including the energy consumed by the AI optimization and testing processes themselves in the assessment of the net energy benefit.

2. Theoretical Background and Related Research

2.1. Energy Profiling of Software Components

Jagroep et al. developed the Stubbed Energy Profiling Method (StEP) for estimating energy consumption at the level of architectural elements within a particular software system [1]. The method essentially compares a reference version of the software system with versions in which individual functional elements are replaced by stubs under the same test workload. The resulting differences in measured energy consumption are used to create an energy profile and identify the elements with the greatest contribution to energy consumption [1]. In this paper, the authors extend StEP by linking the energy contribution to component execution frequency, operational emissions, and AI-assisted code optimization.

2.2. Carbon Emission Intensity of Software Components

The ISO/IEC 21031:2024 standard describes a methodology for calculating the carbon emission rate of a particular software system, namely its Software Carbon Intensity (SCI) score [2]. The SCI specification includes operational emissions associated with electricity consumption and the corresponding share of embodied emissions from the hardware used by the software, with the result expressed relative to a functional unit [5]. In the proposed method, operational emissions are used to compare components, with the original and optimized versions measured under identical experimental conditions. Although the SCI methodology also includes the embodied emissions of hardware, the ranking in this paper is limited to the estimated operational emissions associated with the execution of software components.

2.3. Application of AI Large Language Models in Energy-Oriented Code Optimization

Peng et al. proposed the use of large language models as code optimizers with the aim of reducing energy consumption and achieved improvements in three of the six programs analyzed [3]. Cursaru et al. demonstrated that explicitly prompting a model to generate energy-efficient code does not always guarantee an improvement and recommended measuring its energy consumption before integrating it into a software system [4]. These results justify the inclusion of functional and energy validation in the proposed method.

3. Proposed Method

3.1. Method Overview

As shown in Table 1, the proposed method comprises five phases: decomposing the system into active functional components, estimating their energy contribution by applying principles from the StEP method [1], ranking the components according to their estimated annual operational emissions using elements of the SCI methodology [5], AI-assisted

optimization of priority components, and functional and energy validation of the changes generated during AI optimization. The optimization is considered acceptable only when it preserves functional correctness and achieves a positive net energy benefit.

***Table 1** – Overview of the phases of the proposed closed-loop method*

Method Phase	Activity	Methodology	Contribution
1. Decomposition	Isolation of modules, services, or API endpoints	System architecture and test scenarios	List of active components for analysis
2. Profiling	Measurement and estimation of energy contribution	StEP method (baseline vs. stubbed version)	Component energy profile (ΔE_i)
3. Prioritization	Calculation of annual operational carbon emissions	SCI standard, execution frequency (N_i), and intensity (I)	Priority ranking list for optimization ($O_{i,year}$)
4. AI Optimization	Generation of energy-efficient code using LLMs.	Source code, functional tests and prompts.	Candidate versions of optimized code.
5. Validation	Correctness verification and net benefit calculation.	Regression testing, formulas for (NEB_i) and (BEP_i)	Verified code with confirmed green ROI.

3.2. Selection and Decomposition of Active Software Components

The proposed method first defines the boundaries of the software system and decomposes it into active functional components that can be isolated, executed through a representative business scenario, and for which the execution frequency can be determined. A component may be a module, a specific service, an API endpoint, or a background process of the software application. For each selected component, a stub is created that returns a predefined response, thereby enabling the execution of the remainder of the system without the original implementation of the component under consideration [1]. Components that cannot be reliably isolated are recorded as a limitation of the method and, as such, are not included in the individual ranking.

3.3. Measurement of Energy Contribution and Component Ranking

The energy contribution of each analyzed software component is estimated by comparing the reference version of the software system with a version in which the component under consideration is replaced by a stub. Both versions are executed under the same test workload and in the same experimental environment. In accordance with the principle of the StEP method, the difference between the measured energy consumption of the reference and stubbed versions is attributed to the energy effect of the component under consideration [1]. Since the stub also consumes a certain amount of energy, the resulting value represents only an estimate of the component's energy contribution rather than its complete and direct measurement [1]. Each measurement encompasses a single execution of the software component under consideration within the defined test scenario. The estimated energy contribution of each analyzed component is calculated according to Eq. (1).

$$\Delta E_i = \overline{E_B} - \overline{E_{s_i}} \quad (1)$$

In Eq. (1), $\overline{E_B}$ represents the average energy consumed during the execution of the reference version of the system, $\overline{E_{s_i}}$ represents the average energy consumed by the version in which the component denoted by index (i) is replaced by a stub, while ΔE_i represents the estimated energy contribution of the component under consideration per single execution.

The energy contribution measured per single execution does not necessarily determine the overall annual significance of a component. A component with lower energy consumption per execution may actually have a greater annual impact if it is executed considerably more frequently. Therefore, the value obtained according to Eq. (1) is related to the annual number of executions of the component under consideration. The estimated annual energy contribution of each analyzed component is calculated according to Eq. (2).

$$E_{i,year} = \Delta E_i \cdot N_i \quad (2)$$

In Eq. (2), the estimated energy contribution of the component per single execution is multiplied by the annual number of executions of that component, N_i. The resulting value represents the estimated amount of energy attributable to the software component under consideration over an entire year. Weighting the energy contribution by execution frequency represents an extension introduced by the authors in this paper.

To estimate the environmental impact, the estimated annual energy contribution obtained according to Eq. (2) must be related to the carbon intensity of the electricity used. The SCI specification defines operational emissions as the product of energy consumption and the carbon intensity of electricity [5]. Before applying this calculation, the energy value must be expressed in a unit corresponding to the unit used for carbon intensity. For example, if carbon intensity is expressed in grams of CO_2e per kilowatt-hour, the annual energy contribution must be expressed in kilowatt-hours. The estimated annual operational emissions of each analyzed component are calculated according to Eq. (3).

$$O_{i,year} = E_{i,year} \cdot I \quad (3)$$

In Eq. (3), the estimated annual energy contribution of the component is multiplied by the carbon intensity of electricity. The resulting value represents the estimated annual operational emissions of the software component under consideration. After this calculation has been performed for all analyzed components, the resulting values are ranked in descending order. Components with the highest estimated annual operational emissions are assigned the highest priority for AI-assisted optimization.

3.4. AI-Assisted Optimization of Priority Components

AI-assisted optimization is applied to software components according to the order established by the ranking presented in Section 3.3. The source code of the component itself, the necessary functional requirements, existing tests, and technical constraints are provided to the large language model, together with an instruction to preserve the existing behavior and reduce energy consumption. The use of large language models as energy-efficiency optimizers was previously examined by Peng et al. [3]. However, since an explicit request for energy-efficient code does not guarantee an actual improvement [4], each generated version must undergo functional and energy validation before final acceptance.

3.5. Functional and Energy Validation

Each AI-generated candidate version of the component is first subjected to functional validation. The candidate version must pass the same unit, integration, and regression tests as the original version of the component and produce the expected output results for the same input data. A version that fails to satisfy any of the predefined functional criteria is rejected and cannot be included in the energy evaluation.

Candidate versions that pass functional validation are executed under the same test workload and in the same experimental environment as the original version of the component. Measurements of the original and optimized versions are repeated an equal number of times, after which their final average energy consumption is calculated. The estimated energy savings per single execution are determined according to Eq. (4).

$$\Delta E_{opt,i} = \overline{E_{orig,i}} - \overline{E_{\mathrm{AI},i}} \tag{4}$$

In Eq. (4), the average energy consumption of the original version of the component is reduced by the average energy consumption of its AI-generated version obtained after AI optimization. A positive value indicates that the candidate version consumed less energy than the original version during the observed execution, while a zero or negative value indicates that the modification did not achieve any actual energy savings or improvement. A candidate version may be accepted as an energy improvement only if it has passed functional validation in the preceding processes and if repeated measurements confirm a reduction in energy consumption.

3.6. Net Energy Benefit and Break-Even Point

A reduction in energy consumption during the execution of an optimized component does not necessarily mean that the AI optimization process is energetically justified overall. Coignion, Quinton, and Rouvoy use the energy break-even point to determine the number of executions of an optimized program required for the achieved savings to offset the energy consumed in generating the optimization [6]. In this paper, this approach is extended by including the energy consumed during the AI optimization of components and the energy used for the functional and energy testing of candidate versions.

The net energy benefit during the first year of using the optimized component is calculated according to Eq. (5).

$$NEB_i = \left(\Delta E_{opt,i} \cdot N_i\right) - \left(E_{AI,i} + E_{test,i}\right) \tag{5}$$

In Eq. (5), the energy savings per single execution of the optimized software component are multiplied by its annual number of executions within the software system. The energy consumed during AI-assisted code optimization and the energy consumed in testing each candidate version are then subtracted from the resulting annual savings. A positive net energy benefit indicates that the savings achieved during the first year exceeded the one-time energy expenditure associated with optimization and validation.

In addition to the net energy benefit, the number of executions needed to recover the energy used to generate and test each accepted optimization is also calculated. The energy break-even point is calculated using Eq. (6).

$$BEP_i = \frac{E_{AI,i} + E_{test,i}}{\Delta E_{opt,i}} \tag{6}$$

In Eq. (6), BEP represents the number of executions after which the total energy savings of the optimized component equal the energy used for AI optimization and testing. If the expected number of future executions of the software component is lower than the calculated BEP value, the optimization is not considered energy-efficient within the observed period.

4. Discussion and Limitations of the Proposed Method

The method proposed in this paper combines energy profiling, the estimation of annual operational emissions, AI-assisted code optimization, and the assessment of net energy benefit into a single procedure and process. However, its practical application depends on the ability to reliably isolate the selected software components, the availability of data on execution frequency, and the accuracy of energy consumption measurements.

The resulting ranking also depends on how representative the selected test workload is, since a component may have a different energy contribution under different input data, workload intensities, and usage patterns.

The method presented in this paper has not been empirically validated, so it cannot be claimed that its application will necessarily reduce energy consumption or harmful emissions. In addition, the ranking is limited to operational emissions associated with the execution of software components and does not include embodied emissions from hardware. Future research should examine the reproducibility and practical value of the method in real-world software applications.

5. Conclusion

This paper proposes a comprehensive and methodologically coherent framework for identifying and optimizing the software components that contribute most to the system's overall energy footprint. By combining energy profiling, code execution frequency, and local carbon intensity with AI-assisted optimization, the proposed model evaluates code not in isolation, but within its actual operational context. A particular contribution of the paper lies in introducing the metrics of net energy benefit and break-even point, which enable engineers to accurately assess whether the optimization process itself consumes more energy than it ultimately saves.

However, it is important to emphasize that the procedure and methodology proposed here are, at this stage, primarily conceptual and theoretical in nature. Due to the absence of empirical validation on real-world systems, the effectiveness of the method and the stability of AI-generated solutions cannot yet be definitively confirmed in practice.

Therefore, the next phase of research on this topic will focus on the practical application of this model in a real production environment within complex software applications. The planned steps include setting up a strictly controlled test environment that will enable repeatable energy consumption measurements, analyzing the behavior of LLMs when generating code in different programming languages, and rigorously verifying the functional correctness of the code through regression testing. Only through such empirical validation will it be possible to accurately quantify the actual net energy benefit and determine the broader applicability of the model in the software industry.

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Airborne Formaldehyde Exposure Among Students During Practical Activities

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Abstract

Formaldehyde is widely used for the preservation of anatomical specimens; however, its continuous release during cadaver dissection represents a potential health concern for medical students. Despite its indispensable role in medical education, the use of formalin-preserved cadavers represents a major source of airborne formaldehyde, exposing medical students to repeated inhalation during practical dissection sessions. Because of its high water solubility and chemical reactivity, inhaled formaldehyde is rapidly absorbed by the mucosal surfaces of the upper respiratory tract, where it induces local irritation and inflammatory responses.

This study evaluated airborne formaldehyde concentrations during routine anatomy practical sessions and assessed students' inhalation exposure under real educational conditions. Air sampling was conducted in two anatomy classrooms over 20 teaching days using a constant-flow sampling system, and formaldehyde concentrations were determined by the chromotropic acid spectrophotometric method. Mean concentrations were 0.48 ± 0.46 ppm in Classroom 1 and 0.30 ± 0.18 ppm in Classroom 2, with maximum values of 1.39 ppm and 0.62 ppm, respectively. A statistically significant positive correlation was observed between the two classrooms (r = 0.594), indicating common temporal variations in formaldehyde emissions. Although average concentrations remained below the OSHA permissible exposure limit, they exceeded the considerably lower NIOSH recommended exposure limit, while short-term peak concentrations reached levels associated with sensory irritation. The results demonstrate that medical students are routinely exposed to airborne formaldehyde during cadaver dissections and that exposure intensity is strongly influenced by local environmental conditions, particularly ventilation performance. Continuous monitoring and improved engineering controls are recommended to minimize inhalation exposure while maintaining the educational value of cadaver-based anatomy teaching.

Keywords

Formaldehyde, Inhalation exposure, Indoor air quality analysis, Education, Medical students.

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1. Introduction

Formaldehyde (FA) is one of the most extensively produced industrial chemicals worldwide and remains an indispensable component in numerous manufacturing processes, including the production of synthetic resins, plastics, wood-based materials, textiles, disinfectants, and chemical intermediates [1,2]. Owing to its strong antimicrobial and tissue-fixing properties, aqueous formaldehyde solution (formalin, typically containing 37–40% FA) has become the standard preservative for biological specimens and human cadavers used in medical education [3]. Consequently, anatomy laboratories represent one of the most important indoor environments where repeated occupational and educational exposure to airborne formaldehyde occurs.

Unlike many industrial settings, exposure in educational laboratories is characterized by intermittent but repetitive emission episodes associated with practical teaching activities. Opening cadaver storage tanks, manipulation of preserved specimens, dissection procedures, and inadequate dilution ventilation may generate localized peaks of airborne formaldehyde within students' breathing zones [4]. Since practical exercises are performed in close proximity to preserved tissues, students may experience substantial short-term inhalation exposure despite spending only a limited number of hours per week in the laboratory. This exposure pattern differs considerably from that of professional workers and therefore requires independent evaluation.

Inhalation represents the predominant route of formaldehyde exposure in anatomy laboratories [5]. Because of its high water solubility and chemical reactivity, inhaled formaldehyde is rapidly absorbed by the mucosal surfaces of the upper respiratory tract, where it induces local irritation and inflammatory responses. Even at relatively low airborne concentrations, exposure may cause eye irritation, lacrimation, nasal discomfort, sore throat, coughing, and impaired respiratory comfort [6]. Individuals previously sensitized to formaldehyde may develop allergic contact dermatitis or asthma-like symptoms at concentrations considerably below those producing effects in the general population [7]. Importantly, olfactory perception cannot be considered a reliable indicator of hazardous exposure because sensory adaptation develops rapidly during continuous exposure, reducing the ability to recognize increasing airborne concentrations.

While acute health effects are generally reversible following cessation of exposure, increasing attention has been directed toward the potential consequences of repeated exposure to low concentrations over extended periods. Chronic formaldehyde exposure has been associated with persistent mucosal irritation, respiratory sensitization, impaired cognitive performance, headaches, fatigue, sleep disturbances, and decreased concentration [8]. More importantly, substantial epidemiological evidence accumulated over the past decades has demonstrated an association between occupational formaldehyde exposure and an increased risk of certain malignancies, particularly nasopharyngeal cancer and myeloid leukemia. Based on sufficient evidence in humans, the International Agency for Research on Cancer (IARC) has classified formaldehyde as a Group 1 human carcinogen, emphasizing the need to minimize unnecessary exposure whenever technically feasible [9,10].

Although occupational exposure has been extensively investigated among embalmers, pathologists, histotechnologists, anatomy instructors, and healthcare professionals, considerably less attention has been devoted to university students participating in routine practical training. This population represents a unique exposure group because students generally have limited experience in handling preserved specimens, may be unfamiliar with effective exposure reduction practices, and often remain in close proximity to emission sources throughout practical sessions. Moreover, classroom occupancy, teaching dynamics, ventilation efficiency, and seasonal environmental conditions may

substantially influence personal exposure, resulting in considerable variability between practical classes.

International organizations have established occupational exposure limits for formaldehyde based on both short-term and time-weighted average exposure metrics. However, these limits differ substantially among regulatory agencies, reflecting continuing scientific discussion regarding safe exposure thresholds, particularly for carcinogenic and sensitizing substances. Consequently, direct measurements performed under actual teaching conditions remain essential for evaluating whether existing control measures adequately protect both educational staff and students.

Despite the widespread use of formalin-preserved cadavers in medical education, relatively few studies have comprehensively characterized airborne formaldehyde concentrations specifically during practical teaching activities while simultaneously evaluating potential health implications for students. Furthermore, available data frequently originate from laboratories with different ventilation systems, cadaver preservation techniques, and educational practices, limiting their applicability to other institutions.

Accordingly, the present study aimed to quantify airborne formaldehyde concentrations during routine practical sessions in an anatomy teaching laboratory, characterize students' inhalation exposure under real educational conditions, compare measured concentrations with internationally recognized occupational exposure limits, and provide a scientific basis for assessing potential health risks and identifying opportunities to improve exposure control in educational laboratory environments.

2. Material and Methods

2.1. Study Design and Sampling Strategy

This study was designed to characterize airborne formaldehyde (FA) concentrations under routine educational conditions and to evaluate the inhalation exposure of medical students during anatomy practical sessions. Measurements were performed in two anatomy teaching laboratories where cadaver dissections constitute an integral component of undergraduate medical education. Practical dissection of preserved human anatomical specimens represents an indispensable element of medical training, enabling students to acquire three-dimensional anatomical knowledge and essential manual skills that cannot be adequately achieved through theoretical instruction alone. However, because the specimens are preserved in formalin, these educational activities also represent one of the primary sources of formaldehyde exposure within medical faculties.

Air sampling was intentionally conducted during the pre-examination practical sessions, which represent the period of greatest laboratory utilization. During this stage of the academic year, a substantially larger number of preserved anatomical specimens are simultaneously removed from storage containers and manipulated by students, resulting in increased evaporation of formaldehyde and consequently higher airborne concentrations than those typically encountered during routine practical classes. Sampling under these conditions was selected to characterize exposure during a realistic worst-case educational scenario.

To ensure that the measured concentrations accurately reflected actual student exposure, all measurements were performed during regular teaching activities without any modification of laboratory procedures, occupancy, specimen handling, or ventilation practices. Neither instructors nor students altered their normal work routines during sampling,

thereby minimizing potential observational bias and ensuring that the obtained data represented authentic environmental conditions.

2.2. Air Sampling Procedure

Airborne formaldehyde was monitored at two representative locations within the anatomy laboratories using a constant-flow personal air sampling system (PRO EKOS 401-x). Sampling locations were selected to represent areas where students spend the majority of practical sessions while performing dissections and examining anatomical specimens.

Air was continuously drawn through Drechsel absorption bottles equipped with diffuser frits containing a chromotropic acid absorption solution. The absorbing reagent was freshly prepared by adding 9.5 mL of concentrated sulfuric acid and 0.5 mL of 1% chromotropic acid to each absorption bottle. Throughout sampling, the airflow was maintained at a constant rate of 0.5 $dm^3\ min^{-1}$ in accordance with the analytical method.

Because the chromotropic acid reaction product exhibits limited temporal stability, all collected samples were transported immediately to the laboratory and analyzed on the same day to minimize analytical uncertainty and preserve measurement accuracy.

2.3. Analytical Determination of Formaldehyde

Quantitative determination of formaldehyde was performed using the chromotropic acid spectrophotometric method, a well-established analytical technique widely applied for environmental and occupational monitoring of airborne formaldehyde due to its high sensitivity and selectivity.

For each collected sample, 4.0 mL of the absorption solution was transferred to a reaction vessel, followed by the addition of 0.1 mL of 1% chromotropic acid and 6.0 mL of concentrated sulfuric acid. After gentle mixing, the reaction mixture was allowed to cool and develop the characteristic purple coloration for approximately 2–3 hours under controlled laboratory conditions.

Subsequently, the reaction solution was transferred into a 2-cm optical cuvette, and absorbance was measured at a wavelength of 580 nm using a Hach DR 5000 UV–Vis spectrophotometer (Germany). A reagent blank, prepared using deionized water and processed identically to the collected samples, was analyzed concurrently to account for background absorbance. Formaldehyde concentrations were quantified using a previously established external calibration curve generated from standard formaldehyde solutions.

2.4. Exposure Assessment

The primary objective of the exposure assessment was to characterize inhalation exposure experienced by medical students during routine cadaver dissection under real teaching conditions and to evaluate whether measured airborne concentrations indicate a potential need for improved engineering controls, ventilation strategies, or additional preventive measures within anatomy teaching laboratories.

3. Results and discussion

Airborne formaldehyde concentrations were monitored during routine anatomy practical sessions in two teaching laboratories where undergraduate medical students

performed cadaver dissections. A total of 40 air samples were collected over 20 teaching days (20 measurements per classroom), providing representative exposure data under authentic educational conditions.

The results of measuring formaldehyde concentration levels are shown graphically in Figure 1, while descriptive statistics of the measured formaldehyde concentrations are summarized in Table 1. In Classroom 1, airborne formaldehyde concentrations ranged from 0.01 to 1.39 ppm, with a mean concentration of 0.48 ± 0.46 ppm (95% CI: ±0.22 ppm). The median concentration (0.31 ppm) was noticeably lower than the arithmetic mean, while the positive skewness (0.92) indicates that the distribution was influenced by several high-exposure events. The slightly negative kurtosis (−0.48) suggests a relatively flat distribution with greater variability than expected under a normal distribution. Collectively, these findings indicate that although moderate formaldehyde concentrations predominated, occasional high-emission episodes substantially increased overall student exposure.

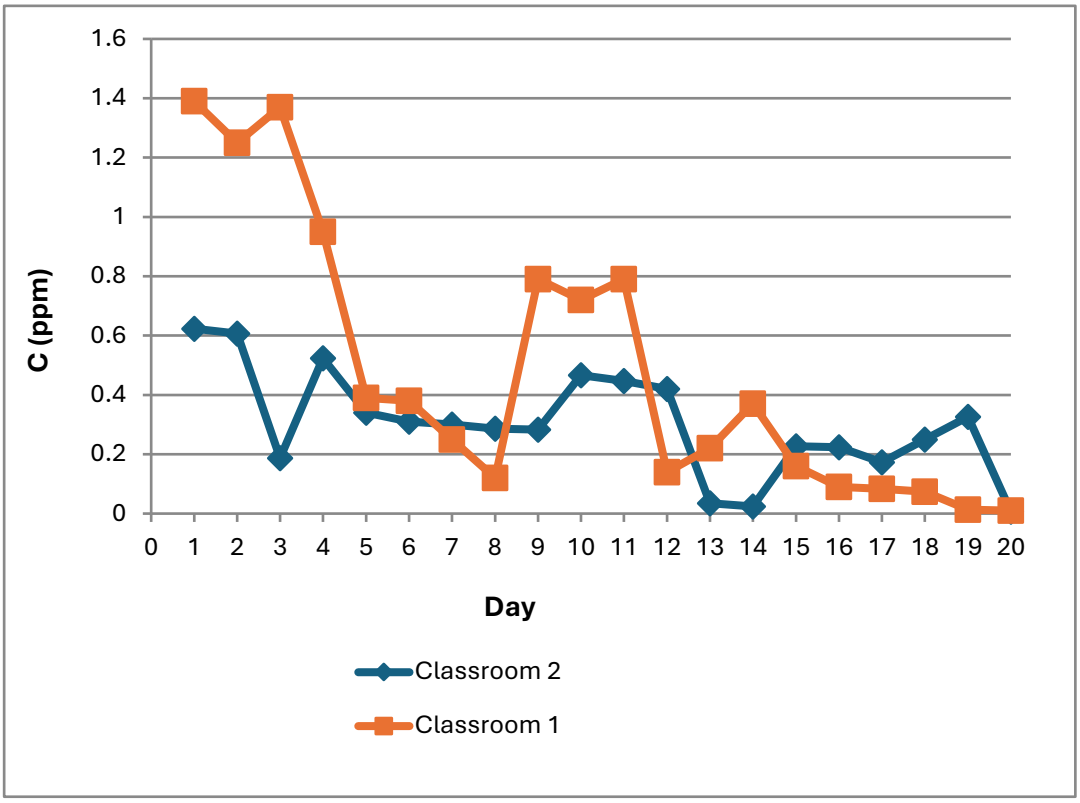


Figure 1 *– Formaldehyde concentrations in the classrooms during the measurement campaign*

In Classroom 2, formaldehyde concentrations varied between 0.01 and 0.623 ppm, with a mean value of 0.30 ± 0.18 ppm (95% CI: ±0.08 ppm). The proximity of the mean (0.303 ppm) and median (0.29 ppm), together with the skewness value close to zero (0.093), indicates a nearly symmetric distribution of measurements and considerably greater temporal stability than observed in Classroom 1. The narrower concentration range (0.61 ppm) and lower standard deviation further demonstrate that airborne formaldehyde concentrations remained relatively consistent throughout the monitoring campaign.

Although identical practical activities were conducted in both classrooms, students in Classroom 1 experienced consistently higher airborne formaldehyde concentrations and markedly greater day-to-day variability. The approximately 58% higher mean concentration observed in Classroom 1 suggests that exposure was primarily influenced by environmental characteristics rather than by differences in teaching methodology. Factors such as room geometry, ventilation effectiveness, air exchange rate, occupancy density, and the number

and positioning of formalin-preserved anatomical specimens likely contributed to the observed differences in airborne contaminant levels.

Table 1 *– Descriptive statistics of formaldehyde concentrations measured in Classroom 1 and Classroom 2.*

	Classroom 1	**Classroom 2**
Mean	0.48	0.30
Standard Error	0.10	0.04
Median	0.31	0.29
Mode	0.79	#N/A
Standard Deviation	0.46	0.18
Sample Variance	0.22	0.03
Kurtosis	-0.48	-0.38
Skewness	0.92	0.09
Range	1.38	0,62
Minimum	0.01	0.01
Maximum	1.39	0.62
Confidence Level (95,0%)	0.22	0.08

The measured concentrations confirm that medical students were repeatedly exposed to airborne formaldehyde throughout routine dissection sessions. Mean concentrations in both classrooms substantially exceeded the Recommended Exposure Limit (REL) established by the National Institute for Occupational Safety and Health (NIOSH) for an 8-hour time-weighted average (0.016 ppm). Nevertheless, the average concentrations remained below the Occupational Safety and Health Administration (OSHA) permissible exposure limit of 0.75 ppm [11]. Although these findings indicate compliance with the current OSHA occupational standard, they should be interpreted cautiously because occupational exposure limits were developed for healthy adult workers and may not adequately reflect the characteristics of educational environments, where students include individuals with varying susceptibility and without routine occupational health surveillance.

Particular attention should be paid to the maximum concentration measured in Classroom 1 (1.39 ppm), which exceeded several internationally recommended short-term exposure guidelines. Such peak concentrations are of special importance because acute formaldehyde toxicity is primarily associated with short-term inhalation peaks rather than long-term average exposure. During cadaver dissections, transient increases in formaldehyde emissions may occur when multiple preserved specimens are simultaneously removed from storage and manipulated in close proximity to students, resulting in elevated concentrations within the breathing zone.

Pearson correlation analysis demonstrated a statistically significant positive correlation between formaldehyde concentrations measured in the two classrooms ($r = 0.594$), indicating that temporal fluctuations occurred simultaneously in both teaching areas. This moderate positive relationship suggests that common determinants—including teaching schedules, cadaver preparation procedures, occupancy patterns, and the overall ventilation regime of the anatomy department—affected airborne formaldehyde concentrations in both

classrooms. However, the consistently higher concentrations and greater variability observed in Classroom 1 indicate that local environmental conditions exerted an additional influence on students' inhalation exposure.

From the perspective of occupational hygiene, these findings demonstrate that anatomy practical sessions constitute a continuous source of inhalation exposure to formaldehyde for undergraduate medical students. While the average exposure levels complied with the OSHA permissible exposure limit, they substantially exceeded the considerably more stringent NIOSH health-based recommendation.

The exposure levels observed in the present study are consistent with reports from anatomy laboratories worldwide. Akbar-Khanzadah et al. reported 8-hour time-weighted average formaldehyde concentrations ranging from 0.07 to 2.94 ppm during gross anatomy dissections [12], with the majority of participants exceeding the ACGIH ceiling value and nearly one-third exceeding the OSHA action level. Similar investigations have consistently documented eye irritation, nasal irritation, sore throat, lacrimation, and respiratory discomfort among medical students during cadaver dissection, supporting the conclusion that formalin-preserved specimens remain the dominant source of indoor formaldehyde exposure in anatomy teaching laboratories.

Overall, the present findings demonstrate that undergraduate medical students are routinely exposed to measurable concentrations of airborne formaldehyde during practical anatomy education. The pronounced differences observed between the two classrooms further emphasize that student exposure is strongly influenced by local environmental conditions and ventilation performance. Continuous environmental monitoring, optimization of ventilation systems, implementation of engineering controls, and adoption of low-emission cadaver preservation strategies should therefore be considered essential measures for reducing inhalation exposure while maintaining the educational benefits of cadaver-based anatomy teching.

4. Conclusion

This study demonstrated that undergraduate medical students are routinely exposed to airborne formaldehyde during cadaver-based anatomy practical sessions. Although the average concentrations measured in both classrooms remained below the current OSHA permissible exposure limit, they consistently exceeded the more stringent NIOSH recommended exposure limit, while peak concentrations reached levels capable of causing acute sensory irritation. The higher and more variable concentrations observed in one classroom highlight the importance of local environmental conditions, particularly ventilation efficiency, in determining students' exposure. These findings emphasize the need for continuous environmental monitoring, optimization of ventilation systems, and implementation of engineering and administrative control measures to minimize formaldehyde exposure while preserving the educational benefits of cadaver-based anatomy teaching. Improving indoor air quality in anatomy laboratories should be considered an essential component of providing a safe and sustainable learning environment for future healthcare professionals.

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Automatic Classification of Machine Interpretability in Building Regulations: A Two-Phase NLP Approach

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Abstract

Making building regulations understandable to machines is no small challenge, yet it lies at the heart of any serious effort to automate compliance checking in construction projects. Researchers in Automated Rule Interpretation (ARI) have made meaningful progress over the years, but one question has remained largely unaddressed: how do we systematically determine whether an individual regulatory clause is actually interpretable by a machine, without relying on manual judgment?

This paper takes on that question directly. We propose a two-phase classification framework, developed and tested on British and Finnish Building Regulations. In the first phase, we examine over 25,000 individual clauses and ask a deceptively simple question — can this clause be understood on its own, or does it depend on something else to make sense? Clauses are accordingly labelled as self-contained or non-self-contained. In the second phase, we take the 1,000 clauses identified as self-contained and look more closely at their nature, sorting them into three types: subjective, numerical, or combined. This distinction matters in practice, since it helps practitioners quickly identify which clauses are ready for direct automation and which still require human review.

Both phases are grounded in a carefully hand-annotated dataset, built to serve as a reliable reference point for future work in this area. We evaluated a range of classifiers, such as: Random Forest, SVM, and Logistic Regression using TF-IDF and Word2Vec features, as well as BERT, through 5-fold cross-validation. The results were encouraging: TF-IDF-based models exceeded 99% accuracy, while BERT reached 97%, confirming the viability of this approach for domain-specific regulatory text.

Keywords

Building regulations, machine interpretability, sentence classification, natural language processing, automated rule interpretation.

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1. Introduction

The challenge of Automated Rule Interpretation (ARI) in the Architecture, Engineering, and Construction (AEC) sector is a critical concern, especially given the complexity and volume of building regulations. Traditionally, ARI has relied on manual methods to parse these regulations, a process that is time-consuming, prone to errors, and not scalable for the vast amount of data involved in modern construction projects. The automatic translation of these regulations into machine-readable formats is essential for the development of efficient ACC systems. However, the focus has typically been on the document level, overlooking the granularities and specificities that individual clauses offer.

Single-clause classification addresses this gap by honing in on the fine details contained in each clause of a building regulation. These clauses are the fundamental units containing critical rules and guidelines vital for various aspects of building design, safety, and compliance. The ability to interpret these clauses accurately and automatically is paramount for streamlining the compliance process, reducing errors, and ensuring the safety and integrity of construction projects.

Moreover, the digitisation of these regulations and their interpretation aligns with the ongoing digital transformation in the AEC sector. It supports the integration of advanced technologies like Building Information Modeling (BIM) and other digital tools, facilitating a more cohesive and integrated approach to construction project management.

This expanded focus on single-clause classification, therefore, represents a significant step forward in the field of ARI. It promises not only to enhance the efficiency and accuracy of compliance checks but also to contribute to the broader movement towards digitalisation and integration in the AEC sector. This study's exploration into a two-phase machine learning approach for single-clause classification within UK Building Regulations is poised to make a substantial contribution to this evolving field.

This paper is organised as follows: Section 2 summarises relevant studies on the classification of building regulations, compliance checking frameworks, and the use of NLP techniques in legal text analysis. Section 3 details the methodology implemented for the two-phase classification approach. Section@4 describes the dataset used in this study, which consists of over 25000 individual clauses extracted from the UK Building Regulations and the English translation of the Finnish Regulations. To the best of our knowledge, this is the largest English dataset available for this task, structured with two levels of granularity. First, clauses are classified as self-contained or non-self-contained, and second, the self-contained clauses are further categorised into numerical, subjective, and combined classes. Section 5 reports and discusses the results obtained from the application of various machine learning techniques, evaluated through a rigorous 5-fold cross-validation method. Finally, Section 6 concludes the paper, summarising the key findings and implications of this research in the broader context of AEC compliance and digital transformation.

2. Related Work

Text classification, a fundamental task of natural language processing (NLP), plays a crucial role in organizing text into predefined categories. The integration of machine learning has revolutionized text auto-classification, streamlining the categorization of vast textual datasets. [28] provides an overview of how machine learning improves automated text categorization, showing its superiority over traditional knowledge-engineering methods, especially for handling large and varied text collections. Here, emphasis is placed on selecting feature like TF-IDF, Word2vec and algorithms such as Support Vector Machines

(SVM), logistic regression to achieve higher accuracy in text classification, crucial for developing complex models for tasks like automated compliance checking (ACC) for building regulatory codes.

The dynamic nature of text classification extends to the integration of dynamic word embeddings, as proposed by [35], enhancing the adaptability and accuracy of classification models. They introduce a method for dynamically learning changes in semantic relations over time in word embeddings. It is most appropriate in situations where terminologies used in a particular area, for instance, building codes. The presented embeddings are time-dependent, which can better reflect the context for more accurate classification of the given text in the domains where the meaning of words may change in time.

Brown et al., [4] further elaborates on this concept by investigating the role of large-scale language models, such as GPT-3, in scenarios requiring limited training data, showcasing the potential of advanced models in text classification. In their experiments, they show, these models with only trivial training can reach near state-of-the-art performance in many NLP tasks, such as text classification [4]. This approach is very useful for applications like building code classification where the generalizing ability to classify single clauses based on limited examples is most important. The general applicability of such models provides a particular advantage for enhancing the interpretability of classification difficulty associated with building codes through maxing out the model for the recognition of task-oriented language.

Mikolov et al., [23] contribute to the field by introducing the Skip-gram model. The inherent applicability of such models provides a particular advantage for enhancing the interpretability of classification difficulty associated with building codes through maxing out the model for the recognition of task-oriented language. which enables fast learning of coefficient representation of words. These vectors reflect syntactic and semantic associations that facilitate identification of the context for utilization of particular terms in the field of NLP. Besides isolating and identifying words, the ability of the model to express phrases is advantageous as it can analyze clauses that may comprise many words with several technical terms or building industry terms closely associated with the set of words [23]. This capability is crucial for accurately interpreting dense and technical building codes extracted from legal documents.

Based on [19] research, a comprehensive analysis of learning models like logistic regression, Support Vector Machines (SVM) and decision trees for supervised textual content classification is presented, highlighting their role in achieving accurate classification results. His study also shows the effectiveness of using SVMs for text classification tasks especially when combined with appropriate feature extraction methods [19]. These experiments on stop-word removal's effect on model accuracy provide valuable insights into enhancing text preprocessing techniques which are essential for improving system interpretability and optimizing learning models in text classification.

Lastly, Damayanti [10] proposes the use of a dual logistic regression and SVM model for classifying hate speech on Twitter, showcasing the effectiveness of this approach in addressing classification challenges in online platforms. Their studies suggest that this setup can achieve high classification accuracy indicating the potential success of similar hybrid models in tasks like interpreting construction codes. The aggregate of the efficiency of the logistic regression that is fast and simple together with SVM that is ideal at handling nonlinear facts, that brings out a wonderful strategy of building sound learning for training the classifiers for single clauses within the technical and legalistic language of building codes and other texts [10].

2.1. Data Preparation and Optimization

Data preprocessing is an essential step in organizing textual content categories, significantly influencing the performance of the classification model. Naive Bayes is a simple, yet powerful probabilistic classifier commonly employed in text classification tasks. However, its performance is highly dependent on the quality of feature selection. The authors present evaluation metrics multi-class odds ratio (MOR) and class discriminating measure (CDM), tailored for Naive Bayes in multiclass text datasets. These metrics are tailored to enhance the choice of capabilities that contribute most effectively to sort the task. In their experiments, it was reveals that each MOR and CDM considerably outperform distinctive feature choice strategies in improving the accuracy of Naïve Bayes classifiers on multiclass datasets [8].

The MOR and CDM metrics are compared by comparing the discriminative power of functions throughout a couple of trainings. MOR specializes within the ratio of the odds of a feature being found in a single class as compared to all other class, while CDM assesses the extent to which a characteristic can distinguish among class. This approach to feature selection highlights the need to tailor preprocessing strategies to suit the characteristics of the chosen class set [8].

Another technique for characteristic choice in text class includes **synonym merging**. Synonym merging is specifically useful in natural language processing (NLP) tasks, where unique words with similar meanings might be used interchangeably across numerous files. In conventional feature selection methods, words that might be semantically comparable but have different spellings or forms are probably handled as different capabilities, leading to redundancy and probably diluting the significance of tremendous features. SM-CHI solves this issue by combining synonyms into a single feature before using the CHI statistic for feature selection. Scientist show that this technique reduces the characteristic size but also improves the accuracy of text classification models. The aggregate of synonym merging and the refined CHI formula ensure that the most relevant and unique features are retained, which complements the model's ability to categorize textual data correctly. This method emphasizes the need to include language expertise in the preprocessing phase to optimize feature selection.

In the context of **feature selection** and imbalanced datasets, where certain classes are significantly under represented, feature selection becomes even more crucial. Du [4] address this as their study on health facility readmission prediction, where they propose the method known as Joint Imbalanced Classification and Feature Selection (JICFS). The technique is therefore a combination of feature selection with a form of categorization that is particularly useful in class imbalance where caution is taken to ensure that the model is not skewed due to the fact that some classes might be underrepresented. The JICFS technique involves constructing a loss function with sample weights to handle class imbalance. This technique also involves L1-norm regularization, which assists in selecting the most allowable features while maintaining the model's stability. After number of experiments on six real-international medical institution readmission datasets, they showed that their proposed method performs better than several methods in terms of classification accuracy.

Frank [15] overview the utility of ML in computational technology and engineering. They speak how ML algorithms can accelerate simulation strategies, which include computational fluid dynamics and molecular dynamics and enhance the precision of simulations. ML's capability to create efficient surrogate models and process massive datasets in remodeling medical studies and engineering practices.

2.2. The Role of Machine Learning in Modern AI

This innovative area of digital history known as Machine Learning (ML) is helping distinct segments by providing sophisticated tools for prediction, pattern acknowledgment and choice. In mental health, healthcare and engineering ML offers various effective methods to solve complex problems using large amounts of data and advanced algorithms.

Goldberg [16] discuss the application of ML and Natural language processing (NLP) in psychotherapy. They used ASR to investigate consultation recordings from a college counseling center, attempting to identify therapeutic alliances based on language content. ML algorithms could modestly expect purchaser rankings of therapeutic alliance highlighting the ability of ML to automate and decorate the evaluation of key psychotherapy variables.

Baek [1] focus on improving breast cancer prognosis through system-learning knowledge. To achieve high diagnostic accuracy, they incorporated ultrasound parameters into ML techniques. The authors developed a framework that outperformed conventional strategies and provided a color-coded probability map of malignancy by reading biophysical features and applying support vector machines, demonstrating ML's ability to decorate diagnostic precision.

The concept of 'Machine Unlearning' which involves effectively removing training data to comply with privacy regulations. They suggest a linear filtration approach to effectively "delete" training data from type models, thus helping compliance with records protection regulations together with the "right to be forgotten." This highlights the importance of Machine Learning methods aligning with privacy requirements while maintaining performance standards [2].

Souillard-Mandar [29] utilized ML to analyze records from a virtual Clock Drawing Test, a tool for diagnosing cognitive situations. By inspecting subtle behaviors recorded via a digitizing pen, the researchers evolved kind models that finished high accuracy in identifying cognitive impairments. This study highlights ML's functionality to decorate diagnostic gear by means of supplying distinct, statistics-driven insights.

Daghistani and Alshammari [9] evaluate two famous machine learning algorithms, Random Forest and Logistic Regression to predict diabetes. Using a dataset of 66,325 statistics from Saudi Arabia's Ministry of National Guard Hospital Affairs, the inspection evaluates the overall performance of these algorithms based totally on metrics including precision, Recall, True Positive rate, False Negative rate, F-measure and the vicinity below the ROC curve (AUC). The Random Forest model executed higher rankings across all metrics in comparison to the Logistic Regression model.

Short Text Classification Using Semantic Random Forest. Bouaziz [3] introduce an enhanced Random Forest approach for short text classification by means of incorporating semantic records. Traditional random forests struggle with short, sparse texts because of the dearth of contextual information. The proposed technique enhances short texts with semantically similar information from external information assets and adjusts the learning method to account for semantic relationships. This technique set up a 34% enhancement of precision versus standard Random Forests and a 20% advancement as far as Maximum Entropy models in classifying search snippets to prove that it is well capable of addressing brief textual content classification tasks.

Researchers have used Deep Support Vector Machine (DSVM) to categorize hyperspectral images. They examine how DSVM equipped with various kernel functions, processes hyperspectral images of Indian Pines and University of Pavia. DSVM proved to be superior to traditional classifiers that include, but are not limited to, SVM, DNN, GMM, KNN and KM, with class accuracy of up to 99% and 24% for Indian Pines and 98% for the rest of the context, namely Pinellas, Foothills and Palm Beach. 74% for Polytechnic of Milano and 79% for University of Pavia. This indicates that DSVM is a reliable method for analyzing

hyperspectral images, offering high accuracy and demonstrating its superiority over alternative methods [26].

A comprehensive review of the advancements of Support Vector Machines (SVMs) with detailing of the algorithm's issues and potential directions for development. SVMs are identified for their robustness in type and regression duties throughout diverse medical and engineering fields [6].

Cemiloglu [5] follow SVM to predict the uniaxial compression strength (UCS) of geographic rocks. Using a dataset of 120 samples from Maragheh, Iran, the observer compares SVM's predictions in opposition to conventional curves. The SVM model completed with an accuracy of 91% and an R2 of 0.967, outperforming conventional methods. This demonstrates the effectiveness of SVM in supplying dependable UCS predictions which is vital for geo-engineering and production applications.

Zhang [33] discuss the challenges of **automating code compliance checking** for policy construction. The observer identifies gaps in rule representation and interpretation, emphasizing the need for improved methodological frameworks. Despite advances in automatic compliance checking (ACC) issues continue to be in knowledge and representing regulations appropriately.

2.3. Text Representation Techniques in NLP

The integration of machine learning and natural language processing has revolutionized text auto-classification, streamlining the categorization of vast textual datasets.One of the advance approach , Word2Vec, which is an innovative technique in NLP that has transformed how we understand and use phrase representations in vector spaces. This evaluation investigates Word2Vec's foundational standards and evolution, comparing it to other techniques such as BERT and GloVe highlighting the most recent packages and improvements. Word2Vec, which was added with [23] is a version that learns word embeddings through training on large text corpora. The model uses two number one architectures: continuous bag of words (CBOW) and skip-gram. The CBOW version predicts a word based on its surroundings whereas the Skip-Gram version predicts the context words given a target phrase. This method accurately captures semantic and syntactic relationships among phrases by positioning them in a continuous vector space. Some of the most recent studies have demonstrated credible Word2Vec word embedding in other fields.

For instance, [11] used the Word2Vec set of rules to enhance the triage class in the suspected major ischemic stroke patients. The model thereby precipitated by harnessing, phrase embeddings to interpret scientific text statistics performed an astonishing area underneath the curve (AUC) score of 93 out of 100 cases of stroke incidents; only 1% is misclassified as fake negatives admitting it is useful in early analysis and decreasing the menace of such negatives. This application demonstrates the knowledge of the Word2Vec tool in improving decision-making processes in clinical facilities.

[18] prolonged the talk with the resource of evaluating Word2Vec with different manners, including Doc2Vec and machine-analyzing classifiers like SVM and logistic regression in sentiment evaluation. Their research confirmed that, while Word2Vec is robust in capturing phrase semantics and combining it with different methods and classifiers consistently yields superior outcomes. This suggests that while Word2Vec gives a robust base for text example, integrating it with extra techniques can enhance its overall performance for unique duties.

While Word2Vec established a new standard for phrase embeddings, BERT (Bidirectional Encoder Representations from Transformers) has further advanced the field. Unlike Word2Vec, which operates with a lengthy and fast-length context window, BERT process all of the words in a sentence simultaneously, shooting more nuanced relationships

through its deep bidirectional structure. This allows BERT to acquire state-of-the-art overall performance on diverse NLP benchmarks surpassing advanced models like Word2Vec in responsibilities along with question answering and sentiment evaluation [12].

Another notable approach is GloVe (Global Vectors for Word Representation) introduced by [27]. GloVe builds on the strengths of matrix factorization strategies by incorporating international word-phrase co-occurrence data into training system. It effectively captures the global statistical information of phrases across massive corpora, presenting vector representations that reflect each semantic and syntactic property. Unlike Word2Vec's focus on local context GloVe offers a greater holistic view of phrase relationships which enhance its overall performance on responsibilities like word analogy and similarity.

2.4. Advancing Text Classification with Deep Learning

Deep learning has emerged as a milestone of modern Natural language processing (NLP), extensively improving the overall performance of text classification duties. This evaluation makes a uniqueness of new improvements and comparative research that spotlight the effectiveness of deep learning manners in handling complex text statistics. One of the most high-quality advancements in deep mastering for NLP is BERT. Unlike in advance methods that study textual content sequences in a single path (either left-to-proper or right-to-left) BERT study textual content in each command simultaneously. This bidirectional approach allows BERT to capture extra nuanced contextual information, leading to big enhancements in overall performance at some point of quite a few NLP obligations. BERT's structure has set new benchmarks in text kind, query answering and language inference demonstrating its superiority in understanding and decoding complex textual facts [13].

Lu et al. [22] finished a comparative study of various deep learning models for textual content classification of unstructured scientific notes. The observer evaluated several deep learning approaches, such as Convolutional Neural Networks (CNNs), Recurrent Neural Networks (RNNs) and transformer-primarily based models to determine their effectiveness in coping with numerous stages of class imbalance. The findings underscore the strengths of deep gaining knowledge of models in extracting significant styles from unstructured text records and adapting to imbalanced datasets; it is crucial in scientific packages wherein some situations are uncommon but vital.

These advancements illustrate the ongoing evolution of deep learning strategies in NLP showcasing their ability to address complicated text-type situations and enhance the accuracy of predictions in several domains.

2.5. Model Evaluation and Data Challenges

Cross-validation is a fundamental method in machine learning for assessing predictive models' overall performance and generalizability. Recent enhancements in cross-validation methodologies have targeted improving the performance and accuracy of models, in dealing with out-of-sample predictions. [30] posted a study, in Machine Learning that address the challenge of obtaining reliable performance estimates from cross-validation, particularly when handling out-of-sample predictions. Their research introduces a technique that integrates bootstrapping with traditional cross-validation techniques to enhance the accuracy and performance of the validation approach. This hybrid technique enables more reliable overall performance calculation and reduces the risk of over-fitting, thereby improving the model's generalizability to unseen data.

These developments are especially beneficial in situations related to large and complicated datasets, where traditional cross-validation strategies might be computationally

prohibitive or very less powerful in taking authentic predictive, overall performance of a model.

Data imbalance is a common machine learning problem that would significantly impact the performance of models. One of the most well-known strategies for managing imbalanced facts is the Synthetic Minority Oversampling Technique (SMOTE). It generates artificial samples for the minority class by using interpolating amongst current samples, which allows to balance distribution and improve prediction performance on imbalanced datasets. This approach has been broadly followed because of its effectiveness in mitigating large imbalance and improving the performance of classifiers in numerous domains [7].

In addition to SMOTE [33] compare several strategies for addressing imbalanced classification together with sampling, oversampling and SMOTE. Their examine, published in Information, evaluates the effect of those techniques in the context of tutorial facts mining. The authors discover that while SMOTE normally improves overall performance, the selection of approach can vary depending on the unique traits of the dataset and the class hassle.

Werner de Vargas et al. [32] provide a comprehensive systematic mapping examine on imbalanced facts and preprocessing techniques in their article posted in Knowledge and Information Systems. Their studies highlight a variety of preprocessing approaches as well as the oversampling and under sampling methods. The offers insights into the strengths and limitations of different techniques emphasizing the need for a tailored approach based totally on the dataset's nature and the precise class undertaking.

Jafarigol and Trafalis [20] assess recent improvements in deep learning techniques for handling imbalanced records and describe future trends. Their overview available on arXiv discusses rising methodologies and the utility of advanced algorithms to address class imbalance. They advise that integrating new techniques, including deep learning strategies and reinforcement getting to know should further enhance the overall performance of classifiers on imbalanced datasets.

The utility of deep reinforcement getting to know for multi-class imbalanced learning in healthcare settings. Their examine, posted in Machine Learning, demonstrates that deep reinforcement learning can efficiently handle magnificence imbalance by means of optimizing the gaining knowledge of techniques through praise mechanisms. This method shows ability for enhancing type performance in complex and imbalanced healthcare datasets [34].

2.6. Class Overlap and Performance Indices

Vuttipittayamongkol et al. [31] address the issue of overlap between classes in imbalanced data classification in their article published in Knowledge-Based Systems. They examine the correlation between overlapping competencies in classes and its impact on model reliability, proposing measures to address this overlap. They emphasize the importance of understanding class overlap when suggesting preprocessing changes and evaluating overall model performance.

Mullick [25] highlight the importance of using appropriate performance indicators in skewed statistical classification, as demonstrated in their article published in Pattern Recognition. They consider various performance metrics such as precision and the F1-score to evaluate their performance on models trained with imbalanced data. They propose effective strategies to choose appropriate performance metrics for a comprehensive evaluation of model performance in the presence of class imbalance.

3. Methodology

Our research methodology is divided into two distinct phases, the first is a Binary Classification that is a self-containment classification and the second is a Trinary Classification that focus on Clause Type classification. Self-containment classification involves the binary classification of building regulation clauses into self-contained (independent clauses) or non-self-contained (clauses that rely on other clauses or contain ambiguity). The main focus in this phase is on identifying whether a clause can stand alone or requires additional context for interpretation. Where as in Clause-Type Classification, the self-contained clauses are further classified into three categories: numerical, subjective, or combined. This classification determines whether the clause can be automatically checked (e.g., numerical clauses with measurable parameters like door width) or requires expert evaluation due to subjective language. To illustrate our approach of clause classification clearly, we have represented its workflow in Figure 1.

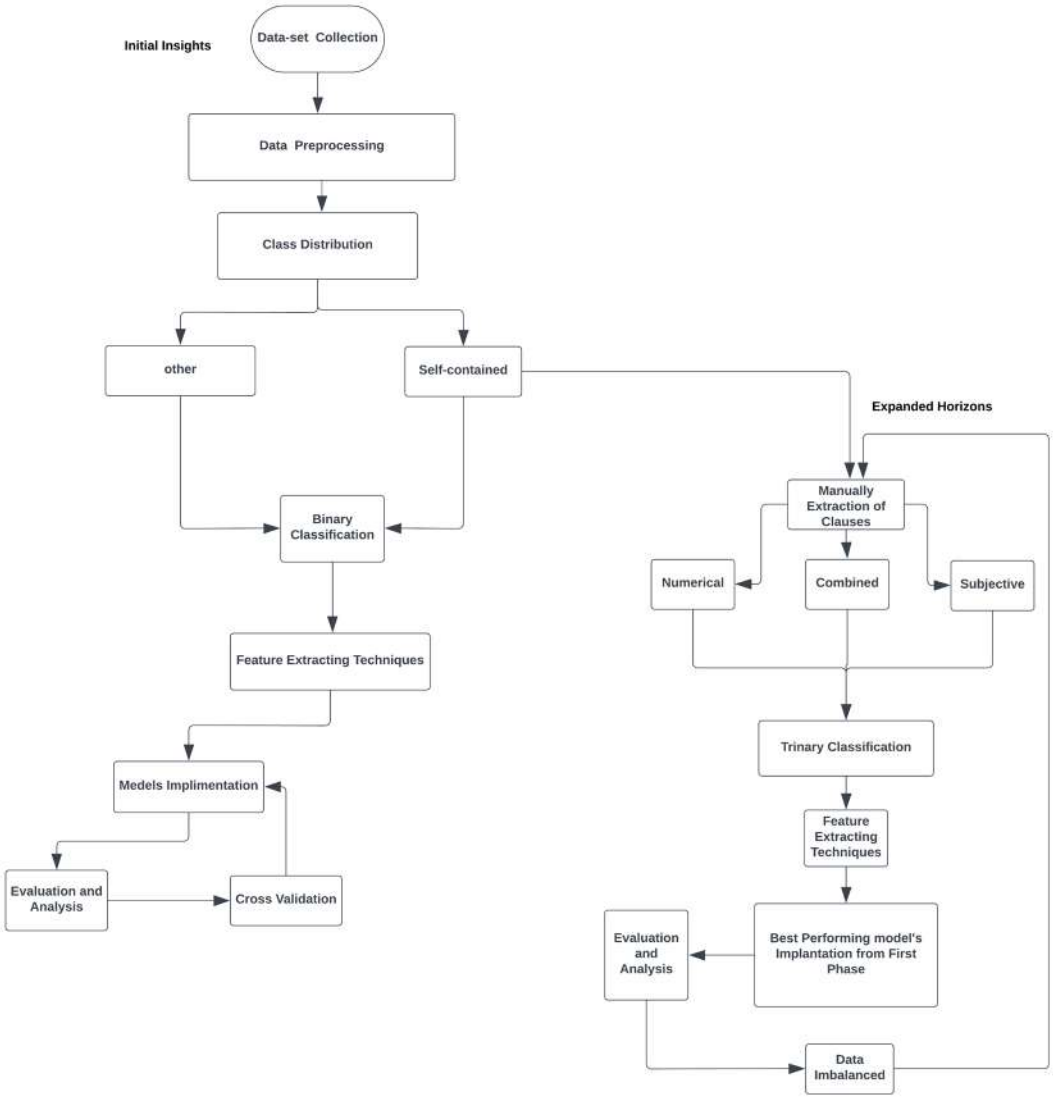


Figure 1 – *Two-Phase Single Clause Classification Workflow*

3.1. Phase 1: Self-Containment Classification

The self-containment classification involves the binary classification of building regulation clauses into self-contained (independent clauses) or non-self-contained (clauses that rely on other clauses or contain ambiguity). The main focus in this phase is to identifying whether a clause can stand alone or requires additional context for interpretation.

3.1.1. Data Partitioning

Before employing the machine learning and feature extraction strategies we have divided our dataset into training and testing subsets with the help of Python commands, so that a robust classification model can be ensured and give the high validation value for their performance and generalizability on unseen clauses. Specifically, we have used 80% data for training and 20% for testing initially. It is a common approach in which a sufficient amount of data reserved for training and a quantified portion for evaluating model performance. However, after primary testing scientists have **adjusted** this ratio to **70%** for training and **30%** for testing. It was due to insignificant results of different modelling algorithms. After this adjustment, we have lager test set to evaluate model's performance on unseen clauses and the risk of over-fitting is reduced as well. Furthermore, we have set the **random state** value to 42, it guarantees the reproducibility of results. By setting a random state value, we have safeguarded the randomness of data involved in the data splitting process remains coherent on multiple iterations. It was the most important step for reproducible experiment and evaluation of results.

3.1.2. Feature Extraction and Representation

Once the data partitioning is completed, our dataset is ready for the implementation of different feature extracting techniques. For our ongoing experimentation, we have selected three most widely used techniques because of their outstanding effectiveness in the field of text classification namely **TF-IDF, Word2vec** and **BERT**, so that we can analyse which will perform stupendous for machine interpretability of clauses. Their ability to analyse simple term frequency of word to advanced contextual embeddings are exceptional.

We have started with the utilization of **TF-IDF (Term Frequency-Inverse Document Frequency)** technique. Firstly, the building regulatory clauses in our dataset (which is our one of the main contributions in the in the field of automated compliance checking of UK regulatory codes in English language and it is larger of the size as compared to the existing ones in English) were tokenized and then splitting them into individual words. After that, calculated the Time frequency for each word in UK building regulatory clause dataset and then computed the inverse document frequency of all the documents in the corpus. Using Python libraries like scikit-learn, we implemented the TF-IDF vectorizer to generate TF-IDF matrix. In this matrix, each row is equal to a document and each column is equivalent to a unique word in corpus. Matrix values represent the TF-IDF score of the words inside the dataset.

As features are now well tuned, we progressed for implementing a number of machine learning algorithms that perform outstanding in the case of binary and trinary classification scenarios. These analysations will give us the best performing models for our study. We have started with the execution of **logistic regression, random forest, Support Vector Machine, and K-Nearest Neighbour.** All of these models were performing well with high accuracies of 97%, 99%, 99%, and 99% respectively.

3.1.3. 5-Fold Cross-Validation Technique

Despite these promising results, we became uncertain about the factual performance of the models. Because only high accuracy doesn't mean that the model is generalizing effectively as it can be misleading due to possible over-fitting or data distribution biases. To ensure the algorithm's robustness over various UK building regularity codes and for the validation of its performance across unseen clauses, more evaluation techniques should be utilized. As we have already changed the test-train subsets rations and the results were the same that's why we moved toward **5-Fold Cross-Validation** technique to have more reliable evaluation method for the performance of model. After conducting 5-fold cross-validation, we were having, again, high results with trivial variations in the case of all implemented models and concluded on the fact that models are performing outstanding as dataset is so much pure and clean.

3.1.4. Integration of Word2vec and Machine Learning Models

After the implementation of TF-IDF we progressed with the implementation of Word2vec technique, a more advanced approach for generating word embeddings. It captures the semantic relationship between words by learning distributed representation of words in a continuous vector space as compared to TF-IDF. As we are already done with data preprocessing and data partitioning steps, we will now begin implementing the Word2vec. Firstly, we have tokenized the textual data into separate sentences and words, where each word was mapped as a vector in a multi-dimensional space (usually 100 to 300 dimensions). It will help the deployed technique in capturing the word sequences and context more effectively. This process allows the model to place semantically similar words closer to each other in vector space. To represent each document e.g., regulatory code or sentence, researchers have averaged the word vectors for all words present in that document. In this way, we have generated a single vector representation for each document, and it will save the overall meaning and context based on the words it contains.

Since the features are now properly adjusted according to Word2ve library, we have progressed to implementing a range of machine learning algorithms from our previous research study. This will help us in studying the impact and behaviour of algorithms when feature extraction techniques are changed and in understanding the subtleties of how different methods impact model performance and accuracy in text classification scenarios. Our research study begins with the implementation of **logistic regression, random forest,** and **Support Vector Machine**. All of these models, again, delivered strong performance with high accuracy rates and it is already justified that it is due to the quality and consistency of the pre-processed data and as well as the effectiveness of the applied feature extraction techniques. That's why it was decided not to apply cross-validation methods in this phase.

3.1.5. Leveraging BERT as Classifier

The research study of first phase is in its final stage. To analyse the ability of deep learning techniques, in Natural Language Processing (NLP) for the enhancement of text classification and feature extraction, we have used BERT as a classifier. The process starts with selection of pre-trained BERT model which was trained for fetching the deep contextual information from text. Firstly, we have tokenized each clause into words or sub-words using special tokens like CLS at the beginning of the sequence and SEP's to specify the end of a clause or to separate multiple clauses if required. These tokenized clauses then converted into integer IDs using BERT's predefined vocabulary. This prepared input was then fed into BERT model, which produces embeddings for each token by processing it through its transformer layers. As our study based on classification problems, so our focus was on the

output of CLS token because it summarizes the meaning of entire regulatory clause. A classification layer, which is embedded on the top of BERT output, maps the CLS embedding to classified output without the external references.

During the fine-tuning process, the BERT model was trained on labelled examples of UK building regulatory clauses and at that point model make predictions regarding their interpretability as well. The predictions are then compared with original labels and calculated the loss using cross-entropy. Basically, this loss is backpropagated through the network and the weights of the BERT model. To minimize the loss, classification layers were updated continuously using Adam optimizer over successive training iterations. Now the model was ready to be evaluated on a test subset to assess its performance in classifying the interpretability of unseen clauses. It was performing well with high accuracy rate, and it is already clarified that it is due to the quality and consistency of the pre-processed data and as well as the effectiveness of the applied feature extraction techniques.

3.2. Phase 2: Clause Type Classification

After the successful completion of our initial phase's experimental study, we have broadened the scope of our research that will concentrates on optimising the classification algorithm to refine its operational efficiency and output quality. For this purpose, we have selected the "self-contained" class from the foundational part of our research. As our dataset is already pre-processed and in most pure form, that is why we do not need to perform any preprocessing technique. Form this class, we have extracted about **1000** regulatory clauses **manually** under the supervision of annotators from the field. We have then categories these rules into three classes, **numerical, subjective**, and **combined**, on the basis of characteristics that a regulatory code contains.

3.2.1. Implementing TF-IDF and Machine Learning Model

In our second phase, we have progressed from binary classification to **trinary classification** and data is classified into three distinct categories. Once again, we are going to apply the three best feature extraction techniques named as TF-IDF, Word2Vec, and BERT. We have started by deploying TF-IDF feature-extracting technique. After tuning the features, we have implemented the best-performing model, **Random Forest**, from the previous phase which is a key factor of this study. By leveraging this model, we assess its performance in more complex scenarios and make comparisons. This time the results weren't satisfied with a low accuracy of 75% as compared to initial stage results.

3.2.2. Addressing Imbalanced Data for Enhanced performance

This time the results weren't satisfied with low accuracy of 75% as compared to initial stage results. To understand this, we have again analysed the extracted dataset and it came into consideration that we are facing data imbalanced problem which is the root cause of bad performance. It was arised due to the uneven distribution of the categories. To resolve this issue, we have again extracted more clauses for numerical and combined classes under the strict supervision of scientists from domain, so that the model could remain unbiased and perform well across all categories. Now the dataset is in balanced stage and ready for the algorithmic operations. We have again applied the random forest, and it was performing outstanding with high value of accuracy.

3.2.3. Leveraging Word2Vec and Machine Learning Model

After the implementation of TF-IDF technique, we progressed in our study and started to implement the Word2Vec library, so that we could understand the performing behaviour under a more complex environment. These experimentations give deep insights into the model's ability to process and generalize in higher-dimensional feature spaces. Now features are well tuned and ready for the implementation of the random forest algorithm which is one of the best performing models from the first phase of research. In the case of word2vec, the random forest model was performing exceptionally well.

3.2.4. BERT Integration as classifier

In the final stage of our study, we have implemented BERT as a classifier to confirm its effectiveness in complex textual analysis in domain-specific contexts using Python language libraries and commands. We were getting low accuracy results initially as it was due to data imbalance, but we have tackled this issue by extracting more clauses. Again, we have applied BERT as a classifier and got really high-performing results. There wasn't any chance of model overfitting as we have already performed data precautionary strategies like 5-Fold Cross-validation and concluded that techniques and models are performing exceptional due to data pureness and cleanness. These results reaffirm BERT's suitability for automated compliance checking and rule interpretation in highly specialized regulatory frameworks.

4. Dataset

The labelled dataset, we are providing is the large dataset compared to the existing ones, in English (most of the existing ones are in Chinese), and fine-granular one with different classes. It is one of the main contributions of our study, in the field of automated rule interpretation. In the current dataset, we have about 25,879 regulatory codes. These rules were collected by the implementation of data annotation process, which is a structured and systematic approach to label the data for automated rule compliance in architecture, engineering, and construction (AEC) [37]. In this study, two annotators carried out the annotation across two rounds, with a significant improvement in inter-annotator agreement (IAA) by the second round.

4.1. Data Collection

First round started with splitting the text into sentences by semicolons, periods, and newlines. Next, these sentences were filtered according to conditions like if a rule is expressed in one line (when we say one line it's mean it start with a capital latter and ends with full stop), and we do not need to read the whole paragraph or to read the following sentence or the previous sentence to understand it, classified as a **self-contained** rule as it is self-explanatory. However, if a rule is not explained in one sentence and it require to read the full paragraph or the following sentence or the preceding sentence, it was categorized as **others** because it is expressed over many sentences. At the end of first round, IAA (a metric, which is a measure of reliability that reflects the percentage of agreement on annotations between the two annotators [21]) was calculated at approximately 75%.

In the second round, for trinary classification, we have first introduced new criteria for categorizing the data manually, such as if a rule from self-contained class have quantitative measures (e.g., checking the width or height or length of the door) belong to Numerical class,

if it possess qualitative measures (e.g., house should be big, airy and peaceful) it was labeled as Subjective and if it is the combination of both properties it was labeled as Combined. After strictly following the guidelines and discussions, manually extracted, 1000 building regulatory codes were classified. This time we got the score of 98% for inter-annotator agreement (IAA).

4.2. Data preprocessing

Data preprocessing was an essential step in organizing, and categorizing textual data of building regulation documents. It consists of numerous methods like dependency parsers, entity recognition, and Context-Free Grammar (CFG), which performs a vital role in enhancing the efficiency, scalability and accuracy of text classifiers for effective rule interpretation and compliance checking [38]. Selecting the right features can reduce data size and noise which was be achieved by removing unnecessary ones and ensuring that only the most important features could be used for required operation.

4.2.1. Phase 1: Self-containment classification

In the first phase of our research, we have collected number of files from two main sources: the UK Building Regulations and the English Translation of the Finnish Regulations. Each file corresponds to a different document from the data sources provided above, i.e., the chapters in the UK regulations (regulatory codes, definitions and other information related to Architecture and Construction domain). To obtain a single file, so that text categorization operations can be perform, we have merged the extracted files into a single file. During this procedure, we have gone through each file one by one and carefully performed the concatenation process [17]. Then researchers have started the experimentation process by deploying the next step data preprocessing techniques, so that the raw building regulatory data can be converted into structured patterns and become more suitable for the implementation of machine learning and feature extracting techniques for automated compliance checking. It was a really challenging step as it involves addressing issues like data integration (merging datasets from multiple sources), data vulgarity (removal of irrelevant or unwanted columns), handling null values and data cleansing, which include steps like removing punctuation, converting the text to lowercase, removing stop words, stemming, and lemmatization. As preprocessing progressed, there were other issues like dimensionality reduction, outlier removal, data normalization and standardization. After resolving these problems our dataset was ready for the implementation of machine learning models and techniques. The team has deployed Python commands and libraries for pre-processing steps and classification operations to have automated rule interpretation (ARI).

Table 1 – *Overview of Regulation Clause Fields*

Field Name	Description
ID	It contains the unique IDs for each regulatory clause
Class	Contains the classification labels of building regulator
Text	Contains a Set of rules, definitions and Other regulations related to the Architecture and Construction domain

We have three fields under the label of" ID, Class, and text". Each field shown in table 1, has specific characteristic that are crucial for automated rule interpretation; e.g., 'text' field contains the textual data related to UK buildings. The field provides the content from which

features are extracted to classify the building regulations into different classes, these features were selected based on feature selection methodologies.

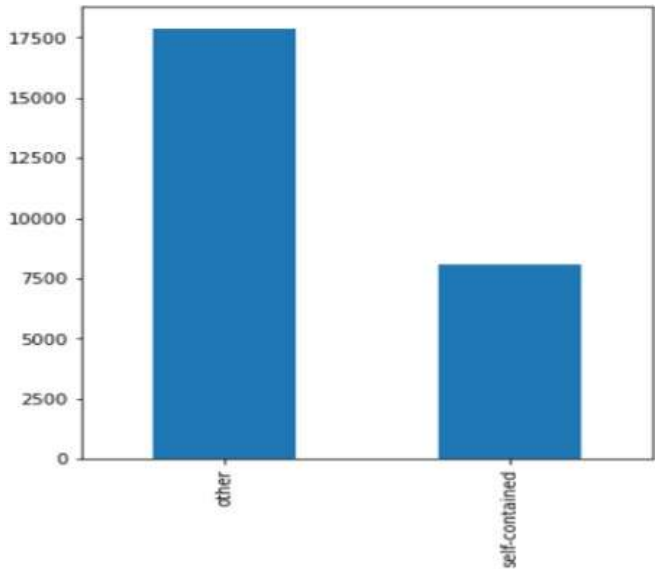


Figure 2 – *Dataset Purification*

We have plotted the graph 2 to understand the features and patterns of the dataset. These visualizations provide a valuable insight of fields distribution and their characteristics for first phase experimentation. Through graphical representation it has been illustrated, that due to spelling mistakes and case errors our text class was divided into six categories. According to the analytical facts, all these categories belong to just two classes “Other” and “self-contained”. Therefore, we have mapped these classes into these two primary categories. The dataset has been cleansed and ready for the interpretation of the building regulations through machine learning, and deep learning, techniques and models. The analyzation of Graph 1 has shown that the “Others” class contains about $17{,}600$ sentences, whereas the “self-contained” class have approximately 7500 sentences. It is a data imbalanced issue and we know that, generally models favor the class with high volume of data and can affect model’s accuracy. Machine learning models, due data pureness were performing well without favoring any class that is why this imbalance was negligible.

4.2.2. Phase 2: Clause Type Classification

As we progress through our research, we have tried to broaden our horizon from binary classification to trinary classification (clause type classification) which will be helpful for scientists and engineers from the domain for detail categorization and in-depth analysis of regulatory codes. To support this effort, we have extracted about 1000 sentences manually, under the observation of annotators from domain, from “self-contained” class of initial phase dataset. Dataset was already pre-processed and cleaned as a result; we didn’t need to clean it again.

Categorizing clauses into appropriate labels manually was a challenging task. To address this, we have introduced a new criteria for categorizing the building regulatory codes under the Inter-Annotator Agreement (IAA). Agreement classify the rules into three classes named as “subjective”, “numerical", “combined" on the basis if the text contains qualitative rules it was assigned to subjective class, if the rule contain quantitative measures it was added into numerical class and if code is the mixture of both characteristics, quantitative and qualitative, it was added into combined class. At the end of annotation, we have calculated the Inter-Annotator Agreement score of 98%, ensuring the high quality of annotated data.

After the observation of graph 3, it was analyzed that most of the sentences (about 750) belong to the subjective class which is comparatively a very large quantity to numerical class (about 170) and combined class (about 80). This presents a challenge of data imbalance, which is a result of uneven distribution of regulatory clauses across labeled classes. It can cause biased prediction, and challenges in evaluating metrics like F1 score, precision, and recall. To enhance model's stability and prediction capability for building regulatory codes, advanced solutions are required [7].

To balance the dataset, we have again manually extracted more sentences from first phase dataset, for classes numerical and combined from the self-contained class. The new dataset approximately consists of 1700 manually extracted sentences from which about 700 belong to the subjective class, 600 to the numerical class and 400 to the combined class as shown in given graph 4. A balanced dataset will ensure that machine learning models have a robust foundation for accurately interpreting the different types of UK building regulatory clauses so that the field of automated rule interpretation can be advanced.

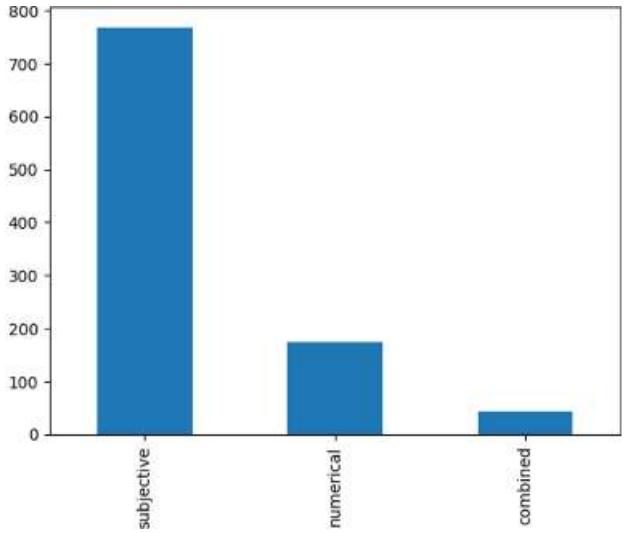


Figure 3 – *1000 Manually Annotated Sentences*

5. Evaluations

We have deployed different machine learning, and deep learning models using outstanding feature extraction techniques like TF-IDF, Word2vec and BERT. As our study is divided into two phases of research, elaborated as initial phase and expended horizon, that's why we are going to analyse and evaluate results step by step in two different sections of research. In the initial phase of our research, we have applied three best performing machine learning algorithms in the field of text classification namely logistic regression, random forest Classifier and Support vector machine Classifier. For feature extraction techniques, we have started with TF-IDF, Word2Vec, and BERT respectively to ensure optimal performance and in-depth analysis of their effectiveness.

All of these models performed exceptionally with accuracy results of 97%, 99%, 99% respectively without any considerable difference. At this point we become suspicious about results Because only high accuracy doesn't mean that the model is generalizing effectively as it can be misleading due to possible over-fitting or data distribution biases. To make sure, the applied models and the feature extraction techniques are performing robustly over unseen codes, more evaluation techniques should be employed. Firstly, we changed the test-train subset rations from 20%-80% to 30%-70%, but the results were the same again. Then, we selected the 5-fold Cross-Validation technique. After applying the 5-fold Cross-validation,

we were again getting the highest accuracies but this time with minor differences. So, we have concluded that it is due to the quality and consistency of the pre-processed data as well as the effectiveness of the applied feature extraction techniques.

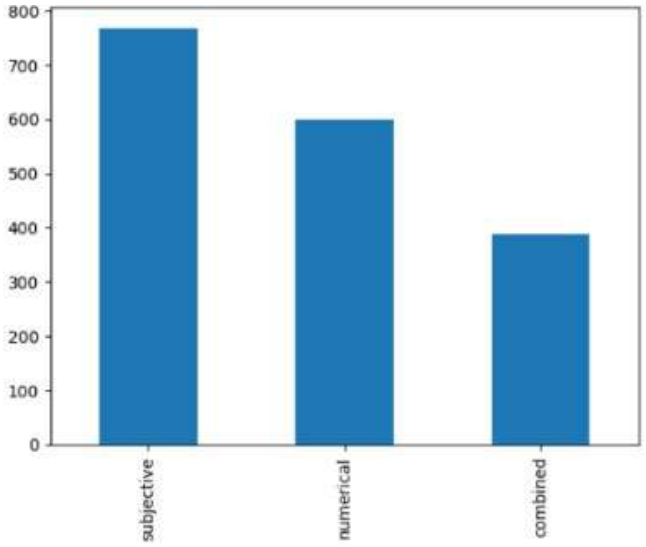


Figure 4 – *Balanced Dataset*

Modelling	Logistic Regression	Random Forest	Support Vector Machine
Accuracy Using TF-IDF	97%	99%	99%
TF-IDF (5-Cross Validation)	96.6%	99.3%	99.1%
Accuracy Using Word2Vec	87%	98.9%	95.6%
Accuracy Using BERT as Classifier	95%		

As we have progressed in our research, we have applied the same modelling techniques but with different NLP library, Word2Vec. Using Wor2vec we were getting higher accuracy but with a bit of variation, that's why It wasn't necessary to apply the 5-cross validation technique, as these results are again pointing toward the purity of our dataset and as well as the best implementation of modelling techniques.

We have deployed the Deep learning feature extracting technique, BERT as a classifier. It was also giving the marvellous accuracy of 95%. Overall, our results in the first phase was notable. Now let's move toward our Second phase. Where we have analyzed best modelling techniques and algorithms under more complex environment.

5.1. Phase 2: Expanding the Research Horizon

As our research progressed, we have extracted 1000 sentences, manually, under the strict observation of annotators from our refined dataset's class "self-contained". Then we have implemented the best performing model, Random Forest, from our foundational study. Initially our results weren't that satisfied as compared to first phase's performing results of accuracy where, we were getting the marvellous results and from it was clear that our dataset was pure and clean. There was another issue called data imbalance, because we have categorised the Self-contained class into 3 streams on the basis of regulatory clause's

characteristics and they weren't divided equally. To resolve this issue, we have again extracted more clauses for numerical and combined classes under the strict supervision of scientists from domain, so that the model could remain unbiased and perform well across all categories. Now we have again implemented the outstanding feature extracting techniques and best performing model, Random Forest, from first phase. This time, we were getting the notable results. We have analysed that in this phase BERT was also performing exceptional with accuracy of 95%.

Modelling	Imbalanced Dataset Accuracy	Balanced Dataset Accuracy
Random Forest Using TF-IDF	77%	92%
Random Forest Using Word2Vec	75.6%	93%
BERT as Classifier	74%	95%

Acknowledgment

This work is funded by the European Union's Horizon Europe research and innovation programme under grant agreement no [101056973] (ACCORD). Birmingham City University is supported by UKRI grant number [10038999].

Data Availability Statement

The authors confirm that the data supporting the findings of this study are publicly available at the following link: [https://github.com/Engr-Hassan-Subhani/Automated-Compliance-Checking-of-Construction-Projects.git].

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BIM Adoption in Montenegro: Current Practices, Key Barriers, and a Framework for National Implementation

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Abstract

Building Information Modelling (BIM) is a central component for the digitalisation of the construction-sector, yet its adoption remains uneven in smaller and emerging markets. This study evaluates the current state of BIM adoption in Montenegro and identifies the conditions required for broader and more systematic implementation. A structured online survey collected 138 valid responses between 20 May and 20 June 2026 from professionals involved in building and infrastructure projects, organisations of different sizes and diverse construction disciplines. The questionnaire examined current BIM use, experience, project coverage, CDE and BEP practices, implementation drivers, market demand, expected adoption, perceived benefits and barriers, and attitudes towards regulation. The findings reveal an emerging market positioned between interest and implementation. Only 19.6 % of respondents currently use BIM, while 49.3 % are interested in BIM but have not yet adopted it. Implementation remains largely project-specific and driven by individual initiative, employers, or business partners, whereas formal information-management practices are inconsistent. The key barriers are insufficient training, shortages of competent professionals, limited client demand, missing standards and guidance, cost, and lack of time. Nevertheless, respondents recognise substantial benefits in visualisation, documentation quality, coordination, lifecycle info, and project monitoring, and broadly support gradual regulatory introduction. Based on the survey and regional evidence, a staged national framework combining governance, practical guidance, capacity building, pilot projects, proportionate public-procurement requirements, and periodic monitoring is proposed.

Keywords

BIM adoption, Montenegro, digital construction, Common Data Environment, BIM Execution Plan, public procurement, national roadmap.

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1. Introduction

Digitalisation is transforming the built-asset lifecycle, with BIM as a key enabler of integrated project information management, advanced model-based collaboration, lifecycle decision-making, sustainability, and emerging technologies such as Digital Twins and AI. BIM maturity therefore reflects the broader digital readiness of the construction sector. BIM extends beyond semantic 3D modelling by affecting processes, responsibilities, information requirements, contracts, quality assurance, and organisational culture. Its adoption therefore depends on coordinated development of technology, skills, processes, standards, client capabilities, and institutional support [1].

BIM adoption must consequently be assessed beyond only software use by examining its application across project types, information-management practices, implementation drivers, and expected market and regulatory development. Such assessments help distinguish professional awareness, project-based use, and systematic organisational implementation, particularly in smaller and emerging markets where economic, institutional, and sector conditions strongly affect adoption. The following sections review relevant national studies, economics and the wider factors needed to position BIM adoption in Montenegro.

1.1. Related national BIM adoption studies and geographic dependencies

There are significant differences in regional adoption of BIM across Europe. For example, Northern European countries consistently outpace Southern European counterparts [2] in BIM adoption. Denmark (78 %), the UK (74 %), and Finland are among the highest adopters [3], while Southern and Southeastern European countries like Portugal, Greece, North Macedonia, and Malta remain at early stages; North Macedonia reported just 2.5 % of professionals fully delivering designs in BIM [4]. This gap is strongly linked to government mandates: Finland mandated BIM for public projects in 2007, the Netherlands in 2011, and the UK in 2016, Slovenia in 2025, and Portugal in the near future, whereas countries such as North Macedonia lack formal mandates.

BIM adoption is not uniformly low across Southern Europe. Spain achieved the highest BIM maturity [5] in a 146-project comparison using the BIM Maturity Measure, outperforming Germany and Ireland within that sample. The finding indicates that Southern European teams operating within a single international firm under consistent organisational processes can match or exceed their Northern European counterparts. Differences in adoption may therefore reflect national policy environments, market conditions, institutional support, and implementation frameworks more than inherent regional capacity. Portugal and Spain are also developing national BIM roadmaps and progressing toward public-sector mandates, which could narrow gaps if accompanied by investment in training, standardisation, and funding. Two national studies provide relevant methodological and regional benchmarks. Research on BIM adoption in North Macedonia connected survey findings with professional awareness, capacity building, and a national implementation roadmap [4]. It identified limited use despite considerable professional interest, with insufficient training, weak client demand, missing standards and guidelines, shortages of experienced professionals, and initial implementation costs as major barriers. BIM adoption in Slovakia was analyzed through repeated surveys and a broader maturity perspective [6], examining project coverage, professional experience, Common Data Environment use, BIM Execution Plans, implementation drivers, and policy development. Their findings demonstrate that software use alone does not represent systematic BIM implementation and that longitudinal measurement is valuable for monitoring market development.

1.2. Economics and construction market

Differences in BIM adoption cannot be explained by geography alone, because they are associated with economic development and institutional capacity. One study found that 65 % of countries with existing or planned BIM mandates are classified as economically "developed," [7] while countries with lower GDP per capita are less likely to introduce mandatory requirements. This helps explain why some Central and Eastern EU countries, including the Czech Republic with an adoption rate of 25 % [3], remain behind despite not belonging to Southern Europe. Financial capacity is especially important for small and medium enterprises (SMEs), which are more exposed to initial software, training, process-development, and organisational costs. In emerging markets, these pressures are reinforced by shortages of experienced professionals, limited education opportunities, resistance to change, and weak regulatory frameworks [8]. Nevertheless, economic conditions do not determine outcomes automatically. Spain achieved the highest BIM maturity in a multi-country project comparison, showing that coherent firm-level processes can overcome less favourable national conditions. Several Southern European countries are preparing national roadmaps and introducing public-sector requirements, which may gradually reduce differences [7,9]. The key implication is that effective adoption depends on converting policy ambition into affordable training, practical guidance, client demand, and scalable implementation support [9]. The Montenegrin questionnaire was aligned with the aforementioned studies to enable regional comparison while reflecting specific characteristics of its national construction market.

2. Materials and Methods

A structured online questionnaire investigated BIM adoption among professionals in Montenegro's construction sector. The instrument comprised 17 questions covering personal and organisational profiles, region, project focus, organisation size, professional activity, current BIM use, past experience, proportion of BIM-enabled projects, self-assessed competence, Common Data Environment (CDE) and BIM Execution Plan (BEP) use, implementation drivers, market demand, expected adoption, perceived barriers and benefits, and attitudes towards regulation. Data were collected from 20 May and 20 June 2026, yielding 138 valid responses. The chambers of engineers and architects distributed the questionnaire to professional communities. Participants represented Montenegro's central, coastal, and northern regions and worked on building and infrastructure projects. The professionals were from architecture and engineering organisations, contractors, investors, developers, facility-management organisations, surveying practices, universities, public bodies, and suppliers of construction products and technologies. Participation was voluntary, and responses were self-reported. The analysis was descriptive and exploratory. Single-choice questions were analysed using frequencies and percentages, while multiple-response questions were treated as separate categories; consequently, cumulative percentages may exceed 100 %. Inferential testing was omitted because sampling did not support population-level generalisation. Figure 1 summarises the structure, progressing from respondent profiles and BIM adoption to information-management maturity, market conditions, and strategic outlook. This enabled the distinction between general awareness, project-based use, and systematic organisational practices involving CDEs, BEPs, client requirements, and repeatable workflows. The study establishes a baseline for the participating community rather than a representative census and informs the identification of implementation gaps and development of a national BIM roadmap.

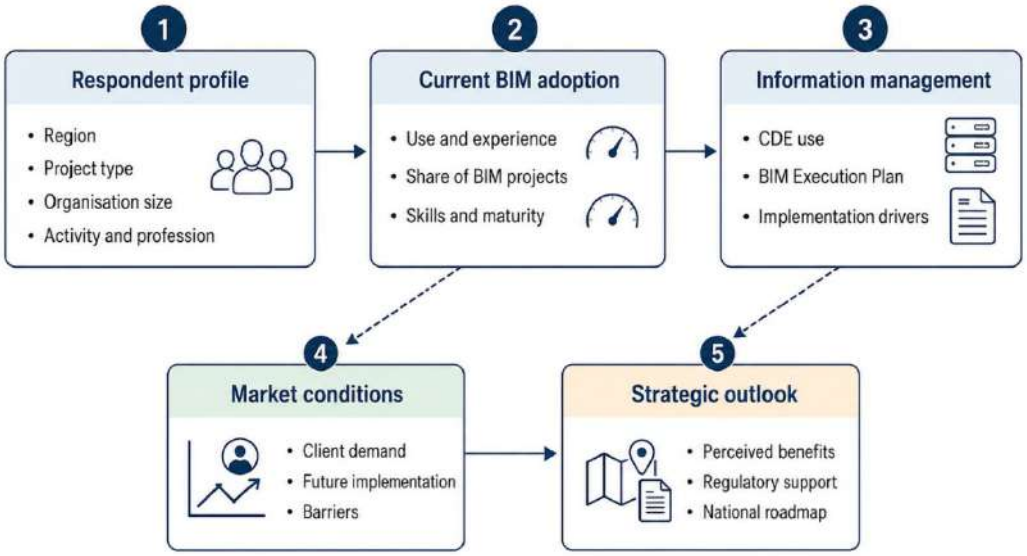


Figure 1 *– Analytical structure of the Montenegro BIM adoption survey.*

3. Results

3.1. Respondent and organisational profile

Figure 2 shows that micro-organisations with 1–4 employees formed the largest group, accounting for 53 of 138 respondents (38.4 %), followed by organisations with 5–10 employees (15.9 %). Civil engineers were the dominant profession, representing 48 respondents (34.8 %), followed by electrical engineers (13.8 %), architects (10.9 %), and HVAC engineers (9.4 %). Current BIM users are highlighted in green, indicating adoption across organisational sizes and professions.

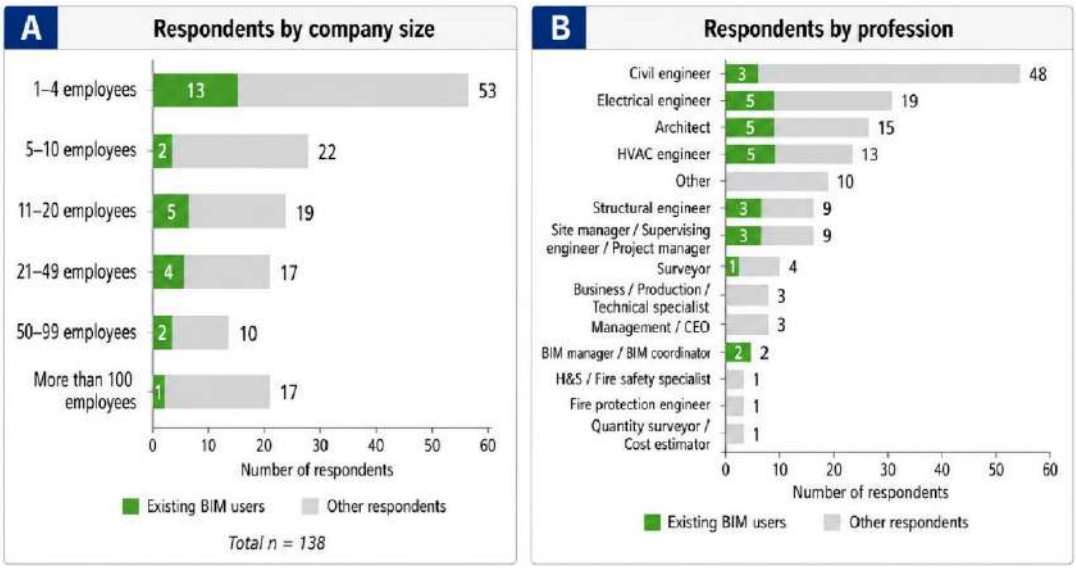


Figure 2 *– Respondents by company size (left - A) and profession (right - B)*

3.2. Current BIM adoption

The responses identify three groups: 27 professionals (19.6 %) already use BIM, 68 (49.3 %) are interested but have not yet adopted it, and 43 (31.2 %) do not use it. As shown in green in Figure 2, users occur across professions and organisation sizes, with micro-organisations employing 1–4 people forming the largest BIM-user group (13 respondents). The gap between active use and interest confirms that BIM remains at an early stage.

3.3. Information-management maturity

Figure 3 shows that BIM process maturity remains limited among current BIM users. In building projects 31.8 % use a CDE, compared with 20.0 % in infrastructure projects. BEP use is also more developed in buildings, where 9.1 % use it on every project and 45.5 % on some projects. In infrastructure, BEP is used only on some projects by 40.0 %. These results indicate that collaborative information-management practices are emerging but remain inconsistent, with model production developing faster than formal CDE and BEP procedures.

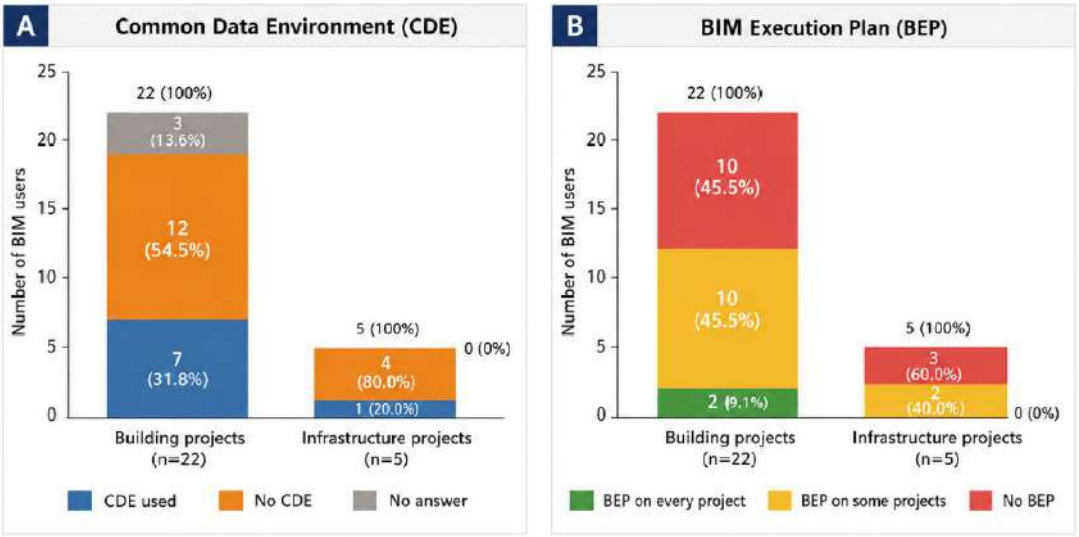


Figure 3 *– Maturity in terms of CDE (left - A) and BEP (right - B) in building and infrastructure*

3.4. Drivers and market demand

Figure 4 shows that BIM adoption is still mainly driven by internal and project-level factors. In building projects, the strongest driver is own initiative (50.0 %), followed by business-partner requests (31.8 %) and employer requests (18.2 %). In infrastructure projects, initiative and employer requests are equally important (40.0 % each). Market demand remains limited, in building-project 61.4 % had not yet received BIM requests, while only 19.3 % received BIM requests and 9.1 % required BIM from partners. Similarly, in infrastructure-projects 66.0 % reported no BIM requests, 16.0 % received such requests, and only 1 required BIM from partners. This confirms that BIM implementation in Montenegro is still more strongly driven by individual initiative and selected organisational or partner requirements than by a broad market demand.

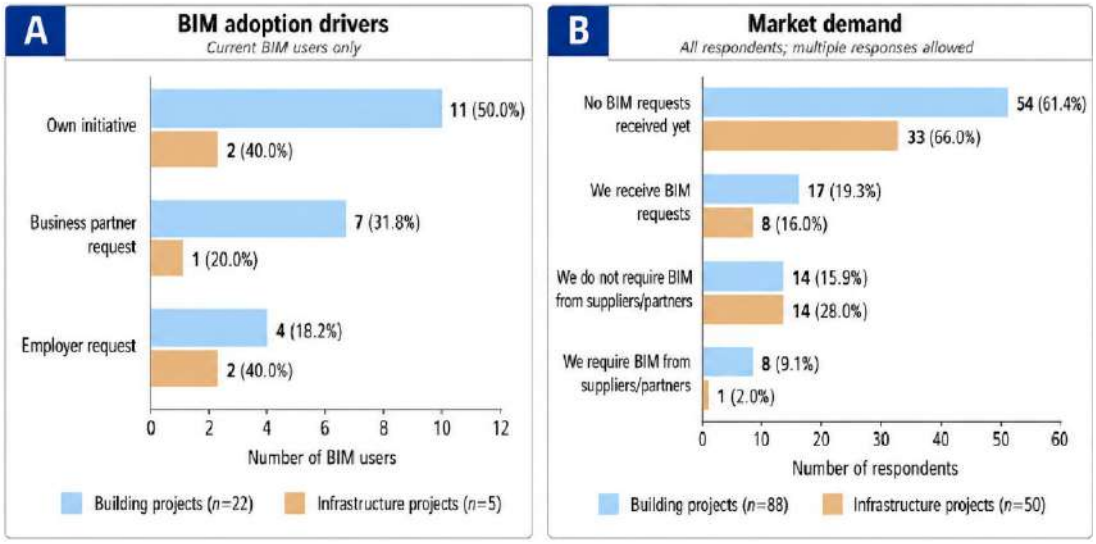


Figure 4 *– BIM adoption drivers (left - A) and market demand for BIM (right - B)*

3.5. Expected BIM use in the future, perceived barriers and benefits

Figure 5 indicates clear growth potential in organisational BIM adoption: 23 respondents expect implementation within one year, 34 within two years, and 44 within five years, while 19 report that their organisation already uses BIM (note: 27 respondents use BIM) and 18 do not anticipate future use. The difference suggests that some professionals use BIM individually or on selected projects, although their organisations have not yet adopted it systematically. The leading barriers are lack of BIM training (60 responses), insufficient client BIM requirements (52), shortage of competent professionals (42), and lack of standards and guidelines (41). The most recognised benefits are better visualisation of project solutions (38), faster work (20), more opportunities for engineering thinking (20), integrated lifecycle data, collaboration and coordination, and easier project monitoring (17 each). These findings suggest that limited adoption reflects capability, organisational maturity, and implementation constraints rather than weak interest.

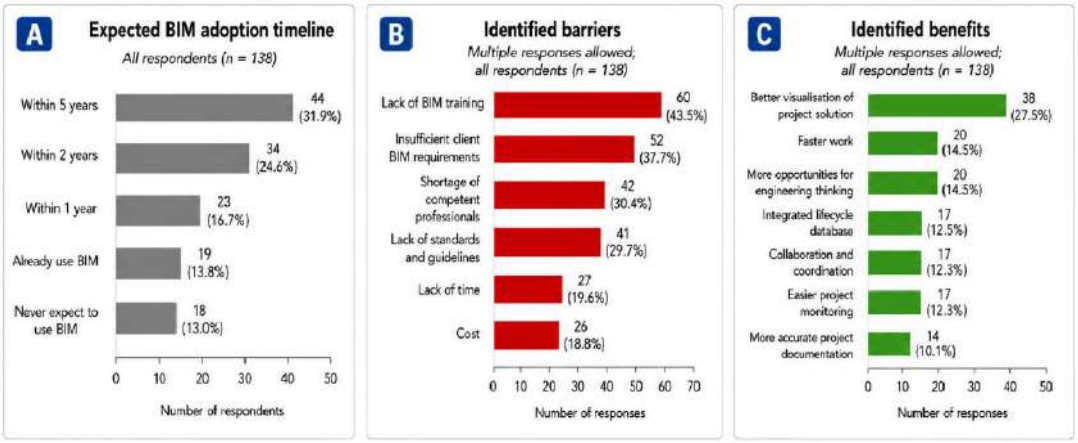


Figure 5 *– Expected timeline (left - A), identified barriers (middle - B) and benefits (right - C)*

4. Discussion

The Montenegrin findings closely reflect evidence from North Macedonia, where professional interest exceeded systematic BIM implementation and training, client demand, standards, skills, and cost were identified as major barriers [4]. As summarised in Figure 6, this pattern indicates that the principal challenges are interconnected market and institutional gaps rather than isolated organisational limitations.

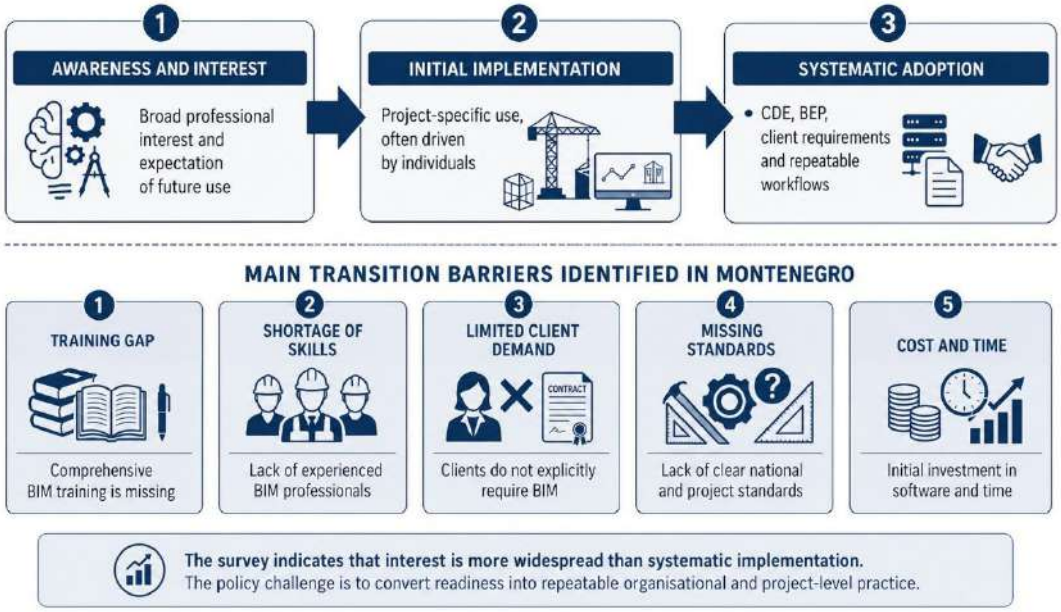


***Figure 6** – BIM framework with identified transition barriers: professional interest is more widespread than systematic implementation. Training and skills shortages are key barriers.*

Although the identified barriers are comparable to those reported in neighbouring countries, the Montenegrin construction market exhibits several specific characteristics that influence BIM implementation. The market is dominated by micro- and small-sized organisations, which often operate with limited financial and human resources and without dedicated BIM specialists. In addition, public procurement procedures still rarely include explicit BIM requirements, reducing the incentive for companies to invest in organisational transformation. Consequently, BIM adoption is frequently driven by individual initiative and international project exposure rather than by consistent market demand.

Unlike several European countries that have already established national BIM strategies or introduced BIM requirements in public procurement, Montenegro currently lacks a formal national BIM framework, dedicated standards, and publicly mandated implementation procedures. This institutional gap may partly explain the discrepancy between professional interest and the relatively limited level of systematic BIM adoption observed in the survey. These characteristics suggest that national implementation measures should prioritise practical guidance, affordable training opportunities, and gradual regulatory introduction adapted to the capacities of local stakeholders.

The Montenegrin findings confirm the need to distinguish between producing digital models and establishing repeatable, collaborative information-management processes. Future assessments should therefore avoid treating software ownership or occasional model production as sufficient evidence of BIM maturity. The strong role of personal initiative is characteristic of an early adoption stage. Individual champions may initiate change, but sustainable implementation requires management commitment, clearly defined responsibilities, internal standards, training, and documented workflows. Client capability is equally important, since poorly specified BIM requirements may increase project costs

without generating corresponding information value. The results also indicate that implementation measures must be scalable and proportionate. As many participating organisations are small, national guidance and templates should remain software-neutral and adaptable to project size and complexity. Simplified CDE and BEP procedures may suit smaller projects, while more comprehensive requirements should apply to complex public buildings and infrastructure. These findings provide the basis for the staged national framework proposed below.

4.1. Proposed national BIM implementation framework

Figure 7 presents a staged national framework derived from the survey findings and on regional evidence. It should begin with establishing a national BIM working group to define governance, terminology, objectives, and stakeholder responsibilities. The next stage is the preparation of practical ISO 19650-aligned BIM guidance [10] covering information requirements, BEPs, CDE procedures, naming system, classification, and quality control. Capacity building should then be coordinated through universities, professional chambers, public clients, and industry organisations, with training addressing information management, collaboration, and software skills. Selected public building and infrastructure projects should serve as evaluated pilots, followed by the gradual introduction of proportionate BIM requirements through public procurement for strategic, complex, or high-value projects. Adoption should finally be monitored through repeated surveys and pilot evaluations, allowing guidance and requirements to evolve with market capability.



***Figure 7** – Proposed staged roadmap for national BIM implementation in Montenegro.*

In Montenegro, universities and professional organisations may play a particularly important role in this transition. Given the relatively small size of the national construction sector, cooperation between higher education institutions, engineering chambers, public authorities, and industry stakeholders could accelerate knowledge transfer and reduce implementation costs. Initiatives such as continuing professional education, micro-credential programmes, and joint pilot activities may contribute to developing a sustainable BIM ecosystem and improving the sector's digital readiness.

4.2. Limitations of the study

Survey participation was voluntary, so the sample may overrepresent some, digitally more engaged professionals, and may understate resistance within the industry. Uneven coverage across regions, professions, organisation sizes, and project types further limits generalisation. Because responses were self-reported, BIM, CDE, BEP, and competence may have been interpreted inconsistently, while organisational maturity and project performance were not independently verified. These findings should therefore be treated as an informed warning rather than definitive proof, and tested through interviews, case studies, maturity assessments, and repeated surveys using core questions.

5. Conclusions

The survey reveals a Montenegrin BIM market positioned between interest and implementation. Only a limited group applies BIM in practice, while a larger community recognises its value but lacks systematic, repeatable workflows. A notable finding is that 62 of 64 interested non-users who answered the regulation question support national BIM requirements. This indicates that policy demand is strongest among those awaiting appropriate implementation conditions, and that the main challenge is not resistance to BIM, but the absence of coordinated support for adoption. Current implementation remains fragmented. BIM use is shaped mainly by individual initiative, employer expectations and business partners rather than by consistent client demand or national requirements. Insufficient training, shortages of skilled professionals, missing standards, limited demand, cost and time continue to slow progress. Evidence from Montenegro, North Macedonia, and Slovakia therefore supports a staged strategy based on governance, guidance, education, pilot projects, proportionate public procurement requirements and monitoring. Montenegro's key challenge is to transform readiness into coordinated, value-driven information management.

The results contribute to the Skill2Sustain project by identifying the skills, knowledge gaps and institutional conditions required for the green and digital transformation of the construction sector. They show that BIM competence development should not be limited to software training. It should also include information management, openBIM principles, CDE, BEP, collaborative workflows, client information requirements, lifecycle thinking, sustainability assessment and structured data for decision-making. These areas are essential for developing future-oriented learning outcomes, training modules and capacity-building actions.

The study is also relevant for sustainable construction. BIM can support sustainability only when information is structured, reliable and reusable across the asset lifecycle. Model-based information can improve coordination, reduce errors and rework, support quantity take-off, enable energy and environmental analysis, improve facility management and provide the basis for renovation, circularity and asset performance. BIM adoption in Montenegro should be understood not only as a digitalisation measure, but also as an enabler of sustainable planning, construction, operation and renewal. In the longer term, BIM implementation is a prerequisite for Digital Twins, smart infrastructure, AI applications and Digital Building Logbooks. AI-supported optimisation, automated compliance checking, predictive maintenance and portfolio-level decision support require consistent, machine-readable and trustworthy asset data. Similarly, Digital Building Logbooks and related European initiatives require reusable information on building performance, renovation potential, materials and lifecycle processes. Without clear information requirements, and data-governance principles, these initiatives risk remaining isolated demonstrations.

Acknowledgement

This study was partly supported by the EU-funded SKILL2SUSTAIN project (Project No. 101178204) under the Erasmus+ Programme. The authors gratefully acknowledge Dr. Tomáš Funtík for sharing the survey questionnaire developed within the framework of the European Council of Engineering Chambers (ECEC). Special thanks are also extended to the Chamber of Engineers of Montenegro and the Chamber of Architects and Planners of Montenegro for distributing the questionnaire, and to all respondents for their time and valuable contributions.

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Case Study Analysis of a Residential PV System Using Digital Energy Monitoring Tools

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Abstract

This paper presents a case study of a residential photovoltaic (PV) system based on real operational data obtained through a digital monitoring platform. The study evaluates energy production, household consumption, and self-consumption performance under real operating conditions while examining the role of digitalization in improving energy management and sustainability. The analysed PV system, installed in Bosnia and Herzegovina, has a capacity of 13.4 kW and includes a 10.2 kWh battery storage unit. The system generates approximately 13,053 kWh of electricity annually and covers around 79.1% of the household's total electricity demand. The results reveal significant seasonal variations in electricity generation, with energy surpluses during summer months and reduced production during winter, resulting in increased dependence on the electricity grid. Battery storage contributes to balancing the mismatch between production and consumption and improves the utilization of locally generated renewable energy. Digital monitoring enables continuous tracking of energy flows and provides valuable insights into consumption patterns, supporting more efficient operation and higher self-consumption rates. The environmental assessment indicates that the PV installation reduces carbon dioxide emissions by approximately 9.1 tCO_2 per year compared to conventional grid electricity supply. In addition to environmental benefits, the system increases household energy independence and demonstrates the potential for long-term energy savings. The findings highlight the importance of smart energy management, battery storage, and digital technologies for optimizing residential PV performance. Furthermore, the study confirms that residential photovoltaic systems can make a significant contribution to energy sustainability, decarbonization, and the efficient integration of distributed renewable energy resources.

Keywords

Energy efficiency, solar energy, PV panels, sustainability, digital technologies.

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1. Introduction

Solar energy is a key renewable and green energy source to build a sustainable energy system, playing an important role in future energy transition and climate change mitigation. Solar PV is considered one of the most decarbonized electricity generation systems, offering a promising solution to mitigate climate change and enhance energy security. By reducing greenhouse gas (GHG) emissions and providing a scalable and reliable energy source, solar PV plays a key role in addressing global sustainability challenges Beyond its environmental benefits, solar PV aligns with the United Nations' SDGs “Sustainable Development Goals”, particularly SDG 7, by enhancing access to affordable, reliable, and sustainable energy. [1]

Many countries have issued a bunch of policies to encourage solar photovoltaic (PV) power generation, which has witnessed rapid growth in recent years. In 2023, Solar PV generation accounted for three-quarters of worldwide renewable capacity additions, and the additions are predicted to more than double by 2028. Though Solar PV generated 5 % of all electricity in 2023, it is predicted to be beyond 30 % by 2050 [2]. Compared with large-scale utility PV, distributed solar PV on commercial, industrial, and residential sites has the advantages of high flexibility, near to the load centre and less land occupancy, which is expected to have a high penetration in the future [2]. By 2022, global installed solar PV exceeded 1 TW, of which distributed ones accounted for 43 %, and the residential sector accounted for 17 %. [3]. The residential sector is a key contributor to global carbon emissions and is of great importance for clean energy transition. With the accelerated electrification of residential energy consumption, residential solar PV is a crucial pathway. Besides, households’ solar PV provides an avenue for families to reduce electricity bills, increase income, and raise awareness of clean energy, showing a great potential to reduce energy poverty and improve welfare. With the aim to Net Zero Emissions by 2050, the number of households using solar PV will increase to more than 100 million by 2030 and 240 million by 2050, from 25 million in 2020 [4]. The global solar PV industry has experienced remarkable growth in recent years, with cumulative installed capacity reaching 1.6 TW in 2023, up from 1.2 TW in 2022 [5]. Although many studies analyze residential PV systems, limited research focuses on the practical integration of digital monitoring tools and AI-based self-consumption optimization in small-scale residential systems in Southeast Europe. Digital tools and intelligent energy management systems have the potential to significantly improve system efficiency, optimize electricity consumption patterns, and enhance the economic viability of residential PV installations [3,4]. In addition, these technologies contribute to overall sustainability by enabling more efficient use of renewable energy resources, reducing energy losses, and lowering greenhouse gas emissions.

This paper contributes to the understanding of residential PV system optimization by combining real operational data with digital monitoring and intelligent energy management concepts. The study highlights the role of digital technologies in improving self-consumption, reducing grid dependency, and supporting more efficient residential energy use. The aim of this paper is to analyze the impact of digital monitoring and smart energy management strategies on self-consumption optimization in a residential photovoltaic system. First, the challenges of self-consumption of PV systems in residential buildings and the ways in which digitalization can improve and enhance their use are explained. After that, the system being studied is presented together with the accompanying data. Finally, the results of the system implementation and suggestions for further improvement are provided.

2. Self-Consumption Challenges in Residential PV Systems

The self-consumption concept in residential photovoltaic (PV) systems refers to the direct use of electricity generated by PV panels within the same household or building, rather than exporting it to the grid. Although this approach is considered one of the most effective ways to increase the economic viability of residential PV systems, recent studies show that several technical, economic, and regulatory challenges still limit its full potential: [1-5]

- mismatch between energy production and consumption,
- high costs of battery storage systems,
- distribution grid limitations,
- regulatory issues and net-metering policies,
- seasonal variations in energy production,
- the need for smart energy management.

One of the main challenges is the mismatch between electricity generation and consumption. PV systems typically produce the highest amount of energy during midday hours, while household demand often peaks in the morning and evening. This temporal mismatch reduces the self-consumption ratio and leads to surplus electricity being exported to the grid under less favourable economic conditions [5]. Another significant barrier is the high cost of energy storage systems, particularly batteries. While storage technologies such as lithium-ion batteries can significantly improve self-consumption rates, their high initial investment and limited lifetime still make them economically challenging for many households [6,7]. The integration of PV systems into low-voltage distribution networks also presents technical difficulties. High penetration of residential PV can cause voltage fluctuations, reverse power flows, and grid congestion, which require additional grid reinforcement or advanced management systems. In addition, regulatory and market-related barriers play an important role. In many regions, policies such as net-metering or feed-in tariffs are being revised or reduced, which directly affects the financial attractiveness of self-consumption systems. The lack of standardized regulations across different countries further slows down adoption. Finally, user behaviour and awareness are also critical factors. Many households are not sufficiently informed about energy management strategies that could increase self-consumption, such as load shifting or smart home energy systems [6,7,8]

3. Digitalization and Smart Energy Management in Residential PV Systems

Digitalization solves the problems described in Chapter 2. Digitalization plays a crucial role in improving the performance, efficiency, and economic viability of residential photovoltaic (PV) systems. The integration of digital technologies such as smart meters, Internet of Things (IoT) devices, artificial intelligence (AI), and advanced energy management systems enables better monitoring, control, and optimization of electricity generation and consumption in households [9,10].

One of the key benefits of digitalization is the real-time monitoring of energy production and consumption. Smart meters and digital platforms allow users to track how much electricity is generated by PV panels and how much is being consumed within the household. This improves awareness and encourages more efficient energy use, which directly increases the self-consumption rate. Digital technologies also enable smart energy management systems (EMS) that automatically control household loads. For example, appliances such as washing machines, water heaters, or electric vehicle chargers can be

scheduled to operate when PV production is highest. This reduces dependency on the grid and maximizes the use of locally produced renewable energy. [10]

Another important aspect is the integration of artificial intelligence and predictive algorithms, which can forecast solar production and household demand based on weather data and consumption patterns. This allows for better planning of energy usage and improved coordination with battery storage systems. Digitalization also supports grid integration and stability. With increasing penetration of residential PV systems, distribution networks face challenges such as voltage fluctuations and reverse power flows. Digital control systems help utilities and prosumers manage these issues more effectively through demand response programs and smart grid technologies.[11]

Overall, digitalization is a key enabler for the transition toward smarter, more efficient, and decentralized energy systems. It not only increases the economic benefits of residential PV systems but also supports higher renewable energy penetration and improved grid stability.

4. Methodology and Case Study Description

Further in the paper, the PV system and the relationship between the system's operation and household electricity consumption are presented and described in more detail. Parameters related to the installed power of the PV system, the battery, and consumption data that are further processed are shown. A proposal of data on a monthly basis is provided, while the results analyze annual parameters.

4.1. System Description

The solar power plant was designed in the area of the Municipality of Prnjavor in Republika Srpska, Bosnia and Herzegovina. The installed capacity of the PV system is 13.4 kW over an area of 59.7 m². A total of 30 panels are mounted at a height of 3 m with an east–southeast orientation (**Figure 1**). The system includes equipment such as an inverter and a 10.2 kWh battery storage unit. The design and calculations were carried out using the Solarintelligent application.



***Figure 1** – PV solar plant for residential building*

4.2. Data Collection, Monitoring and Evaluated Parameters

The house supplied by this power plant has an area of 250 m² and an annual electricity consumption of 16,500 kWh, including heating, cooling, ventilation, and household

appliances. The heating, cooling, and ventilation system was designed using a heat pump system. The total annual energy production of the solar power plant is 13,053 kWh.

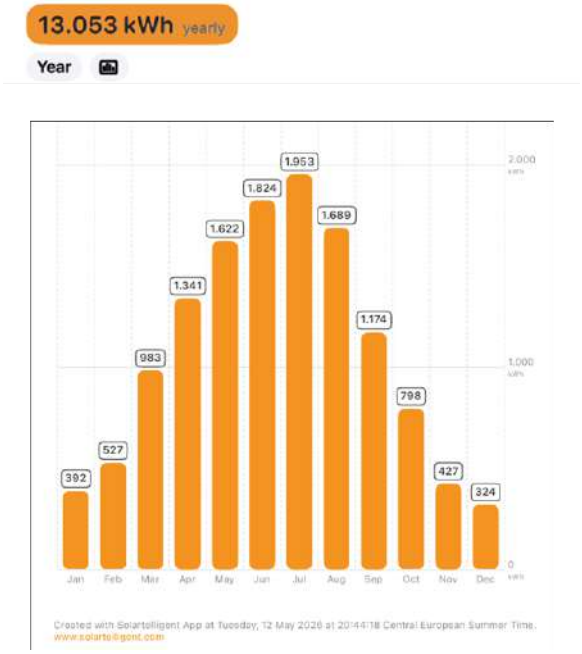


***Figure 2** – Annual energy production overview*

Figure 2 indicates strong seasonal dependence of PV generation, with peak production occurring during summer months due to higher solar irradiation levels. During winter periods, reduced generation increases grid dependency and lowers the self-sufficiency ratio. The highest solar irradiation occurs in July and amounts to 1,953 kWh, while in December it is 324 kWh. Total solar insolation is 1.546,0 kWh yearly per m². The results confirm strong seasonal variability, which significantly affects grid dependency during winter months. The electricity annual consumption is 16,500 kWh. The table (**Figure 3**) provides an overview of the relationship between energy consumption on a monthly basis. The diagram shows the additional amount of electrical energy that must be supplied from the distribution grid to compensate for the energy deficit not covered by the photovoltaic panels. It can be observed that no additional electricity is required from the grid during seven months of the year, whereas during the remaining five winter months, a portion of the required electrical energy must be supplied by the distribution network. The balance between production and consumption during months with lower energy generation can be maintained using a **10.2 kWh battery**.

The back-up power supply systems with long autonomy, electrical aggregates, are most often used for back-up power supply of general consumption of buildings (not only for the operation of technological processes, pumps for heating, air conditioning and ventilation of spaces, special fire protection systems, but also for powering security systems, alarm and video systems, computers, servers, access control systems, all types of automatic doors and electric locks, etc.). However, with the development of new battery technologies, primarily lithium, these options are increasingly being used for periods of uninterrupted power supply. When it comes to energy obtained from renewable sources, the storage of electricity can take one of the main roles in systems for backup power supply by means of capacitors and batteries in which electricity is stored. [12,13]

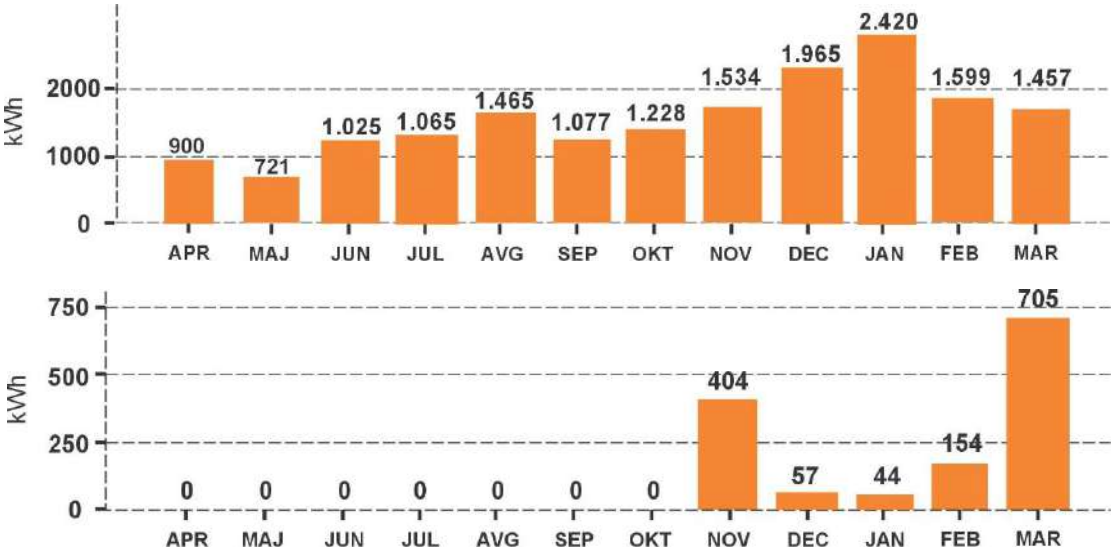


***Figure 3** – Diagram of the difference between consumption and over one year*

To demonstrate the importance of the battery, it is necessary to monitor energy storage during months when production is lower, such as **January, February, October, November, and December**. The key parameters for the overall scenario analysis are the relationship between annual energy consumption and annual energy production. The results and further analysis are presented in the following chapter.

5. Results and discussion

The environmental impact of the analysed residential photovoltaic (PV) system was evaluated through the estimation of avoided carbon dioxide (CO_2) emissions. The calculation was based on the annual electricity production of the PV system and the average grid emission factor for Bosnia and Herzegovina. The avoided CO_2 emissions were calculated using the following expression [14]:

$$\boldsymbol{CO_2 = E_{PV} \times EF_{grid}}$$

where:

- $\boldsymbol{E_{PV}}$represents the annual PV electricity production [$\boldsymbol{kWh/year}$],
- $\boldsymbol{EF_{grid}}$represents the grid emission factor [$\boldsymbol{kgCO_2/kWh}$].

For the analysed case study:

- annual PV electricity production was $\boldsymbol{13,053\ kWh/year}$,
- the adopted grid emission factor was $\boldsymbol{0.7\ kgCO_2/kWh}$.

The estimated annual CO_2 emission reduction for this project (**Figure 4**) is therefore approximately $\boldsymbol{9.1\ tCO_2/year}$:

$$\boldsymbol{CO_2 = 13\,053 \times 0.7 = 9\,137.1\ kg\ CO_2/year}$$

***Figure** 4 – Equation and calculation of CO_2 emissions*

In comparison, without the system, this value would be 11.6 tCO_2/year. The obtained results indicate that the implementation of residential PV systems can significantly contribute

to greenhouse gas emission reduction and support the transition toward sustainable and low-carbon energy systems. In addition, higher self-consumption rates achieved through digital monitoring and smart energy management can further enhance the environmental benefits of residential photovoltaic installations. Based on the given values, we can also calculate the energy benefits and the percentage of energy consumption covered by the system from the ratio of production to consumption (**Figure 5**), which means that the system covers about 79.1% of the total electricity demand. [15]

$$SC = \frac{13\,053}{16\,500} \times 100 \approx 79.1\%$$

***Figure 5** – Calculation of self-consumption (SC) rate*

This indicates a high level of energy autonomy, with the remaining demand being supplied from the electrical grid, particularly during periods of reduced solar irradiation.

Further in the study, the electricity consumption was analyzed for two scenarios: without battery storage (Figure 6) and with battery storage (Figure 7).



***Figure 6** – Consumption status without battery*

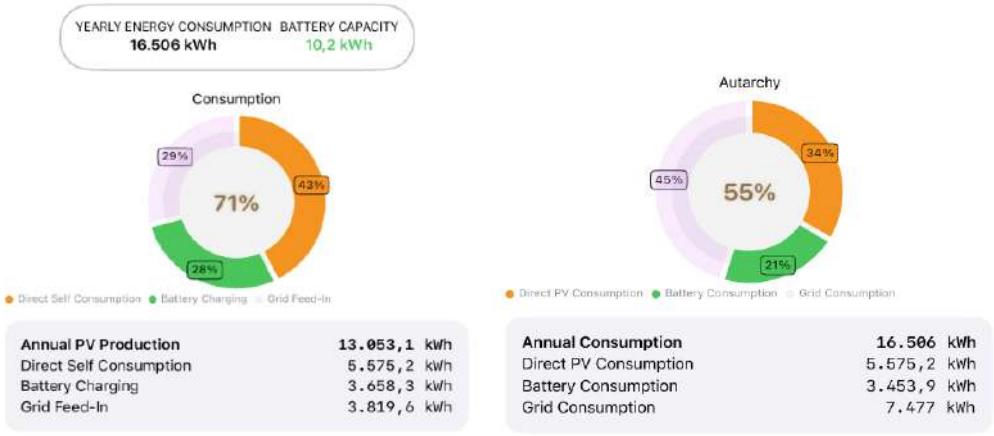


***Figure 7** – Consumption status with battery*

Figure 6 illustrates the performance of the photovoltaic (PV) system without battery storage. The system achieved a **self-consumption rate** of 43%, defined as the share of total PV electricity generation that is consumed directly on-site rather than exported to the grid, indicating that nearly half of the electricity generated by the PV system was utilized within the building. At the same time, the **energy self-sufficiency (net autarky) rate**, which represents the share of the building's total electricity demand covered by its own PV generation, was 34%, meaning that slightly more than one-third of the building's electricity demand was supplied by the PV system, while the remaining electricity was imported from the utility grid.

Figure 7 presents the performance of the PV system with battery energy storage. In this case, the self-consumption rate increased to 71%, indicating that more than two-thirds of the generated electricity was utilized for on-site consumption. The integration of the battery storage system enabled surplus energy produced during periods of high solar generation to be stored and used later when photovoltaic production was insufficient, significantly improving the utilization of the generated electricity. Furthermore, the energy self-sufficiency (net autarky) rate increased to 55%, demonstrating that more than half of the building's total electricity demand was supplied by its own photovoltaic system. Compared to the system without battery storage, these results indicate a significant reduction in dependence on the utility grid and a more efficient utilization of renewable energy. The obtained results confirm that integrating a battery energy storage system increases the self-consumption of photovoltaic electricity, reduces the amount of surplus energy exported to the grid, and enhances the overall energy independence of the building. It should be noted that the self-consumption rate is a generation-oriented indicator describing how much of the PV electricity is used on-site, whereas the net autarky rate is a demand-oriented indicator expressing the extent to which the building's electricity demand is met by its own PV generation.

5.1. Energy scenario, optimization capability

A significant role in the profitability and overall importance of residential PV systems is played by the relationship with the electricity distribution company and the possibility of concluding energy purchase agreements. In such systems, a 1:1 production-to-consumption ratio can be enabled. This means that surplus energy produced during periods of higher solar irradiation is fed into the grid, and the meter records the amount of energy exported by the residential system. During the winter period, when energy production is lower compared to consumption during the summer months, the electricity distribution company accounts for the exported energy and compensates it through reduced electricity bills. Over a longer time horizon, the savings are significant (**Figure 8**). From an economic perspective, the comparison between the two configurations depends on both the initial investment cost and the applicable electricity market regulations. The PV system with battery storage requires an investment of approximately 18.000KM (this system includes prices for solar panels, battery, roof structure, AC cable, DC protection, inverter, installation, administrative and metering costs). However, the owner can also benefit from a 1:1 net metering agreement with the electricity distribution company, under which surplus electricity exported to the grid can be offset by the same amount of electricity imported later, with electricity valued at the current tariff of approximately KM 0.22 per kWh. In Bosnia and Herzegovina, this scheme currently applies to photovoltaic systems with an installed capacity of up to 10 kWh.

From a purely economic standpoint, the most cost-effective solution is a PV system without battery storage, which requires an investment of approximately 12.000 KM, combined with the same 1:1 net metering agreement (**Figure 8**). The significantly lower investment cost results in a shorter payback period while still allowing the owner to benefit from energy exchanged with the grid. However, this solution is associated with greater regulatory uncertainty. Since net metering agreements are typically concluded for a period of one year, their continuation depends on future regulatory decisions. Consequently, changes in legislation or the discontinuation of the net metering scheme could negatively affect the economic viability of such systems. Similar regulatory changes have already occurred in several European countries. For example, in Slovenia, the 1:1 net metering scheme was available from 2016 until 2023, after which it was discontinued for new users. Furthermore, many European countries no longer apply full 1:1 net metering, instead adopting alternative compensation mechanisms such as net billing or feed-in tariffs. Therefore, although a battery-free PV system currently represents the most economically attractive option under the

existing regulatory framework, a battery storage system offers greater long-term energy security and reduces dependence on future regulatory changes.



***Figure 8** – Consumption status with grid fee, system 1:1, without battery and with battery*

In Bosnia and Herzegovina, it is currently possible to enter into a contractual 1:1 net metering agreement with the electricity distribution company. Nevertheless, the analyzed case includes both: a net metering agreement and a battery energy storage system. The battery was selected to improve the operational reliability of the PV system and to ensure an uninterrupted electricity supply during the frequent power outages caused by adverse weather conditions. The least economically viable case occurs when a battery energy storage system is installed at a total system cost of 18.000 KM, without any available incentives and without a 1:1 net metering agreement. In this scenario, the system experiences higher energy losses during the winter months due to reduced solar generation, resulting in a longer estimated payback period of approximately 8 years.

Although this case does not represent the most cost-effective system configuration. With an estimated payback period of approximately 6 years it provides the most secure long-term solution in terms of both economic viability and energy reliability. However, it provides the highest level of operational reliability and energy security, making it the most suitable option for the specific conditions considered in this study. The integration of battery storage reduces dependence on the utility grid, enhances resilience during grid interruptions, and offers greater long-term security despite the higher initial investment.

6. Conclusion

The analysed residential PV system demonstrated that digital monitoring enables improved visibility of energy production and consumption patterns, creating opportunities for higher self-consumption and reduced grid dependency. The construction of photovoltaic systems in residential buildings, as small power plants, can contribute to increasing the sustainability of the region, reducing CO_2 emissions, and being as significant as large solar

power plants. What is certain is that the region has significant potential for the development of such projects. This is supported by the level of solar insolation, which is 1,546.0 kWh/m² per year, as well as the observation that such systems are still relatively rare in the region. Investment in such systems leads to significant energy savings of 79.1% and a payback period of 8 years in the worst-case scenario, while in the best case—when a 1:1 net metering agreement can be concluded—the payback period is reduced to 4-6 years (depending on whether we invest in the battery or not). The optimal and safest option is with a battery and after 6 years, the system generates net profit, which further confirms the economic justification of the investment. The installation of applications and digital systems that enable households to easily manage and monitor data can further encourage the development of such systems. Additionally, CO_2 emissions are reduced by 9.1 tCO_2/year.

Digital technologies significantly improve the overall energy efficiency of residential PV systems by enabling real-time monitoring, precise control, and better coordination between energy production and consumption. One of the most important contributions of digitalization is the increase in self-consumption levels. By optimizing when and how electricity is used within the household, smart systems ensure that a larger share of locally generated solar energy is consumed on-site, reducing energy losses and improving the economic performance of PV installations. In addition, digital energy management plays a key role in reducing stress on the electrical grid. By shifting consumption patterns and enabling demand response strategies, residential PV systems can contribute to grid stability, especially in areas with high penetration of distributed renewable energy sources. Finally, artificial intelligence (AI) represents a major opportunity for the future development of smart home energy systems. AI-based forecasting and optimization tools can further improve energy balancing between production, storage, and consumption, enabling fully automated and highly efficient residential energy ecosystems.

In conclusion, the combination of photovoltaic technology and digital innovation is essential for achieving higher efficiency, greater self-consumption, reduced grid dependency, and a more sustainable and intelligent energy future. This study has shown that residential photovoltaic (PV) systems are becoming an increasingly important component of modern energy systems, particularly in the context of the global transition toward renewable energy sources. However, their full potential is strongly dependent on the integration of digital technologies and intelligent energy management solutions.

This paper contributes to the promotion of, as well as motivation for, the development of such projects in the region.

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Demonstration Centres Within the ULTRA Project: Digital Twin and Blue-Green Infrastructure

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Abstract

The green and digital transition requires more than strategic commitments and the introduction of new technologies. It also requires learning environments in which students, researchers and professionals can observe, analyse and manage the interactions between buildings, infrastructure, environmental processes and digital information. This paper presents two complementary demonstration centres developed at the University of Ljubljana, Faculty of Civil and Geodetic Engineering, within the university-wide ULTRA project: an interactive building digital twin and an outside blue-green infrastructure demonstration centre focused on the urban water cycle. The digital twin connects a Building Information Model with environmental sensor data and interactive desktop and virtual-reality interfaces. It enables users to explore the faculty building, access spatially associated measurements and examine relationships between indoor environmental conditions, building spaces and operational data. The blue-green infrastructure centre transforms the building surroundings into an instrumented living laboratory for studying rainfall, canopy interception, throughfall, stemflow, soil moisture, evapotranspiration and urban microclimate. Although the two centres address different engineering domains, they share a common educational model. Both integrate physical assets, digital representations, real-time or periodically collected data and project-based learning. They therefore provide a practical framework for developing the combined digital, environmental and interdisciplinary competencies required by the twin transition. In line with the findings and recommendations of the SKILL2SUSTAIN project, the paper argues that centres can serve as scalable research and education infrastructures supporting curriculum modernisation, lifelong learning, institutional cooperation and knowledge transfer.

Keywords

Digital twin, blue-green infrastructure, living laboratory, urban water cycle, experiential learning, green and digital transition, ULTRA.

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1. Introduction

Universities are expected to contribute to the transition towards a climate-neutral, resilient and digitally advanced society through education, research, institutional development and cooperation with industry and public authorities. However, integrating sustainability and digitalisation into curricula does not automatically provide students with the ability to apply these concepts in complex real-world situations. The principal challenge is therefore not only to introduce new subject matter, but also to establish environments in which digital and green competencies can be developed together through observation, experimentation and problem solving.

This challenge is particularly relevant to the architecture, engineering, construction and operations sector. Buildings and infrastructure are responsible for substantial resource consumption and environmental impacts, while their planning, construction and operation increasingly depend on digital models, sensor systems, data platforms and analytical tools. Future engineers must consequently understand both physical and environmental processes and the digital systems used to represent, monitor and manage them.

Building Information Modelling has significantly improved the organisation and exchange of information during planning and construction. Nevertheless, many BIM models remain static and are not systematically connected to operational measurements, facility-management processes or interactive learning environments. At the same time, environmental engineering education often relies on individual measurements or predefined datasets that do not fully expose students to the spatial, temporal and uncertain characteristics of natural processes.

Demonstration centres and living laboratories can address these limitations by linking academic knowledge with observable processes in actual buildings and outdoor environments. They allow students to work with authentic data, compare models with measured conditions, test assumptions and understand the limitations of individual technologies. They can also support research, professional training and the demonstration of new methods to external stakeholders.

This paper presents two such demonstration centres developed at the University of Ljubljana, Faculty of Civil and Geodetic Engineering. The first focuses on a building digital twin integrating BIM, Internet of Things data and immersive visualisation. The second focuses on blue-green infrastructure and the urban water cycle at the scale of a university building and its surroundings. The purpose of the paper is not to compare the centres as competing solutions, but to show how they form complementary components of a shared institutional and educational framework.

1.1. The ULTRA project and the Sustainable Spaces framework

The demonstration centres were developed within the ULTRA project, a university-wide reform initiative supporting the transition of the University of Ljubljana towards a sustainable society. The project combines curriculum development, digital transformation, sustainable spatial development, interdisciplinary cooperation and the modernisation of teaching and research infrastructure. Within ULTRA, the Sustainable Spaces pilot addressed the relationship between university buildings, educational programmes, institutional strategies and sustainability objectives. Its activities included the development of sustainable development concepts, guidance for renovation and new construction, the integration of digital information on the university building stock, curriculum renewal and the establishment of demonstration environments.

The Sustainable Building Construction Demonstration Centre was conceived as an infrastructure connecting physical buildings with BIM models, sensing technologies, cloud services and classroom applications. Rather than treating the demonstration centre as a single laboratory, the project developed a distributed environment in which different buildings, sensors and educational activities could be integrated.

The approach supports several levels of learning. At the introductory level, students can observe environmental parameters and relate them to particular rooms, building elements or outdoor conditions. At an intermediate level, they can analyse datasets, assess data quality and compare measured and expected behaviour. At an advanced level, they can develop information models, analytical procedures, simulations and decision-support applications.

This structure is particularly important because the green and digital transition is inherently interdisciplinary. Digital models without environmental knowledge cannot adequately support sustainability objectives, while environmental measurements without structured digital representations are difficult to interpret, combine and reuse. The ULTRA demonstration centres therefore seek to connect these perspectives through the concept of living laboratories.

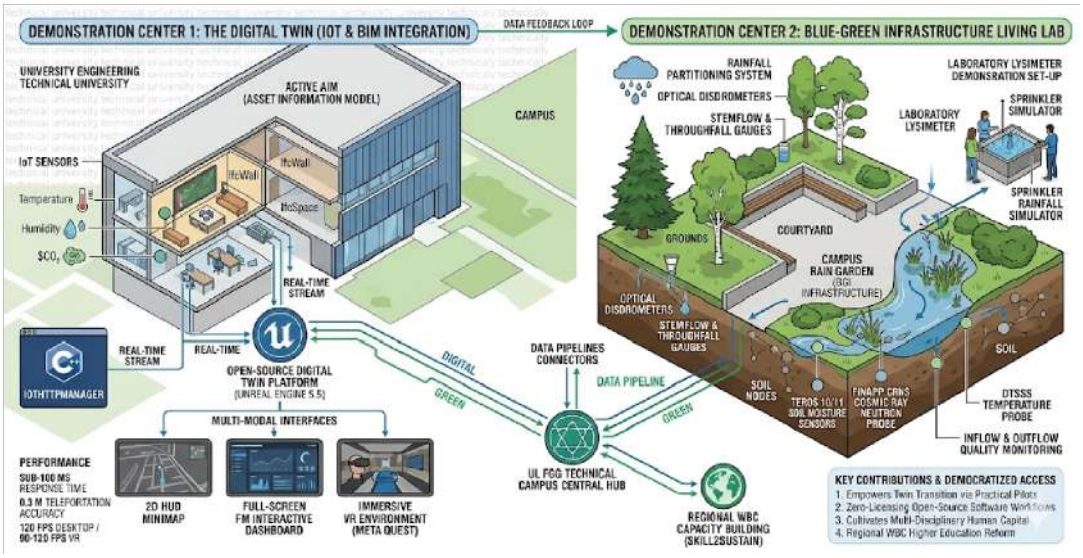


Figure 1 *– Integrated digital and green demonstration centres: a twin transition framework*

Although the two demonstration centres differ in their physical focus, they follow the same fundamental logic. Each consists of four connected components:

- a physical system, represented by the building and its surroundings;
- sensing and measurement technologies;
- structured digital representations and analytical environments; and
- educational and research activities based on authentic problems.

The digital twin centre begins with a building model and connects it to indoor environmental data. The blue-green infrastructure centre begins with observed environmental processes and progressively organises them through digital data, models and visualisations. One therefore moves primarily from a digital representation towards the monitored physical environment, while the other moves from physical environmental processes towards digital interpretation. Together they demonstrate the bidirectional nature of the twin transition. This shared model also supports progressive learning. Students may initially observe a phenomenon, subsequently interpret the associated data, and finally develop or improve a model, interface or engineering intervention. The centres are therefore

not static exhibitions. Their value lies in continued use, modification and integration into teaching and research.

The demonstration centres can also provide a neutral setting for cooperation between universities, technology providers, public authorities and industry. New sensors, software tools and analytical approaches can be tested at a manageable scale before wider implementation. At the same time, external participants can become involved in lifelong-learning courses, professional workshops and collaborative research.

2. Digital Twin Demonstration Centre

2.1. Purpose and building context

The Digital Twin Demonstration Centre addresses the fragmentation between building models, operational data and user interfaces. Its central component is an interactive representation of a faculty building that connects building geometry and spatial information with environmental sensor measurements. The digital twin was developed from a BIM model of the building and implemented in Unreal Engine 5.5. The environment supports both desktop interaction and immersive virtual-reality navigation. Users can move through the virtual building, select floors and rooms, and access measurements associated with instrumented spaces. The interactive 3D environment provides spatial context for interpreting measurements and environmental conditions.

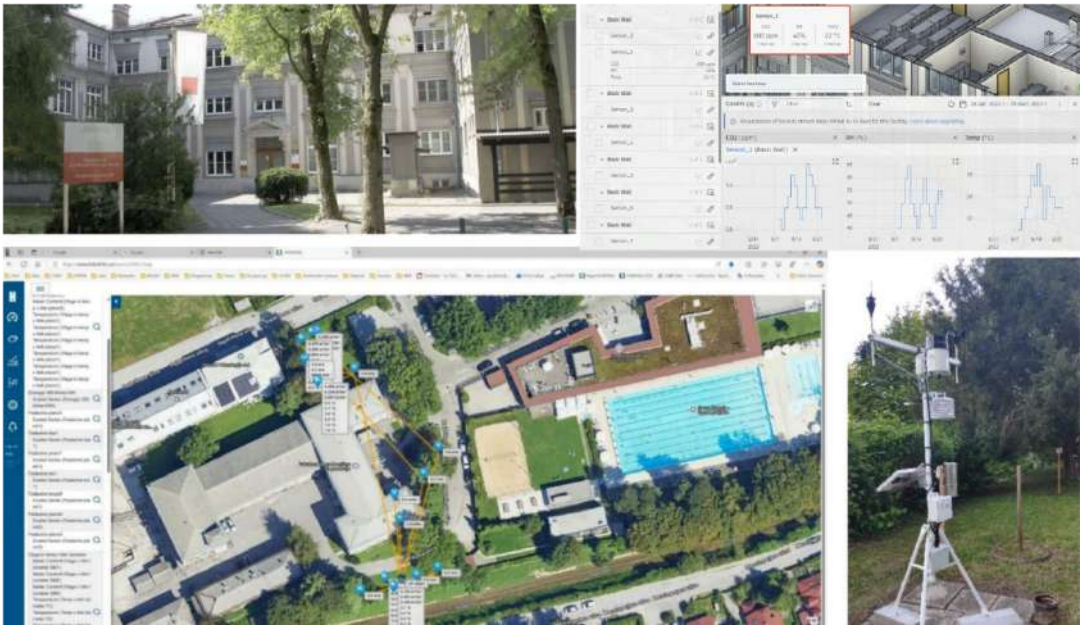


***Figure 2** – Integration of outdoor meteorological sensors and a building rooms measurements in the Digital Twin interface for real-time monitoring*

2.2. Experimental plot and instrumentation

The building model provides the spatial structure of the digital twin. It represents the principal building elements, floor organisation and rooms required for navigation and data association. During implementation, model preparation and interoperability were identified as significant tasks because BIM objects and spatial entities do not always transfer directly into game-engine environments. Room-based interaction was therefore supported through

spatial volumes connected to room identifiers, sensor references and navigation coordinates. When a user enters or selects an instrumented space, the system retrieves the corresponding measurements and presents them within the interface. This process demonstrates an important educational issue: a digital twin is not created merely by importing a three-dimensional model into a visualisation platform. The information must be structured, validated and connected to the physical asset through reliable identifiers, mappings and interfaces. The physical building is equipped with environmental sensors that measure parameters including indoor air temperature, relative humidity and carbon dioxide concentration. Depending on the installed equipment, additional parameters may also be included. The digital twin accesses the sensor information through an application programming interface.

A hybrid implementation using C++ and Unreal Engine Blueprint visual scripting separates data processing from interface configuration. More demanding communication and data-parsing operations are processed in C++, while room configuration and user-interface behaviour can be adjusted through the visual scripting environment. The prototype demonstrated responsive data access and stable operation in both desktop and virtual-reality modes. It also showed that the system must be capable of handling differences between rooms, including incomplete sensor configurations or temporarily unavailable measurements. Such conditions are valuable for teaching because they expose students to the imperfections of operational datasets.

2.3. Educational value and research applications

The digital twin can support teaching in BIM, facility management, building operation, indoor environmental quality, information management, programming and data analysis. Students can explore how measurements relate to building spaces, assess variations in indoor conditions and discuss possible operational or occupancy-related causes. The environment also enables students to examine the entire digital-twin workflow: model preparation, information structuring, sensor deployment, data acquisition, API communication, visualisation and user interaction. This is more valuable than presenting a completed application without exposing the processes and decisions behind it. It also allows learning activities to be organised around authentic problems in which students formulate hypotheses, evaluate data quality and propose evidence-based interventions. Because the same environment can be used by students from different disciplines, it supports collaboration between civil engineering, computer science, architecture and building-services engineering. Repeated use over several semesters can additionally generate comparable datasets for evaluating both building performance and student learning outcomes. In this way, the platform functions not only as a visualisation tool, but also as a shared experimental environment for developing systems thinking and data-informed decision-making. For researchers, the platform provides a basis for testing alternative interaction methods, sensor-data representations, interoperability procedures and predictive applications. Future development may include broader room coverage, automated extraction of spatial boundaries, additional operational data, issue-management workflows and machine-learning methods for recognising patterns and anomalies.

3. Blue-Green Infrastructure Demonstration Centre

3.1. Purpose and urban-water-cycle context

The second demonstration centre focuses on the urban water cycle and the role of vegetation and blue-green infrastructure in climate-adaptive urban drainage. Conventional urban development increases the proportion of impermeable surfaces, reduces infiltration and evapotranspiration, and accelerates surface runoff. During intense rainfall, these changes can contribute to sewer-system overload, combined sewer overflows, local flooding and the transport of pollutants into receiving waters. Blue-green infrastructure seeks to manage rainfall closer to where it falls by using retention, detention, infiltration, evapotranspiration and biological treatment. It can include trees, vegetated areas, rain gardens, permeable surfaces, green roofs, retention elements and related nature-based solutions. In addition to stormwater management, such measures can support biodiversity, mitigate urban heat and improve the quality of public space.

The UL FGG demonstration centre treats the university building and its surroundings as a small urban catchment. Its purpose is to make individual components of the urban water balance visible and measurable and to demonstrate how vegetation influences rainfall transformation.

3.2. Experimental plot and instrumentation

As shown in Figure 3, the experimental area contains mature pine and birch trees equipped to measure rainfall partitioning into interception, throughfall, and stemflow. Gross rainfall is tracked in an open area, throughfall is captured beneath canopies using fixed and moving collectors, and stemflow is gathered via trunk-wrapped spiral systems. By monitoring these pathways alongside soil moisture, infiltration, urban microclimate, and Leaf Area Index (LAI), this setup directly links meteorological conditions to hydrological responses across different species, seasons, and storms.



Figure 3 *– Schematics of the urban water balance experimental plot, illustrating instrumentation for rainfall partitioning, urban microclimate, and soil moisture and infiltration measurements.*

3.3. Educational value and research applications

The centre allows students to move beyond schematic representations of the hydrological cycle and work directly with measurements from an actual urban environment. They can identify rainfall events, examine measurement intervals, calculate rainfall partitioning, estimate canopy storage and analyse relationships between rainfall intensity, canopy condition and soil moisture. Students can also study the limitations of environmental measurements. Throughfall varies substantially across the area beneath a tree; sensors may fail or produce incomplete records; and the interpretation of individual rainfall events depends on the definition of dry periods and event boundaries. These are not merely technical difficulties but important elements of engineering judgement.

Digital tools can be used to retrieve, process, visualise and compare the data. The centre therefore integrates green and digital competencies: students must understand the physical processes while also developing skills in data management, programming, statistical analysis, visualisation and modelling. The demonstration centre additionally creates opportunities for interdisciplinary projects involving environmental engineering, civil engineering, geodesy, architecture, urban planning and computer science. For example, measurements from the experimental plot can be combined with GIS data, terrain models, rainfall-runoff simulations or digital representations of the university campus.

4. Discussion

The implementation of the two centres provides several lessons for universities seeking to support the green and digital transition.

First, demonstration centres should be designed as educational infrastructures rather than isolated technical installations. The acquisition of equipment alone does not ensure learning. Sensors, models and software must be connected to clearly defined learning activities, accessible datasets and suitable interfaces. Second, interoperability and information management are central concerns. A digital twin depends on consistent relationships between physical assets, spaces, sensors and digital identifiers. Similarly, environmental monitoring requires clear metadata, calibrated instruments, appropriate event definitions and documented analytical procedures.

Third, real-world data introduce uncertainty and incompleteness. This is an advantage rather than a deficiency when it is incorporated into teaching. Students learn to assess reliability, identify missing data, distinguish measurement error from actual system behaviour and communicate the limitations of their conclusions. Fourth, open and extensible technologies can improve accessibility and reduce dependence on individual commercial platforms. Nevertheless, open-source or freely available components do not eliminate implementation costs. Expertise is still required for model preparation, programming, integration, maintenance and technical support. Claims of zero-cost implementation should therefore be limited to software-licensing costs and should not obscure the required human and organisational resources.

Fifth, long-term institutional responsibility is essential. Demonstration centres require maintenance of sensors, models, interfaces, data services and teaching materials. Their sustainability therefore depends on integration into regular curricula, research projects and institutional infrastructure rather than temporary project activities alone. This requests a dedication by a university to run the centre on long term as a valuable educational and research infrastructure.

5. Conclusions

The ULTRA project demonstrates how university reform can be translated into operational educational infrastructure. The Digital Twin Demonstration Centre and the Blue-Green Infrastructure Demonstration Centre provide complementary environments for learning about digitally enabled buildings, environmental monitoring, climate adaptation and sustainable urban systems. The principal value of the centres is not a single technological innovation. Their contribution lies in combining physical systems, structured information, measurements and project-based learning. This combination enables students to connect theoretical knowledge with observable building and environmental behaviour and to develop technical, analytical and interdisciplinary competencies. The findings are consistent with the direction established by the SKILL2SUSTAIN project. Its state-of-the-art analysis emphasises the need to integrate green and digital competencies across higher education, strengthen practical and project-based learning, develop interoperable research and education centres, support staff training, expand lifelong-learning opportunities and improve cooperation between universities and external partners. The two UL FGG demonstration centres provide a concrete example of how these recommendations can be implemented. They can support bachelor's and master's education, professional training, micro-credentials and joint international learning activities. Their modular organisation also allows individual components, datasets and exercises to be adapted by partner institutions without requiring replication of the entire infrastructure.

Future work should therefore focus on the systematic evaluation of learning outcomes, the development of reusable teaching modules, common data and interoperability guidelines, staff-development programmes and collaboration with universities in the Western Balkans. Demonstration centres should not remain isolated examples of good practice, but should become nodes in a wider network of digital and green education infrastructures. By connecting institutional reform with living laboratories, universities can move from discussing the twin transition to teaching, testing and implementing it. The ULTRA demonstration centres illustrate how the university campus itself can become an active learning environment for the development of resilient, digitally enabled and environmentally responsible buildings and cities.

Acknowledgement

The demonstration centres were developed within the University of Ljubljana for a Sustainable Society – ULTRA project 4. Sustainable Environment, co-financed by the Republic of Slovenia, the Ministry of Higher Education, Science and Innovation, and the European Union through NextGenerationEU and the Recovery and Resilience Facility. The broader educational interpretation presented in this paper was also supported by the SKILL2SUSTAIN project, "Boosting Digital and Green Skills for a Resilient and Sustainable Western Balkan Society," project no. 101178204, funded by the Erasmus+ Programme.

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Digital Campus and Green Infrastructure Through a 3D Virtual Tour of the Botanical Garden of the University of Banja Luka

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Abstract

The digital transformation of the educational process and the development of green competences imply the application of modern digital technologies that improve the educational process and provide new ways of presentation and use of space. The paper presents the concept of a digital campus through the creation of an interactive 3D virtual tour of the Botanical Garden of the University of Banja Luka as an example of the integration of green infrastructure and modern technologies.

The virtual tour was created using the Matterport Pro3 camera and LiDAR technology, based on which a three-dimensional model of a selected part of the Botanical Garden was developed. MatterTags with educational content about plant species are integrated into the digital model, as well as student architectural interventions realized within the "Green Urban Room" project.

The results show that the developed virtual tour enables an interactive introduction to the space, access to educational content and digital presentation of student projects in a unique environment. At the same time, it supports the teaching of geodesy, architecture and construction and contributes to the development of students' digital and green competencies.

The proposed concept shows the possibilities of applying 3D virtual environments in education, promotion of the university campus and preservation of green infrastructure, thereby contributing to the goals of the Erasmus+ project SKILL2SUSTAIN.

Keywords

Digital campus, green infrastructure, virtual tour, 3D documentation, geodesy, sustainable development.

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1. Introduction

The rapid development of digital technologies has significantly transformed teaching and learning processes in higher education. The use of modern digital tools expands the possibilities of teaching methods, enables easier access to information and the development of new learning models based on interactive work. An important role in engineering education is occupied by technologies for collecting, processing and visualizing spatial data, which provide students with the opportunity to develop the knowledge and skills necessary to work in a digital environment [1,6,8,9,10,11,12].

The concept of sustainable development and environmental preservation has become an unavoidable topic of modern society. Green infrastructure contributes to the preservation of biodiversity, improvement of environmental quality and sustainable spatial planning, while university campuses represent a suitable environment for connecting education, research and sustainable development [2,3].

The development of technologies for 3D documentation of spaces, virtual tours, digital twins and interactive digital platforms enables new approaches to the presentation and use of spaces in education. Such solutions increase the availability of educational content, encourage the development of digital and green competencies and enable more efficient interdisciplinary learning [4,5,8,9,10,11,12].

This research was carried out as part of the Erasmus+ project SKILL2SUSTAIN to strengthen digital and green skills for a more resilient and sustainable society in the Western Balkans, which aims to improve educational programs, develop innovative teaching content and strengthen cooperation between the academic community and relevant stakeholders.

The aim of this paper is to present the concept of a digital campus through the creation of an interactive 3D virtual tour of a part of the Botanical Garden of the University of Banja Luka. The developed solution integrates digital space documentation technologies, educational content and principles of sustainable development into a unique platform intended for students, teachers and the general public.

2. Study Area

The research was conducted at the location of the University Campus in Banja Luka, with a special focus on the Botanical Garden as a recognizable example of green infrastructure within the university area. The botanical garden combines natural values and student architectural interventions, thus representing a suitable environment for the application of modern 3D documentation technologies and the creation of an interactive virtual tour.

2.1. University Campus in Banja Luka

The campus of the University of Banja Luka is a central university complex that houses faculties, research centers, laboratories and supporting infrastructure. In addition to the educational and scientific function, the campus has significant green areas that contribute to the quality of the environment and create a suitable environment for practical teaching and research work.

The Botanical Garden occupies a special place within the campus, which represents a valuable space for the study of plant species, biodiversity and the principles of sustainable management of green infrastructure.



Figure 1 *– Location of the Botanical Garden within the University of Banja Luka Campus. The red outline indicates the boundary of the Botanical Garden*

2.2. Botanical Garden

The botanical garden was chosen as a research location for the purposes of developing a digital campus and promoting green infrastructure. The research included a part of the Botanical Garden where student architectural interventions and educational content were implemented, and because of its functional and educational value, it was chosen for the development of an interactive virtual tour (Figure 2).



Figure 2 *– Panoramic view of the selected study area within the Botanical Garden of the University of Banja Luka, showing the green infrastructure documented for the development of the interactive 3D virtual tour*

In the researched area, 3D documentation was carried out using a Matterport Pro3 camera, which created a detailed three-dimensional model that represents the basis for creating an interactive virtual tour. The tour enables an overview of the space from the user's

perspective, free movement through the digitized part of the Botanical Garden and access to information about individual contents.

2.3. Student Architectural Interventions

An important part of the virtual tour is the architectural interventions that were created as part of the semester project of architecture students on the subject Studio project 6, realized in cooperation with the APLE laboratory and the Institute for Genetic Resources of the University of Banja Luka. The project was aimed at creating a "green urban room" through a series of spatial interventions designed in accordance with the principles of sustainability, preservation of the natural environment and reversible construction.

The special value of the project is reflected in its interdisciplinary character. Students of architecture, civil engineering and geodesy participated in its realization, with geodesy students involved in geodetic measurements and leveling of the derived elements. The theoretical knowledge acquired in this way was applied in real space, with the connection of different engineering disciplines through joint work on a concrete project.



Figure 3 *– Wooden pavilion designed and constructed by architecture students as part of the interdisciplinary "Green Urban Room" project and later integrated into the virtual tour*

By digitizing the performed spatial interventions and integrating them into a 3D virtual tour, a unique digital display was created that unites the natural environment, student projects and modern spatial documentation technologies.

3. Methodology

The research methodology included the application of modern 3D spatial documentation technologies, the creation of a digital model of the Botanical Garden, the development of an interactive virtual tour, the integration of educational digital content and the inclusion of student projects in a single digital environment. The course of the research is presented in the following subsections.

3.1. Matterport Pro3

For three-dimensional documentation of a selected part of the Botanical Garden, a Matterport Pro3 camera was used, intended for fast and precise collection of spatial data using LiDAR technology [4,7]. The device allows for the simultaneous collection of geometric

data and highresolution photographs, which are automatically integrated into a single three-dimensional spatial model.



Figure 4 *– Matterport Pro3 camera used for 3D scanning of the selected section of the Botanical Garden*

Matterport Pro3 was chosen due to its ability to efficiently document open spaces, high accuracy of 3D reconstruction and simple integration with the platform for creating interactive virtual tours. The application of LiDAR technology allows for reliable determination of spatial relationships between objects and vegetation, which results in a realistic digital representation of the research area.

3.2. 3D Spatial Documentation

Before the fieldwork began, a tour of the Botanical Garden was conducted and the scope of the area that would be the subject of 3D documentation was defined. For the research, a part of the Botanical Garden was selected that includes representative elements of green infrastructure, student architectural interventions and educational content planned for integration into the virtual tour.

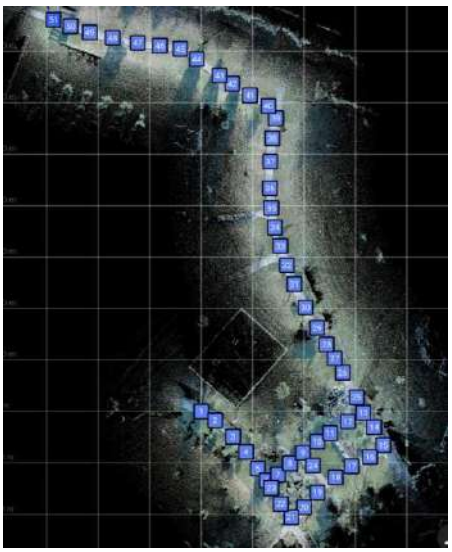


Figure 5 *– Layout of the 51 scan positions used for 3D documentation of the selected section of the Botanical Garden, illustrating the spatial distribution of scan locations and the overlap required for accurate 3D reconstruction.*

The planning of the recording included determining the optimal arrangement of camera positions to ensure sufficient overlap between successive scans and complete coverage of the space. The Matterport Pro3 camera was successively placed at predefined locations, with LiDAR data and high-resolution panoramic photographs being collected simultaneously at each position [4,7].

A total of 51 scans were performed during the fieldwork, the arrangement of which is shown in Figure 5. The collected data were automatically connected into a single three-dimensional model, which represents the basis for further processing and the creation of an interactive virtual tour.

The arrangement of the scans was adjusted to the configuration of the pedestrian paths, the arrangement of vegetation and the position of the student architectural interventions. The scanning positions are determined to ensure continuous overlap between adjacent scans, stable data registration, and smooth navigation through the entire virtual tour space [4,7].

3.3. Creation of 3D Models and Virtual Tours

After the field survey was completed, the collected data was automatically transferred to the Matterport Cloud platform, where it was processed and connected into a single three-dimensional spatial model. The platform automatically registers individual scans, integrates LiDAR data and high-resolution panoramic photographs, and generates a photorealistic digital representation of the documented space [4].

The result of the processing is a detailed 3D model of the Botanical Garden that allows for a view of the space from different perspectives, Figure 6. The model also allows navigation from the user's perspective, which is the basis for creating an interactive virtual tour [4].

Based on the created model, an interactive virtual tour was created that allows for free movement through the space, viewing individual locations, and integration of educational content via MatterTags. The virtual tour is a central element of the developed digital campus concept and the basis for further integration of plant species, student architectural interventions, and other multimedia content.



(a) *(b)*

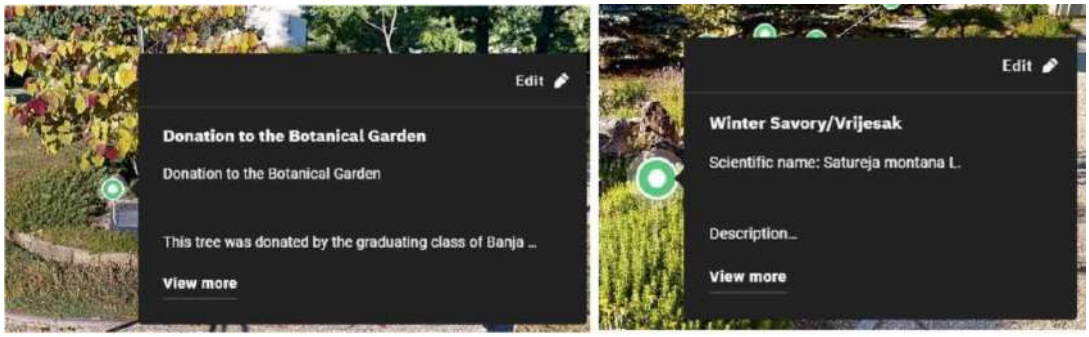
***Figure 6** – Three-dimensional model of the selected section of the Botanical Garden generated in Matterport Cloud, showing (a) the top view and (b) the Dollhouse View, demonstrating the complete digital reconstruction of the study area based on 51 LiDAR scans*

3.4. Integration of Educational Content Using Mattertags

After creating the three-dimensional model and virtual tour, educational digital content was integrated using the MatterTags functionality, which allows connecting individual locations in the virtual space with additional information. MatterTags are interactive information points that allow users to access text, image and other multimedia content during the virtual tour [4].

MatterTags were created for selected plant species, containing the plant name, Latin name, photos and a basic description of the species, including the most important botanical characteristics and information about its significance. In this way, the user can simply select a tag to access educational content without leaving the virtual environment.

The concept was developed in such a way that it allows for easy expansion of existing content by adding new plant species, photos, text descriptions, internet links and other multimedia materials. This makes the virtual tour a dynamic digital platform that can be continuously updated in accordance with the needs of teaching, promotion of the Botanical Garden and future research activities.



(a) *(b)*

***Figure 7** – Integration of educational content using MatterTags: (a) distribution of interactive MatterTags throughout the virtual tour and (b) an example of a MatterTag providing botanical information, images, and educational content for a selected plant species*

3.5. Integration of Student Projects

One of the significant possibilities of the developed virtual tour is the integration of student architectural interventions realised in the Botanical Garden as part of the "Green Urban Room" project. The three-dimensional model includes selected elements of the space, such as a wooden pavilion, a stone wall (bench) and other performed interventions, which enables their permanent digital documentation and interactive presentation.

The display of student projects within the virtual tour allows users to access information about the concept, authors and purpose of individual architectural interventions during the tour. In this way, the virtual tour is not only a digital representation of the space, but also a platform for the promotion of student works and examples of good practice in the fields of architecture, construction and geodesy, Figure 8.

By integrating the natural environment, student architectural projects and educational digital content, a modern tool has been developed that contributes to the improvement of the teaching process and field teaching

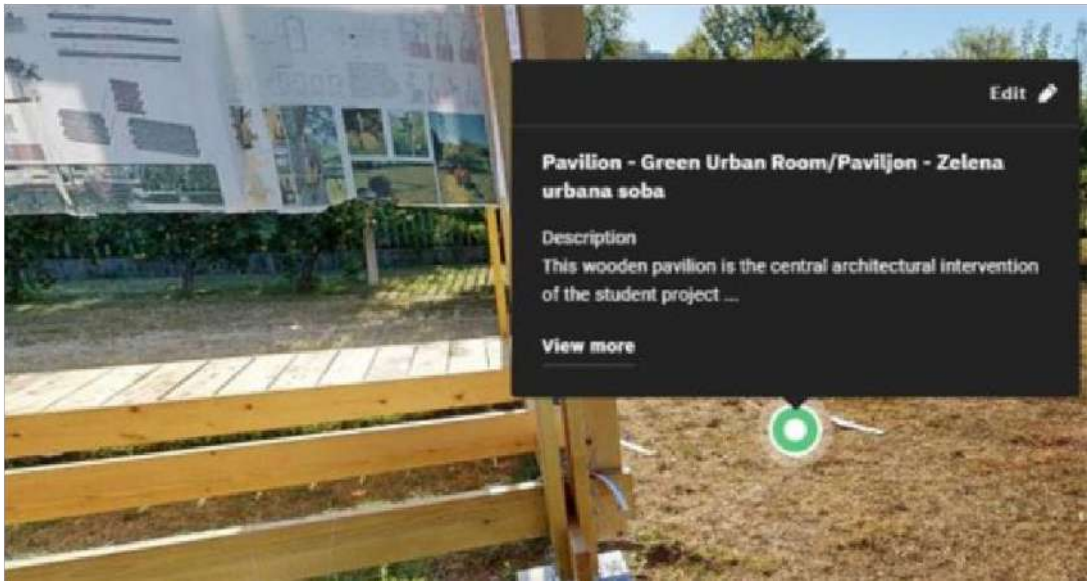


Figure 8 *– Student architectural interventions integrated into the virtual tour, demonstrating the digital presentation of the "Green Urban Room" project within the immersive 3D environment.*

4. Results and Discussion

Using the Matterport Pro3 camera, 3D documentation of a selected part of the Botanical Garden of the University of Banja Luka was carried out. On the basis of the collected data, a threedimensional model of the space and an interactive virtual tour were created, which enables an overview of the space, free navigation and spatial orientation.

The virtual tour includes MatterTags with basic information about plant species, as well as student architectural interventions realized within the "Green Urban Room" project. Thus, natural and built elements are united in a unique digital environment.

The developed virtual tour can be used in the teaching of geodesy, architecture and civil engineering as a support for field teaching, practical exercises and independent learning. At the same time, it contributes to the development of digital and green competences of students and confirms the possibilities of applying modern technologies in education, in accordance with the goals of the Erasmus+ project SKILL2SUSTAIN [1,5,6,8,9,10,11,12]. The complete interactive virtual tour developed as part of this research can be accessed through the following Matterport link: https://my.matterport.com/show/?m=j3BDEaQjSdM

5. Conclusion

The paper presents the creation of an interactive 3D virtual tour of the Botanical Garden of the University of Banja Luka using Matterport Pro3 technology. The virtual tour combines a digital display of space, educational content about plant species and student architectural interventions into a unique platform intended for education and promotion of the university campus.

The results show that this approach can improve the teaching process, encourage the development of digital and green competencies of students, and support interdisciplinary cooperation between geodesy, architecture, construction and related fields. The developed

platform enables further upgrading with new contents and represents the basis for the future development of the digital campus.

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Digital Maturity Assessment Tool for SMEs: A Service-Oriented Approach Within the InnDigit Project

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Abstract

Digital transformation is increasingly recognised as a critical driver of competitiveness, resilience, and innovation in small and medium-sized enterprises (SMEs). While SMEs constitute the backbone of the Western Balkan economy, they face persistent barriers to digitalisation, including limited financial resources, skills shortages, and inadequate institutional support. This paper presents the development and pilot testing of the InnDigit digital maturity assessment tool, designed to evaluate SME readiness across four dimensions: infrastructure, processes, skills, and innovation capacity. Embedded within the InfoBiz PKRS platform of the Chamber of Commerce and Industry of Republika Srpska, the tool combines self-assessment functionalities with aggregated policy insights, thereby operationalising international frameworks such as DESI and OECD models in a local context. Pilot testing with ten SMEs across manufacturing, services, and trade sectors revealed sector-specific strengths and weaknesses, with manufacturing firms excelling in process integration, service firms demonstrating innovation potential, and trade firms remaining at basic infrastructure readiness. Common challenges included cybersecurity vulnerabilities, workforce ICT training gaps, and financing barriers. These findings are discussed in relation to existing literature on SME digitalisation, highlighting both the tool's contribution to the regional SME support ecosystem and its potential for replication across the Western Balkans. Future research should expand testing, integrate financing and training instruments, and incorporate advanced indicators such as cybersecurity resilience and sustainability metrics.

Keywords

Digital maturity, SMEs, innovation, ICT tools, InfoBiz PKRS, InnDigit project.

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1. Introduction

Digitalisation has emerged as a decisive factor for the competitiveness and resilience of small and medium-sized enterprises (SMEs). Globally, SMEs account for the majority of enterprises and employment, yet they often face structural barriers to adopting digital technologies, including limited financial resources, skills shortages, and inadequate infrastructure (OECD, 2023; World Bank, 2022). In the Western Balkans, where SMEs represent over 99% of enterprises, these challenges are particularly acute, contributing to slower progress in digital transformation compared to EU averages (European Commission, 2025).

Academic research underscores that digitalisation enables SMEs to enhance productivity, access new markets, and foster innovation-driven growth. However, the heterogeneity of SME needs requires tailored approaches that go beyond macro-level indicators such as the Digital Economy and Society Index (DESI). Locally adapted tools are necessary to translate policy objectives into operational guidance for SMEs, especially in transition economies where institutional support structures remain fragmented.

This paper presents the development and pilot testing of the InnDigit digital maturity assessment tool, designed to evaluate SME readiness across four dimensions: infrastructure, processes, skills, and innovation capacity. Embedded within the InfoBiz PKRS platform of the Chamber of Commerce and Industry of Republika Srpska, the tool combines self-assessment functionalities with aggregated policy insights. By situating the tool within the broader academic and policy discourse, this study contributes to understanding how digital maturity frameworks can be adapted to local SME realities in the Western Balkans.

2. Background and Context

The InfoBiz PKRS platform was co-financed by the EU and Germany, to support SMEs during the COVID-19 crisis. It offers information on regulations, financing, and chamber activities.

Building on this base, the InnDigit project added a digital maturity assessment module. The aim: SMEs had access to information but lacked a structured way to gauge digital readiness and innovation potential.

The tool was designed to:

- Provide a self-assessment interface.
- Generate tailored digital transformation recommendations.
- Enable the Chamber to aggregate data for policy and programme design.

3. Literature Review

3.1. Importance of Digitalisation for SMEs

Digitalisation has become a critical determinant of SME competitiveness, resilience, and innovation. Studies highlight that SMEs adopting digital tools achieve higher productivity, improved market access, and greater adaptability to external shocks (OECD, 2023; World Bank, 2022). In transition economies, digitalisation is also linked to integration into global value chains and enhanced export potential (European Commission, 2025).

3.2. Barriers to SME Digitalisation

Despite its importance, SMEs face persistent barriers to digital transformation. Common challenges include:

- Financial constraints: Limited access to affordable financing for ICT investments (OECD, 2023).
- Skills shortages: Workforce ICT competencies remain underdeveloped, particularly in smaller firms without dedicated IT departments (European Commission, 2020).
- Infrastructure gaps: Inadequate connectivity and outdated hardware hinder adoption (BMWi, 2022).
- Leadership and strategy: Many SMEs lack digital strategies or leadership commitment, resulting in fragmented adoption (World Bank, 2022).

Recent studies emphasise that SMEs in transition economies often lack structured investment planning and digital strategies, which constrains their ability to move beyond basic infrastructure readiness (Barker, 2021; EU4DigitalSME, 2023).

3.3. Opportunities and Enablers

Conversely, digitalisation offers SMEs opportunities to innovate, expand markets, and improve efficiency. E-commerce adoption, ERP/CRM integration, and supply chain digitalisation are identified as key enablers (OECD, 2023). Public programmes such as Digital Europe and EU4BusinessRecovery emphasise accessible tools and training as catalysts for SME transformation (European Commission, 2025).

3.4. Digitalisation in the Western Balkans

The Western Balkans present a mixed picture. National strategies often prioritise digitalisation, yet operational instruments for SMEs remain limited (OECD, 2023). Research shows that SMEs in the region lag behind EU averages in connectivity, ICT skills, and innovation capacity (World Bank, 2022). Bosnia and Herzegovina, in particular, faces fragmented support structures, with chambers of commerce playing a central role in bridging policy and practice (EU Delegation, 2024).

A recent EU4DigitalSME assessment of SMEs in Bosnia and Herzegovina confirmed these challenges, noting that firms scored lowest in areas such as ICT training, financing, and integration of advanced technologies like cloud computing and robotics (EU4DigitalSME, 2023). The report emphasizes that many SMEs lack structured digital strategies, which constrains their ability to move beyond basic infrastructure readiness.

3.5. Contribution of SME-Specific Tools

Several frameworks have been proposed to measure SME digital maturity, including the DESI, Digital Transformation Scoreboard, and SME Digitalisation Compass. However, these models often fail to capture the realities of SMEs in transition economies. Locally adapted tools, such as the InnDigit project, contribute by combining self-assessment with aggregated policy insights, thereby operationalising international frameworks in a regional context (Local ICT Company, 2025).

4. Materials and Methods

4.1. Tool Architecture

The InnDigit digital maturity assessment tool was developed by a local ICT company using a **service-oriented architecture**. It was integrated into the existing *InfoBiz PKRS* platform. The architecture consists of three layers:

- **Database layer**: structured storage of SME profiles, assessment results, and sectoral benchmarks.
- **Application layer**: algorithms for scoring, recommendation generation, and benchmarking.
- **User interface layer**: dashboards and self-assessment forms accessible via the InfoBiz PKRS portal.

4.2. Indicator Framework

The tool evaluates SME digital maturity across four dimensions (see Table 1):

- **Infrastructure**: connectivity, hardware availability, cybersecurity measures.
- **Processes**: integration of ERP/CRM systems, e-commerce adoption, supply chain digitalisation.
- **Skills**: workforce ICT competencies, training programmes, leadership engagement.
- **Innovation capacity**: ability to develop new digital products/services, R&D activity.

Indicators were selected based on OECD recommendations, EU DESI categories, and local SME needs identified through chamber consultations.

***Table** 1 – Digital Maturity Indicators Framework.*

Dimension	Indicators	Analytical Relevance
Infrastructure	Connectivity, hardware, cybersecurity	Baseline readiness for digitalisation
Processes	ERP/CRM use, e-commerce, supply chain tools	Integration of digital tools in operations
Skills	Workforce ICT skills, training programmes	Human capital for digital transformation
Innovation	New digital products/services, R&D capacity	Potential for innovation-driven growth

4.3. Data Collection

Pilot testing involved **10 SMEs** from manufacturing, services, and trade sectors. Data was collected through:

- Online self-assessment questionnaires completed by SMEs.
- Semi-structured interviews with SME managers.
- Validation by chamber staff to ensure consistency and accuracy.

4.4. Testing Procedure

The testing process followed three steps:

- **Initial assessment**: SMEs completed the tool's questionnaire and received preliminary scores.
- **Validation**: chamber staff reviewed responses and adjusted indicators where necessary.
- **Feedback loop**: SMEs provided feedback on usability, clarity of recommendations, and relevance of indicators.

4.5. Analytical Methods

Results were aggregated to identify sectoral trends and common gaps. Statistical analysis focused on average scores, variance across sectors, and correlation between infrastructure readiness and innovation capacity. The tool also generated benchmarking dashboards to compare SMEs against sector averages.

5. Results

5.1. Profile of Participating SMEs

The pilot study involved 10 SMEs from three sectors:

- Manufacturing (4 firms): medium-sized enterprises engaged in metal processing, food production, and furniture manufacturing.
- Services (3 firms): small IT consultancies, marketing agencies, and professional service providers.
- Trade (3 firms): micro and small enterprises in wholesale and retail distribution.

This distribution reflects the structural composition of SMEs in Republika Srpska, where manufacturing remains dominant, but services and trade are increasingly relevant for employment and growth (OECD, 2023).

5.2. Sectoral Digital Maturity Scores

Average scores across the four dimensions (Infrastructure, Processes, Skills, Innovation) revealed sector-specific strengths and weaknesses (see Table 2).

- Manufacturing SMEs (avg. 65): Strong in process integration (ERP/CRM adoption, supply chain digitalisation). Weaknesses in cybersecurity and financing, consistent with OECD findings that manufacturing firms often prioritise operational efficiency but underinvest in ICT security.
- Service SMEs (avg. 72): Highest scores in innovation capacity, particularly in developing new digital services. However, they reported skills shortages, echoing World Bank (2022) evidence that service firms in transition economies struggle with structured ICT training.

- Trade SMEs (avg. 58): Basic infrastructure readiness (connectivity, hardware), but limited adoption of advanced processes. This mirrors EU (2025) studies showing retail SMEs lag in digital transformation compared to other sectors.

5.3. Relationships Between Sector and Digitalisation

The analysis suggests clear sectoral patterns:

- Manufacturing → Process-driven digitalisation: Adoption of ERP/CRM systems is linked to production efficiency.
- Services → Innovation-driven digitalisation: Service firms leverage digital tools to create new offerings, but lack workforce training.
- Trade → Infrastructure-dependent digitalisation: Retail firms remain at early stages, with digitalisation largely limited to connectivity and basic online presence.

These relationships align with international literature: manufacturing firms often lead in structured process adoption (OECD, 2023), while service firms show higher innovation potential but face human capital constraints (World Bank, 2022). Trade firms, particularly in the Western Balkans, remain digitally underdeveloped (EU Delegation, 2024).

5.4. Common Gaps Across SMEs

Three cross-cutting challenges emerged:

- Cybersecurity gaps: Few SMEs had structured protocols, consistent with EU reports on SME vulnerability.
- Skills shortages: Workforce ICT training was limited, constraining adoption.
- Financing barriers: SMEs reported difficulties accessing funds for digitalisation, echoing OECD findings on financing constraints in transition economies.

5.5. Interpretation Through Maturity Stages

SMEs were mapped against a five-stage maturity model:

- Digitally Present: Trade firms with basic online presence.
- Digitally Active: Manufacturing firms integrating ERP/CRM.
- Digitally Engaged: Service firms experimenting with new digital services.

None of the SMEs reached the Digitally Competitive or Digitally Mature stages, underscoring the need for systemic support.

6. Discussion

The pilot testing of the InnDigit digital maturity assessment tool highlights both the strengths and limitations of SME digitalisation in Republika Srpska. The tool's integration into the *InfoBiz PKRS* platform ensures accessibility for SMEs and sustainability for the Chamber, while its structured indicator framework provides actionable insights at both enterprise and policy levels.

6.1. Contribution to SME Digitalisation Research

The pilot testing of the InnDigit tool provides empirical evidence on the state of SME digitalisation in Republika Srpska. By systematically assessing infrastructure, processes, skills, and innovation capacity, the tool operationalises international frameworks (OECD, DESI, SME Digitalisation Compass) within a local context. This dual function — offering self-assessment for enterprises and aggregated insights for institutions — represents a significant contribution to the SME support ecosystem. It demonstrates how chambers of commerce can act as intermediaries, translating policy objectives into actionable instruments for SMEs, a role highlighted in OECD (2023) studies on SME ecosystems in transition economies.

6.2. Sectoral Insights and Literature Alignment

The sectoral differences observed in the pilot study align with broader academic findings:

- Manufacturing firms showed stronger process integration, consistent with OECD evidence that production-oriented SMEs are more likely to adopt ERP/CRM systems to improve efficiency.
- Service firms demonstrated higher innovation capacity, reflecting World Bank (2022) findings that service SMEs often leverage digitalisation to create new offerings, though they remain constrained by workforce ICT skills.
- Trade firms remained at basic infrastructure readiness, echoing EU (2025) reports that retail SMEs in the Western Balkans lag behind in adopting advanced digital processes.

These results reinforce the heterogeneity of SME digitalisation pathways and the need for sector-specific support measures.

6.3. Common Barriers in Regional Context

The cross-cutting challenges identified — cybersecurity gaps, skills shortages, and financing barriers — are consistent with international literature. OECD (2023) emphasises that SMEs in emerging economies often lack structured cybersecurity protocols, while EU4BusinessRecovery (2024) highlights financing constraints as a systemic barrier. The skills gap observed in service firms mirrors findings from the Digital Transformation Scoreboard (European Commission, 2020), which stresses the importance of workforce training as a prerequisite for digital adoption.

These findings are consistent with the EU4DigitalSME (2023) assessment, which highlighted that SMEs in Bosnia and Herzegovina often struggle with internal equipment maintenance, workforce ICT competencies, and access to affordable financing. The report further recommends targeted training programmes and stronger collaboration between chambers, academia, and support organisations to accelerate SME digitalisation.

6.4. Policy and Practical Implications

The aggregated insights from the pilot study provide actionable evidence for policy makers and business support organisations. Specifically:

- Cybersecurity: Development of SME-focused cybersecurity training and protocols.

- Skills: Integration of ICT training into vocational and lifelong learning programmes.
- Financing: Expansion of targeted financial instruments to support SME digitalisation.

Embedding the tool within the InfoBiz PKRS platform ensures sustainability and accessibility, while its scalability offers potential for replication across the Western Balkans. This could establish regional benchmarks and foster cross-country learning, contributing to the EU's broader digitalisation agenda.

6.5. Limitations and Future Research

The pilot study's scope — limited to 10 SMEs — restricts the generalisability of findings. A larger, more diverse sample is necessary to validate sectoral patterns and strengthen statistical analysis. Furthermore, while the tool identifies gaps, it does not directly provide solutions in financing or training. Future work should integrate these instruments into the platform, alongside advanced indicators such as cybersecurity resilience and sustainability metrics. Comparative studies across Western Balkan economies would also enrich understanding of regional digitalisation trajectories.

7. Conclusion

This study examined the design and pilot testing of the InnDigit digital maturity assessment tool, situating its contribution within the academic literature on SME digitalisation. By adapting international frameworks to local realities, the tool provides actionable insights for both enterprises and institutions. The pilot study revealed sectoral differences and systemic barriers, underscoring the importance of targeted support for SMEs in transition economies.

Future research should expand the sample size, integrate financing and training instruments, and incorporate advanced indicators such as cybersecurity resilience and sustainability metrics. Comparative studies across the Western Balkans would further enrich understanding of SME digitalisation trajectories and support the establishment of regional benchmarks. Structured digital maturity assessment thus represents a critical step toward building a more resilient, innovative, and competitive SME sector in Bosnia and Herzegovina and beyond.

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GIS-Based Approach for the Retrofitting of Residential Buildings for Energy Efficiency: A Case Study of Prijedor

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Abstract

The decarbonisation of the building sector requires spatially explicit, transparent and operational tools that can support both public authorities and end users in prioritising energy renovation measures. This paper presents a geoportal application developed for the assessment of energy-efficiency measures in multi-apartment buildings in the City of Prijedor, Bosnia and Herzegovina. The geoportal integrates architectural, spatial, energy and economic attributes for all 351 multi-apartment buildings recorded in Prijedor by October 2022. Buildings are classified according to national residential-building typology, construction period, geometry, envelope characteristics and heating-system type. The application provides building-level indicators for the existing state and for predefined renovation packages applied to the building envelope and, where relevant, to the heating system. The methodological framework combines field survey, typological classification, GIS-based spatial modelling, a service-oriented geoportal architecture and an economic calculator implemented at database level. The results demonstrate that such an integrated platform can make renovation benefits understandable to citizens while giving local authorities, utilities and policy makers a city-scale basis for estimating investment needs and identifying priority buildings. The scientific contribution of the work is twofold: first, it provides the first comprehensive typological, energy and economic analysis of the complete multi-apartment building stock of Prijedor; second, it develops a transferable database-driven calculation model for linking spatial building information with energy and cost-effectiveness indicators. The approach is aligned with contemporary European policy directions on building-stock decarbonisation, energy-efficiency obligations and data-driven renovation planning.

Keywords

Geoportal, energy efficiency, spatial data infrastructure, multi-apartment buildings, building renovation, energy savings, cost-effectiveness, GIS, Bosnia and Herzegovina.

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1. Introduction

The built environment is a central field of action for urban decarbonisation because buildings are long-lived assets, their energy performance is strongly conditioned by construction period and envelope quality, and their renovation requires coordinated technical, financial and institutional decisions. At city scale, the identification of priority renovation actions is rarely a purely technical problem. It also depends on spatial distribution, building typology, ownership structure, heating-system availability, investment capacity and the ability of public institutions to communicate evidence-based options to citizens and building users.

In this context, geospatial information has become an important infrastructure for energy planning. Spatial Data Infrastructure (SDI) provides the institutional, technological and methodological framework for discovering, evaluating, sharing and using geospatial data among public authorities, data providers, professionals and citizens [1]-[3]. In the field of building-stock decarbonisation, SDI concepts are increasingly relevant because building-level energy indicators can be linked with location, morphology, heating networks, cadastral data and socio-economic information.

In this paper, energy intensity is used as an interpretative concept that helps position building-stock renovation within wider decarbonisation and resource-efficiency objectives (Figure 1).

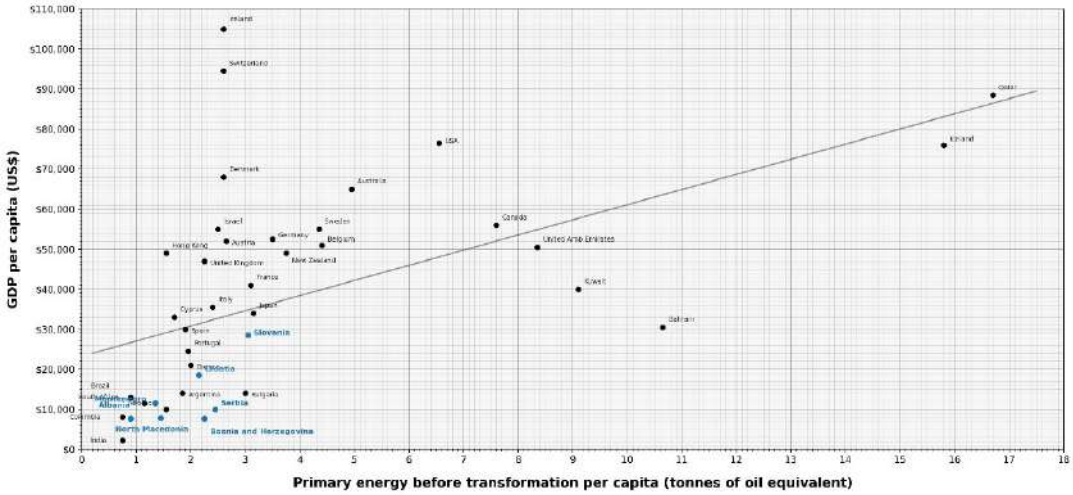


Figure 1 *– Energy intensity expressed through the relationship between GDP per capita and primary energy before transformation per capita (countries of the Skill2Sustain project consortium marked in blue). Source: IEA and World Bank indicators (2022).*

Recent European policy further strengthens the need for transparent and data-driven renovation planning. The recast Energy Efficiency Directive establishes a renewed common framework for energy-efficiency measures and a strengthened 2030 target [11]-[14].

For Bosnia and Herzegovina, the strategic and legislative context of building renovation is shaped by national energy and climate documents and long-term energy strategy documents [19], [20]. These documents define energy efficiency as a prerequisite for reducing final and primary energy consumption, increasing energy-security resilience, lowering greenhouse-gas emissions and aligning the building sector with the European decarbonisation pathway. In the Republic of Srpska, the rulebook on minimum energy-performance requirements provides the basis for assessing the energy performance of buildings [10]. At the same time, renovation strategies emphasise the need for systematic assessment of the existing building stock, prioritisation of cost-effective measures and mobilisation of investment for both public and residential buildings [9], [19].

The City of Prijedor geoportal for energy-efficiency measures in multi-apartment buildings responds to these challenges by integrating field-based building assessment, typological classification, energy calculation and economic evaluation in a web-based GIS environment. The aim of this paper is to present the methodological framework, system architecture and analytical contribution of the geoportal application.

2. Materials and Methods

2.1. Study Object and Scope of Analysis

The research covers the entire multi-apartment residential building stock of the City of Prijedor recorded by October 2022, amounting to 351 buildings. The assessment was designed to identify all relevant buildings, assign them to a typological and construction-period category, collect spatial and architectural attributes, evaluate energy characteristics and calculate the effects of selected improvement measures. The work is based on a multidisciplinary approach involving expertise in geodesy, architecture, mechanical engineering, economics and information technologies, with a shared focus on energy efficiency in buildings.

The typological framework was derived from the Residential Building Typology of Bosnia and Herzegovina [4], while the renovation measures were formulated in relation to European energy-efficiency policy, cost-optimal methodology and the observed state of the buildings [5], [6], [11]-[13]. The building stock was classified according to the national typology into the following multi-apartment building types: MH - multi-apartment buildings; AB1 - perimeter-block buildings; AB2 - large residential blocks and H - high-rise buildings with more than eight storeys. In addition to building type, the stock was divided into six construction periods and other classification (Table 1).

Table 1 *– Classification logic used in the geoportal.*

Dimension	Classes	Analytical relevance
Building type	MH, AB1, AB2, H	Envelope exposure, compactness and representative energy-calculation parameters
Construction period	<1960; 1961-1970; 1971-1980; 1981-1991; 1992-2014; >2014	Construction technology, assumed thermal properties and renovation eligibility
Heating system	District-heated buildings; buildings not connected to district heating	Selection of heating-system improvement scenario and energy/economic indicators
User category	Standard/public users; registered/advanced users	Fixed indicators for public use and editable economic assumptions for advanced analysis

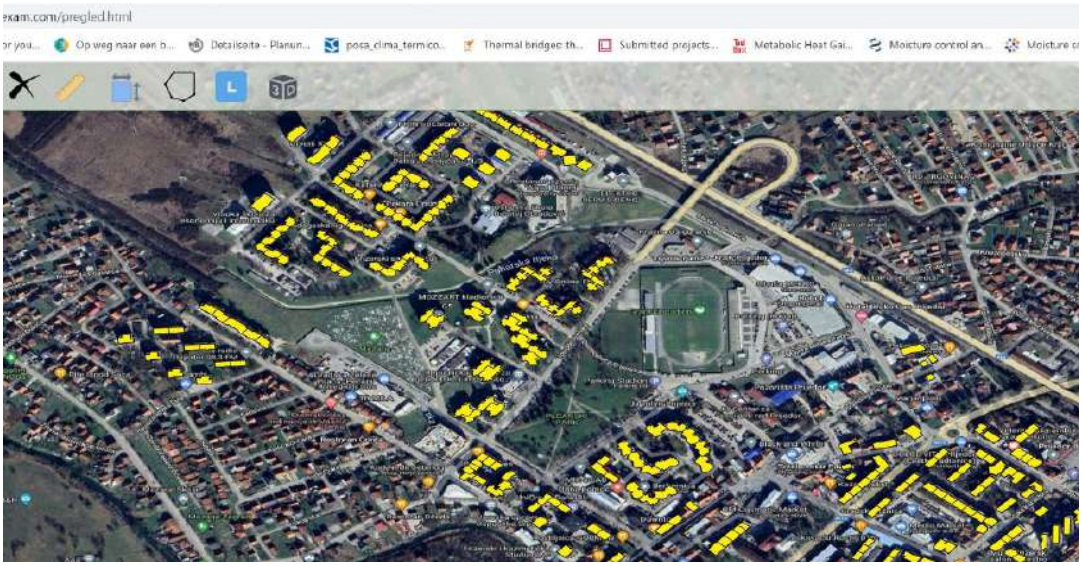
2.2. Data Acquisition, Indicators and Geoportal Architecture

The database was created through the combined use of existing documentation, field survey and expert interpretation. Field work covered 351 buildings and was used to verify or supplement available records. The survey identified building geometry, storey number,

footprint, envelope characteristics, roof and floor assumptions, heating-system type and other parameters required for energy and economic calculations. The procedure was necessary because available documentation did not fully correspond to the observed building stock; several buildings constructed after the reference documentation had to be added and spatially characterised.

The spatial component of the research is not only a background database but the main operational environment for decision support. The 2D and 3D interfaces enable users to locate buildings, compare typological and heating-system attributes, and understand the relationship between renovation needs and the urban fabric (Figure 2).

a) 2D spatial interface



b) 3D building-stock view

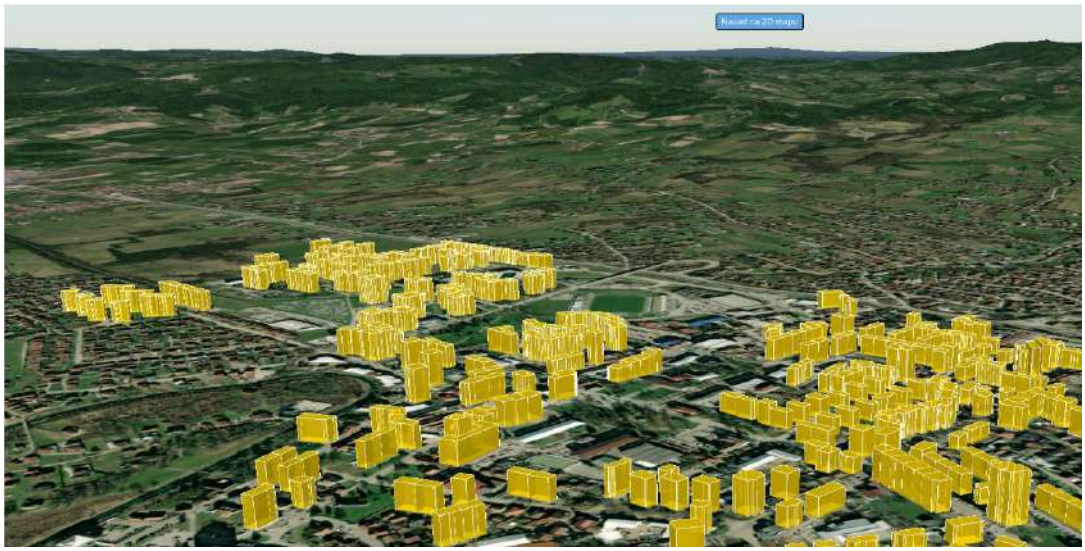


Figure 2 *– GIS visualisation of the Prijedor multi-apartment building stock in the geoportal: 2D spatial interface and 3D building-stock view. Source: Authors*

The geoportal includes a database-level economic calculator implemented through a dedicated SQL library for PostgreSQL. The calculator uses predefined variables and building attributes to determine energy and economic indicators for each building and measure set. The calculated indicators include useful floor area, useful energy demand, delivered energy, primary energy, annual CO2 emissions, specific useful energy demand for heating,

investment cost without and with value added tax, annual net savings, simple payback period, net present value (NPV) and the net present value quotient (NPVQ). Energy and economic indicators were defined after field work and after reviewing relevant institutional documents and previous energy-efficiency projects implemented in Bosnia and Herzegovina [4], [8], [9].

A specific methodological decision concerned windows. Field inspection showed that many users had already replaced original windows. Consequently, window replacement was not included as a separate renovation measure. Instead, the energy calculation treats the windows as new windows with thermal transmittance values aligned with the applicable rulebook on minimum energy characteristics of buildings in the Republic of Srpska [10]. Following SDI principles, the geoportal was developed as a three-tier service-oriented web application. All building attributes are structured in a PostgreSQL database with the PostGIS extension. The middle layer is implemented through GeoServer, which enables communication between the database and the user-facing application via Web Feature Service - Transactional.

The system is aligned with the logic of OGC web-service standards [7], while the broader evolution of web geospatial services is also consistent with the OGC API - Features approach, which standardises the creation, modification and querying of spatial data on the Web [14]. This architecture enables both public visualisation and controlled editing of building attributes by registered users.

3. Results

The geoportal provides a spatially explicit overview of the complete multi-apartment building stock of Prijedor. For each individual building, the application displays location, typological class, construction period and architectural indicators needed for subsequent energy and economic calculations. At aggregate level, registered users can generate graphical summaries of architectural, energy and economic indicators for all buildings, including envelope areas by type and construction period.

At the analytical level, the GIS environment connects individual buildings with aggregated decision-making indicators. This enables the transition from a building-by-building audit to a city-scale renovation logic, where typology, envelope area, heating mode and economic feasibility can be compared spatially (Figure 3).

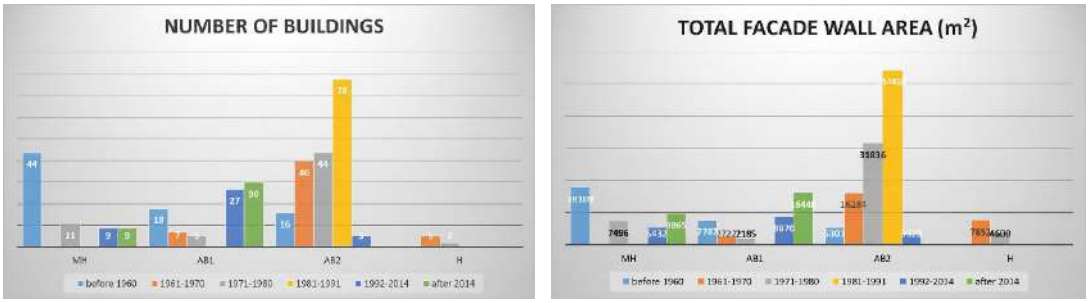
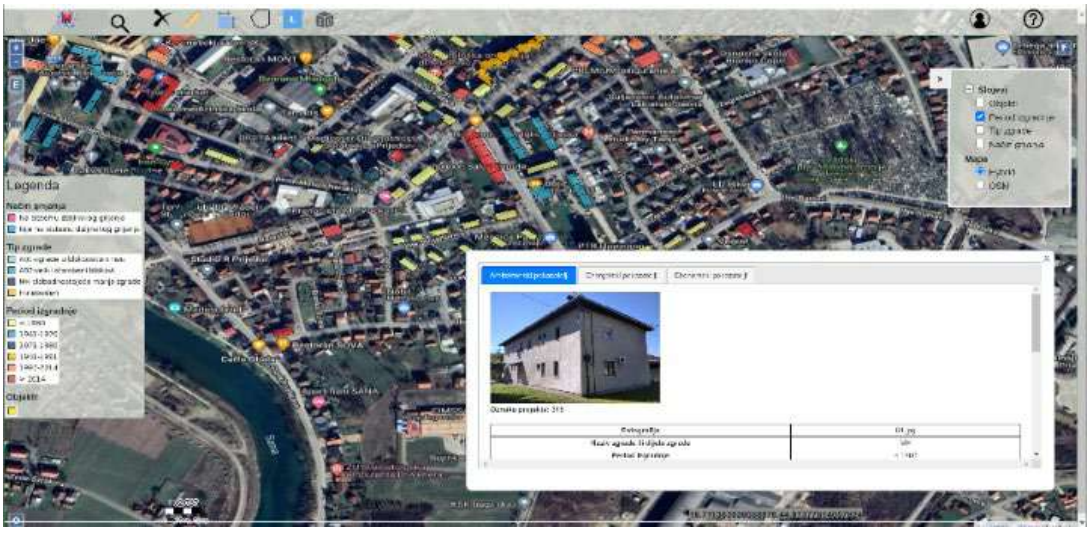


Figure 3 *– Registered-user GIS analytics module used to compare aggregate indicators for building-envelope areas and renovation priorities. Source: Authors.*

The workflow presented to stakeholders also distinguishes between public communication and expert-level updating of the database. Public users can inspect individual buildings and understand the expected effects of renovation measures, while registered users can update attributes, add new buildings and change economic parameters such as energy prices, material prices and interest rates (Figure 4).

a) Public building-level interface



b) Registered-user editing and economic-parameter interface

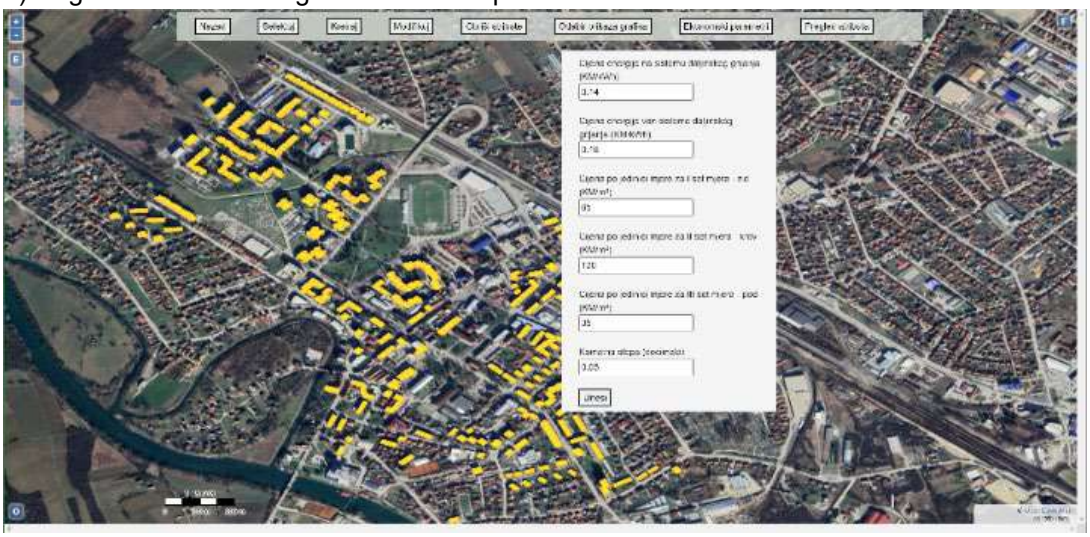


Figure 4 *– Geoportal user workflow: public building-level information and registered-user database editing for updated renovation analysis. Source: Authors.*

For non-registered users, the geoportal allows the visualisation of building content, geospatial queries by available parameters, the loading and overlay of external spatial data and basic map operations such as measurement. This public component is essential because energy renovation often depends on user understanding and acceptance. Presenting renovation benefits at the level of the user's own building makes the information more accessible than aggregated reports.

For registered users, the application contains an advanced module for editing existing building parameters and creating new records according to a predefined schema. Editable parameters include surface areas, building type, geometric dimensions, heating system and selected economic assumptions. Confirmed changes are stored in the system, enabling the geoportal to function as a living database rather than a static publication.

This city-scale view is important for prioritisation. Decision makers need to know not only the energy performance of a typical building, but also how many such buildings exist, where they are located, which envelope components dominate investment needs and whether they are connected to district heating. The geoportal therefore turns a technical building inventory into a planning instrument for local institutions, city administration and public utility companies.

4. Discussion

The tested geoportal offers four envelope-improvement variants: Set I - wall improvement, Set II - roof improvement, Set III - floor improvement and Set IV - combined improvement of walls, roof and floor. After Set IV, one heating-system option is added according to the building category: Set IVa for district-heated buildings, expressed through energy savings, and Set IVb for buildings outside district heating, expressed through both energy and economic indicators.

For each building, the application compares the existing state with renovation variants through useful, final, delivered and primary energy, CO2 emissions, investment with VAT, annual net savings, simple payback period, NPV and NPVQ. Standard users see fixed default values, while registered users can change unit prices, energy prices and interest rates. This is important because price volatility can change the ranking of renovation priorities and the feasibility of individual measures.

The main contribution of the research is the complete typological, spatial, energy and economic analysis of the multi-apartment building stock of Prijedor recorded by October 2022. The second contribution is a database-driven calculation model in PostgreSQL that links spatial attributes with energy and economic indicators and can be adapted for similar municipal geoportals. At the policy and modelling level, this supports data-driven renovation planning and urban energy modelling [15]-[18].

The methodology is suitable for city-scale prioritisation, but it does not replace detailed energy audits before investment decisions for individual buildings. Future work should include calibration with measured energy-consumption data, integration with energy-performance certificates, extension to single-family and public buildings, and inclusion of social vulnerability and life-cycle carbon indicators.

5. Conclusion

This paper presents a geoportal application for energy-efficiency measures in multi-apartment buildings in Prijedor as an operational instrument for urban building-stock decarbonisation. The application combines building typology, field-verified spatial and architectural data, energy-performance indicators and economic evaluation of renovation measures. By providing building-level and aggregate indicators through a web interface, the geoportal makes the purpose and effects of renovation measures more understandable to citizens and more actionable for local authorities.

The research demonstrates that every city requires a context-specific assessment because building typology, construction period, heating systems and user behaviour differ substantially across locations. Nevertheless, the methodological framework developed for Prijedor is transferable: it can support other municipalities in establishing spatially explicit building inventories, evaluating renovation packages and estimating investment needs. The ability of registered users to update economic assumptions further improves the relevance of the tool under unstable market conditions.

Overall, the geoportal contributes to the practical implementation of energy-efficiency policies by translating technical calculations into spatial decision-support information. Its value lies not only in visualising buildings, but in linking the building envelope, heating systems, energy savings, CO2 emissions and investment indicators into a single, maintainable and publicly communicable system.

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How Countries Require BIM for Roads and Railways: Six Approaches

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Abstract

Which countries require BIM (building information modelling) for roads and railways, and how do they do it? Few do so by law. A screening of more than a hundred countries and regions found that binding BIM rules rarely extend to infrastructure and that general BIM laws often leave it out. This paper portrays six countries that do require BIM for road or rail projects, each through a different regulatory mechanism. Lithuania incorporated it into its roads statute. Hungary phases it in through a ministerial decree. Russia attaches it to budget-funded contracts by government decree. Kazakhstan binds it to a ministry list of object types. Germany reached all new federal transport projects through a ministry roadmap and no law at all. Norway's state railway imposes it as a client, through contracts. The regulatory mechanisms differ, and so does the technical detail. The further the rule sits from parliament, the more technical it becomes, from Lithuania's statute, which names no file format, to the Norwegian railway's rulebook, which names IFC 4.3 and validates models by machine.

Keywords

BIM mandate, infrastructure, roads, railways, IFC, open formats.

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1. Introduction

Building information modelling, or BIM, is a collaborative process that uses a data-rich 3D model to design, construct, and manage an asset across its entire lifecycle, replacing traditional flat drawings with a single source of truth.

A screening of more than a hundred countries and regions, carried out for this paper, found just over fifty with some form of public BIM requirement, counting everything from binding laws to agency rules and announced plans. Most of that policy effort has gone into buildings. Roads and railways came later because BIM development for infrastructure simply lagged that for buildings and because the industry's open file format IFC could not fully describe them until the infrastructure extension in version 4.3.

The legal picture reflects that lag. Among those requirements, binding rules aimed at roads and railways turned out to be rare, and the general BIM laws examined often leave infrastructure out. European policy surveys record the same pattern country by country, with infrastructure BIM arriving through transport agencies and programmes [1]. Existing comparisons of BIM policies mostly track who requires what and since when. This paper explores the legal mechanisms, searching for the instrument which carries the duty and what it requires technically.

This paper looks at the countries that do require BIM for road or rail projects. Six countries whose approaches differ most were selected, and the same questions are asked of each:

- Who imposes the duty, and through what kind of rule?
- Which projects does it cover?
- Does it name a file format or a version?
- What must the models contain?
- And does anyone check what is delivered?

Each of the six countries reaches its requirement through a different mechanism. Lithuania uses a statute. Hungary uses an act with a phased ministerial decree. Russia ties a government decree to public funding. Kazakhstan binds a ministry list of object types. Germany relies on a ministry roadmap with no law behind it. In Norway, the state railway acts as a client.

2. Methodology

The screening and document collection behind this paper were carried out with an AI research assistant, Claude (Anthropic), used in an agentic workflow. The assistant screened more than a hundred countries and regions for the legal basis of their reported BIM requirements, collected the source documents, and read and extracted them in their original languages. A requirement counted as public if a state body imposed it through a law, an agency rule, or an announced programme, and the six portraits were chosen to make the mechanisms as different as possible. The selection of the six countries portrayed here was proposed by the assistant and confirmed by the authors. The English wording of the quoted provisions is the assistant's translation, except where an official English edition exists (Germany's roadmap). Every fact was kept tied to a word-for-word quote from the source document, and the quotes were checked against those documents. The study design, the review of the findings, and all final decisions are the work of the authors.

Each country's rules were read as a chain. The chain runs from the act of parliament where there is one, through the decree or regulation under it, to the technical documents to

which those texts point. The paper describes what the texts say, not how they are applied in practice. The six countries are a deliberate selection of differing approaches, and no claim is made that the screening found every mandate.

3. Six national approaches

The portraits run from the rule closest to parliament to the rule furthest from it.

3.1. Lithuania

Lithuania is the only country in this study where the duty for road structures sits in the statute itself. That is the strongest legal form a BIM requirement can take. It binds everyone the law describes, with no contract or ministry decision in between. Since June 2024, the roads law says that roads are designed, built, reconstructed, repaired and maintained applying building information modelling methods for complex structural road elements, meaning viaducts, overpasses, bridges, two-level junctions, intersections, etc. (own translation) [2]. For ordinary linear road objects, the law orders "minimum" BIM requirements. The statute names no threshold for these structures.

What the method must contain arrives one level down, and it arrived late. The statute set a deadline of May 2024 for the implementing acts. The framework took its operative shape months past that deadline, when the 2022 ministerial order on client information requirements was restated in August 2024 [3], and a further amendment followed in June 2025 [4]. The order defines the road minimum as five mandatory model uses. These are existing-conditions modelling, quantity takeoff, functional assessment, design modelling, and 3D clash coordination [3]. Since November 2024 one more piece is fixed. Wherever BIM is mandatory, model elements must carry class codes from the national construction classifier [5]. None of the BIM acts names a model exchange format; IFC appears in none of the five current acts.

3.2. Hungary

Hungary uses two layers. In plain terms, parliament decided that BIM must come and left the what and when to the minister, so the fine print can change without going back to parliament. The 2023 act on state construction investments requires BIM across the whole lifecycle for state investments at or above the EU procurement threshold, and a special chapter extends this to infrastructure [6]. The act also writes in a safety valve. The ministry may deviate from the BIM requirement on economic grounds. The technical content sits in a ministerial decree, which also sets the calendar. Buildings and roads have been covered since September 2024, railways since July 2026, and water and utilities follow later [7].

The decree's core demand is a gate at handover. The designer's and the contractor's performance may only be accepted when the complete data set is delivered in three forms at once. Those are an IFC file saved from the native model, a BCF file, and the native files themselves. No IFC version is named anywhere in the chain. What the models must contain is set per project, in the employer's information requirements (EIR), and the decree's own promise to publish EIR templates for each facility type has not been kept to date, with the rail phase already live.

3.3. Russia

Russia's mechanism is the federal budget. The rule follows the money, so it binds the design of works paid from public budgets rather than construction in general. A government decree makes an information model obligatory for design contracts of budget-funded works concluded after the start of 2022 [8]. A second decree, in force since 2024, names the formats federally. IFC is named for object models and LandXML for terrain models, each with the qualification "or another format with an open specification" (own translation) [9]. A construction rulebook fixes the composition of the models, including attribute tables for linear objects [10]. Models travel to state bodies through the state file-exchange machinery, but which body checks what inside a model, the rules do not say.

One Russian document points at the future. Moscow's city methodology for road models recommends IFC 4.3 together with IFC Road, for one region and without binding force [11]. No law examined in this study names the infrastructure version of IFC; it appears only here and in the Norwegian railway's rulebook.

3.4. Kazakhstan

Kazakhstan starts from the object, not the project. In plain terms, the question is not how big or expensive a project is but what kind of object it produces. If the object type is on the list, models are obligatory; if it is not, they are not. The new construction code, in force since July 2026, makes information modelling obligatory for the object types on a ministry-approved list, and the duty covers both creation and operation of those objects [12]. The first wave of the list begins to bind on 1 August 2026, and it is mostly infrastructure. It covers airports, rail and road tunnels, metro, bridges of 100 meters and more, unique structures, and large schools. Major roads and mainline railways follow in 2028, and nearly everything else in 2030 [13].

The technical content is delegated to state normative documents, and those documents have not yet been issued. In the meantime, the mandate runs on a 2018 technical document that fixes IFC 2x3 or newer, issued under a law that has since been repealed [14]. And the state model-review rules expressly exclude engineering and transport infrastructure, the very objects the first wave starts with [15].

3.5. Germany

Germany requires BIM for all new federal transport infrastructure projects, and it did this without passing a law. In plain terms, nothing here is legislation. The ministry directs its own road authorities from above, and companies meet the requirements because tenders demand them, not because a penalty threatens. In 2015 the federal transport ministry published a roadmap (the "Stufenplan") requiring BIM at a defined performance level in all newly planned federal transport projects from the end of 2020, with no value threshold [16]. A government-funded project, BIM4INFRA2020, prepared the ground. It selected the standard set of model uses by an explicit survey weighing benefit against effort and produced the national templates [17].

The rules are precise about process and deliberately open about technology. All deliverables are digital, and 2D plans must be derived from the 3D models. Tenders may not demand vendor-specific formats exclusively, and handover to the public client is meant to use vendor-neutral formats only. But no format is named as the national standard, and no version. The format and its version number are entered per project in the client's information requirements, with IFC, the German road-data catalogue OKSTRA, and others listed as

typical choices [18]. The rules said openly why. When they were written, IFC could not yet fully describe infrastructure works such as roads, bridges and tunnels, and the extension that covers roads and railways arrived only with version 4.3.

The framework keeps growing. A model directive (MR BIM), announced in the ministry's 2021 masterplan [19] and built up as a set of framework documents, has replaced the project-era guidance. It now holds an eighteen-use-case catalogue for the standard process in its 2026 version, a national object catalogue for classification since 2024, and templates for the client documents [18]. Enforcement is soft. There are no penalties anywhere in the chain; instead, target agreements bind the ministry and the road authorities, project models are checked by the client with checking software, and projects and organisations are scored for BIM maturity.

3.6. Norway

Norway has no BIM legislation in either sector. The state appears here as a buyer, not as a lawmaker. Whoever wants the railway's contracts works by the railway's rules. Norway also hosts the most technically detailed requirements found in this study. They are written by Bane NOR, the state railway infrastructure manager, in its role as customer, and they bind through contracts, project by project [20].

The railway's requirements document makes IFC 4x3 the primary delivery format, in its own words "Primærformatet er gjeldende versjon av IFC 4x3" ("the primary format is the current version of IFC 4x3", own translation). Suppliers must validate their models against machine-readable checking files (IDS) before delivering them. Issues travel in the BCF format; deliveries pass through maturity-indexed acceptance states in the employer's data environment, with fixed revision rules. Everything the five approaches above leave open, the version, the machine validation, the property rules, is fixed here. None of it is law.

4. The six approaches side by side

Table 1 *– Six ways of requiring BIM for road and rail projects.*

Country	The mechanism, binding since	Projects covered	Format named?	Content floor	Checked?
Lithuania	Statute (roads law); 2024	Bridges, viaducts, junctions; minimum for linear roads	No	Five model uses + national classifier codes	No
Hungary	Act + ministerial decree; roads 2024, rail 2026	State investments at or above the EU threshold	Yes (IFC + BCF + native, all three)	Per project (EIR); promised templates missing	Yes (acceptance gate at handover)
Russia	Government decree; contracts from 2022	Budget-funded design contracts	Yes (IFC + LandXML, with open-format qualification)	Composition rulebook, incl. linear-object attribute tables	Unclear (bodies receive, checker unnamed)

Kazakhstan	Ministry object list under the construction code; first wave 1 Aug 2026	Tunnels, metro, airports, bridges over 100 m; more from 2028	Not in the law (old 2018 floor is IFC 2x3 or newer)	Delegated to state documents; unissued	No (infrastructure excluded from model review)
Germany	Ministry roadmap + model directive; end-2020	All new federal transport projects, no threshold	No (open formats; chosen per project)	18 use cases + national object catalogue; rest per project	Client model checks per project; no penalties
Norway	State railway as client; current rulebook 2025	Its own rail projects	Yes (IFC 4x3)	IDS property rules; maturity-gated deliveries	Yes (machine validation before delivery)

5. Conclusions

Three observations stand out. First, there is no standard mechanism. Six countries reached a binding or operative BIM requirement for roads and railways through six different instruments. These were a statute, an act with a phased ministerial decree, a government decree, a ministry object list, a ministry roadmap, and a customer's contract rulebook. A country looking for a model to copy will find six, not one, and that menu is directly relevant to countries still designing their rules.

Second, the technical detail grows as the rule moves away from parliament. The statute names structures but no file format. The decrees name formats but no version. The German ministry's framework names use cases and a classification catalogue and leaves formats to each project. The client's rulebook names the format version and validates deliveries by machine. The same pattern held in the study's wider material on general BIM laws. The further from parliament, the deeper the requirements.

Third, the timing of the format standard explains a lot. Germany wrote its rules when IFC could not yet fully describe infrastructure works and said so in the rules themselves; it fixed process and left technology per-project. The infrastructure version, IFC 4.3, exists now. In the material examined it appears in exactly two places, a regional recommendation in Moscow and the Norwegian railway's contract rulebook, and in no law.

The study has three limits. It reads texts, not construction sites, so whether anyone complies, or checks, in practice is beyond this paper. The documents span several languages, and although every fact rests on a word-for-word quote, translation error cannot be fully excluded. Everything here describes the rules as they stood when the paper was written, and the six countries are a selection, not a complete list.

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Main Challenges and Solutions for Implementing BIM-To-GIS Integration Using CityGML: A Review

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Abstract

The integration of Building Information Models (BIM) with 3D city models (GeoBIM) bridges detaild buidlding data with macro-scale geospatial context, supporting applications such as 3D city analysis, digital permitting, 3D cadastral, digital twins, disaster management, and smart city development. As a result, BIM–GIS integration has become an important research area in urban modelling and digital city development.

This review focuses on IFC-to-CityGML integration, particularly geometric and semantic conversion challenges. Although integration tools are becoming more common and demonstrate notable progress, fully automated interoperability is challanging. Significant interoperability issues remain due to differences in data models, geometric representations, Levels of Detail (LoDs), and georeferencing methods.

Semantic conversion is also limited by differences in conceptual schemas, leading to incomplete class mapping, loss of attributes, and reduced preservation of object relationships. Although methods such as rule-based mapping, ADEs, and ontology-based approaches exist, full semantic interoperability has not been achieved. In geometry conversion robust georeferencing workflows and efficient solid-to-surface conversion remain active research challenges.

While tools and methods for BIM–GIS integration exist, there is still a lack of standardized and comprehensive rules for geometric and semantic conversion and associated requirements of IFC-to-CityGML conversion. Current solutions remain fragmented and application-specific, preventing fully automated and consistent interoperability between two data modes.

Keywords

BIM, GIS, IFC, CityGML, GeoBIM, interoperability.

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1. Introduction

Over the last two decades, rapid urbanization has resulted in substantial pressure on development and land use in urban environments. According to [1] the world will continue to urbanize from 56% in 2021 to 68% in 2050. The rapid urbanization brings along complex interconnected challenges including sustainability and resilience of critical infrastructure manifesting as traffic congestion, insufficient waste management, environment pollution and resource inefficiency.

To address those challenges smart city emerges as a solution, integrating a range of advanced technologies such as Internet of Things (IoT), Artificial intelligence (AI), digital twins and big data analytics to maximize the use of available resources and create new ones. The main goal is to enhance the quality of urban living, improve public services, increase urban resilience and enable more efficient resource management [2]. Besides, the sustainable smart city is related to several Sustainable Development Goal (SDG) such as [3], [4]: SDG 11 Sustainable Cities and Communities through addressing specific targets for SDG 11 including: efficient public transportation by using real-time data to optimize routs and reduce congestion, air and waste management, resource optimization by using smart management of grids for energy and water distribution and smart homes, disaster resilience enabling preparation and quick response to climate-related hazards; SDG 9 Industry, Innovation and Infrastructure advocating sustainable industrialization and resilient infrastructure by monitoring structures in real-time enabling proactive maintained and minimizing environmental impact; SDG 7 Affordable and Clean Energy by minimizing energy waste and boosting renewable energy; SDG 13 Climate Action by reducing the urban carbon emission and increase a building resilience.

The key step in the implementation of the smart city concept is creation of 3D digital city models. The field of Architecture, engineering and construction (AEC) is undergoing digital transformation and integration of Building Information Modelling (BIM) profoundly revolutionizing the way buildings are design, constructed and managed over time. BIM focuses on the single building down to the construction components and involves the creation of detailed 3D models where each physical building element is considered as an independent item. On another hand, 3D Geospatial Information System (GIS) enables tools for modeling, visualizing and analyzing 3D spatially referenced data in large scale. Therefore, 3D models are placed within a broader geospatial context by mapping the relationship between buildings and the surrounding territory.

The exchange of information between BIM and 3D GIS (GeoBIM) combines complementary capabilities of both technologies such as automatic updated of 3D city models with high detailed building information, automatic integration of BIM within wider spatial context, automatic spatial analysis on BIM models, automatic Digital Building Permit procedures, and the representation, management and visualizing of 3D cadastral data.

The integration of BIM models with GIS data has attracted increasing attention from both research community and industry. However, despite significant advances in both domains, seamless BIM–GIS integration remains a major challenge. The first aim of the paper is to examine the current state of BIM-GIS conversion including geometric and sematic. The second aim is to evaluate main challenges in BIM-GIS integration in urban development projects.

2. General Characteristics of BIM and 3D GIS Model

The 3D city models and BIM differ in several aspect (Table 1). The BIM models are more detailed and have semantic that are meaningful for construction or refurbishing, but 3D GIS model have higher level of semantics that are more appropriated for many applications such as navigation and spatial analysis. From 3D geometric representation point of view the BIM is focused on volume-filling physical objects while GIS models the object outer surface (wall surface) and the voids between them (rooms).

BIM uses industry foundation classes (IFC), an object-oriented hierarchical data models, as the open standard exchange format to share information between software's and stakeholders. It contains classes to describe physical and abstract concepts. A BIM model represents a building as a collection of 3D elements such as beams, slabs, windows, doors. These objects can be represented at various level of details high level representation up to the individual elements suc as screw characterized by specific attributes such as materials, dimensions, construction scheduler, and cost information. The amount of information in IFC files can be indicated by five levels of development (LODs)

City objects in GIS environment are described by their geometry, topology, semantics and appearance. For the managing, storing and exchange of 3D city models, 3D GIS uses the City Geography Markup Language (CityGML) as an open international standard implemented as an application scheme of the GML.

The CityGML data model is organized into two interconnected hierarchies: a semantic hierarchy and a geometric hierarchy. Explicit mapping between them ensures that each semantic object is associated with its corresponding geometry. The current version CityGML 3.0 significantly improves interoperability with other standards such as IFC, Land Administration Domain Model (LADM), and INSPIRE. In CityGML 3.0 [5] all city objects are mapped onto semantic concepts of spaces representing volumetric extents in the real world, and space boundaries, which define and connect these spaces.

To improve BIM-GIS interoperability, CityGML v3.0 introduces the AbastractConstructiveElement class, enabling the mapping of constructive elements from IFC standard (IfcWall, IfcRoof) to CityGML. The volumetric components are bounded by different thematic surfaces WallSurface, RoofSurface etc. Therefore, space and space boundary establish the explicit connection between volumetric elements and their thematic boundary surface. In addition, Versioning module and the Dynamizer model are added support the management of temporal changes and time-dependent object properties. To represents city models at different scales and level of complexity City GML employes level of details (LoD).

Table 1 *– Comparison between 3D GIS and BIM*

	3D GIS	**BIM**
Data source	Survey (photogrammetry, laser scanning)	Designs
Geometry	Boundary representation	Parametrical models
Semantics	City/terrain	Building Elements
Georeferencing	Mandatory	Optional
Analysis level	City	Building
Details	LoD 0-3	LOD 100-500

3. State of the Art Review

The primary objective of GeoBIM is to enable the exchange of geometrical and semantic information between BIM and GIS environment. To achieve that, numerous GeoBIM conversion approaches have been proposed, IFC-to-CityGML [6], [7], [8], [9], IFC-to-shapefile conversion [10], or IFC-to-3D tiles [11], [12]. Each approach is designed to satisfy different application requirements and offers varying levels of support for geometry and semantic information.

Regardless of the conversion approach, GeoBIM involves two fundamental tasks: geometrical conversion and semantic mapping. The degree to which these tasks are achieved varies among conversion methods. For example, IFC-to-3D tiles enables quick 3D visualization of BIM model in in 3D WebGIS environment [11], while IFC-to-Shapefile studies are mainly focused on preserve geometrical information with limited support for semantics [13]. Among existing approaches, IFC-to-CityGML is the widely adopted, as it preserves supports the transfer of both geometric and semantic information required for 3D GIS applications. Table 2 summarizes the principal studies on GeoBIM integration, highlighting their research focus, key findings, and the main limitations identified in the literature.

Table 2 *– State-of-the art review of papers related to the GeoBIM integration*

Study	Research Focus	Key Finding	Identified Limitation
[14]	Georeferencing BIM models for BIM/GIS integration	Lack of unified georeferencing understanding in BIM is a fundamental integration barrier	-Need to formalization of georeferencing standards, -Need to embedding LoGeoRef concepts into platforms to support consistent georeferencing
[15]	Bidirectional conversion IFC-to-CityGML and CityGML-to-IFC	Lack of georeferencing in BIM models since it is related to the both harmonization and interoperability, Tools and standards should be improved	-Lack of control on way georeferencing is stored in IFC files, -Improving awareness and control of the georeferencing methods, -Lack of Definition of validity criteria and standards and development of comprehensive methodology.
[16]	Automatic processing of IFC models into generalized GIS models	Full integration is far from straightforward	-Much high variety of geometrical types supported by BIM software compared with GIS, -Geometric and topological errors in BIM models, -Much details of BIM will unlikely be integrated in GIS
[17]	Development and evaluation of two methodologies for BIM-GIS integration	Principal challenge is the adaptation of standards	-Discrepancies in LOD -Georeferencing -Different geometric representation
[18]	Application of Graph in BIM-GIS integration	LPG is more suitable that RDF graph for BIM-GIS conversion	-Solid-to-surface conversion -Class mapping problem -Mapping of instances and attributes to nodes and edges -IFC-to-LPG conversion method
[19]	GIS-BIM standardization trends (ISO/TC59/SC13–ISO/TC211)	Integration processes are currently semi-automatic; improved standards would accelerate business processes	-Difference in specification of object geometry and topology -Diversity in spatial representation and georeferencing

			-Semantic incompatibility regarding the concept of ”service” and concept of ”product” - Different vocabulary on entities and relations -Differences in usage and understanding of metadata
[20]	BIM/GIS integration via ontologies and metamodels	Joint application of ontologies and metamodels for BIM/GIS integration is an unexplored field	-Semantic level solutions are restricted to a specific application without possibility to generalization
[21]	Methodologies for city digital twin development	CityGML 3.0 Dynamizer enables real-time data integration;	-Bidirectional data flow of information between digital model and physical city remains a gap, -Issue of interoperability and data harmonization -Lack of standardized ontologies
[22]	Simplification of BIM models	The BIM model production should be considered as part of BIM-GIS integration	-“quality issue” BIM models satisfy project-specific information requirement resulting in models that may lack the information needed for GIS integration
[23]	Automatic conversion from IFC-to-CityGML	Preserving application-relevant BIM semantic during conversion enables that one CityGML dataset support various applications.	-Different structure of geometry and semantics -Many features cannot be mapped 1:1 (features such as number of stores or building height are not explicitly available in IFC)
[24]	Transforming the IFC-to-CityGML	Defining the Information that needs to be transformed for each LoDs in CityGML	-Lack of formal a descriptive framework for automatic conversion -Difference in data models -Difference in model details
[25]	Review on BIM-GIS application to enhance energy efficiency	GeoBIM application enables significant energy save however large-scale adoption remains challenging	-Insufficient standards -High computational demands of integration frameworks -Lack of consistence quantitative validation over studies -Limited professional training

4. Results and Discussion

The state-of-the-art analysis on GeoBIM integration using CityGML for urban development projects converges on several consistent conclusions. Most integration workflows rely on converting BIM data from IFC to CityGML (Table 2), often supplemented by with external databases to support real-time data management and updates. These studies emphasize the need for open standards and tools capable to preserve both geometric and semantic information while supporting the scalable adoption of BIM-GIS integration [15, 16, 19]. Despite significant advances, data interoperability remains one of the principal barriers to the operational implementation of GeoBIM workflows.

Geometric conversion is primally challenging by differences in data models, geometric representation (particularly solid-to-surface transformation), LoDs, and georeferencing and adopted by IFC and CityGML (Table 2.). The IFC supports multiple geometry representation

including parametric modelling (sweeps, Boolean operations), Boundary Representation and triangulated mashes whereas CityGML primally represents geometry using explicit boundary representation. Consequently, the conversion process requires complex transformations, particularly the conversion of parametric solids into explicit surface-based geometries making interoperability and conversion challenging [18, 19].

Another challenge is difference in model complexity. BIM models typically contains highly detailed building models developed for design and construction, whereas CityGML represts buildings at different LoDs suitable for geospatial applications. Existing studies propose two main strategies for LoD generation: (i) independently generating each CityGML LoD from the IFC models, providing greater flexibility or (ii) generating a detailed LoD3 model first and subsequently deriving lower LoDs which improves computational efficiency.

Georeferencing represents another persistent interoperability issue [14, 15, 17]. BIM model are typically created using local coordinate systems, while GIS application requires coordinate reference system to support spatial integration. Although, IFC supports several mechanisms for storing georeferencing information [14], there are not consistently implemented in practice because accurate georeferencing is generally not a priority during the building design process. As a result, positional accuracy or resulting model is reduced [15, 16].

Overall, substantial progress has been achieved in geometrical conversion, with variety and techniques available to handle conversion. Nevertheless, robust georeferencing workflows and efficient solid-to-surface conversion remain active research challenges [14-19].

Semantic conversion represents an equally significant challenge because IFC and CityGML adopt fundamentally different semantic models [13, 19, 20, 23]. This disparity leads to considerable data loss during conversion. Semantic interoperability involves mapping classes, attribute and relationship standards. Although straightforward one-to-one mappings exist for certain elements (e.g., IfcWindow to Window), many IFC entities require one-to-many or many-to-one mappings. For example, IfcBeam, IfcColumn, and IfcStair may all correspond to the BuildingInstallation class in CityGML. Furthermore, numerous IFC elements have no direct equivalent in CityGML, resulting in incomplete semantic transfer. Moreover, certain information required for GIS applications, such as building height or number of storeys, is not directly represented in IFC models and must therefore be derived through additional processing or manual extraction [22, 23]. Consequently, effective semantic conversion requires careful defined mapping rules and comprehensive understanding of both schemes [18, 19].

To improve semantic interoperability, CityGML provides extension mechanisms such as Application Domain Extensions (ADEs) and Generics, allowing application-specific information to be incorporated into the standard data model [23]. In parallel, international standardization efforts, including ISO/TR 23262:2021 for BIM–GIS interoperability and ISO/TS 19166:2021 for BIM-to-GIS conceptual mapping, have established common interoperability principles. However, their practical effectiveness and widespread adoption remain subjects of ongoing research.

Recent studies have also explored ontology-based approaches, often representing IFC data as semantic graph that graph-based, to improve semantic interoperability [8, 18, 20]. By representing BIM information as interconnected graphs, these approaches facilitate the preservation of object relationships, improve semantic querying, and provide a promising direction for future IFC-to-CityGML integration.

5. Conclusion

This review highlights that BIM–GIS integration through IFC-to-CityGML conversion remains a complex and unresolved challenge. The main difficulties arise from fundamental differences in geometric representation, semantic structures, and georeferencing systems between IFC and CityGML. Geometric conversion is hindered by the need to transform complex BIM geometries into explicit GIS-compatible forms, while semantic mapping is limited by incomplete class correspondences and information loss. Although progress has been made in LoD generation methods, geometry processing, and semantic extension mechanisms such as ADEs, full interoperability has not yet been achieved.

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Project Organization as a Hidden Determinant of Spatial Sustainability: The Mediating Role of BIM in Architectural Decision-Making

[Sandra Šlegl][1]

Abstract

The transition towards sustainable and resilient built environments is commonly addressed through technological innovation, environmental performance, and the implementation of digital tools such as Building Information Modeling (BIM). While extensive research has examined the technical benefits of BIM and sustainable design strategies, limited attention has been given to the organizational conditions under which architectural and spatial decisions are produced. This paper investigates the relationship between project organization, BIM-enabled decision-making, and spatial sustainability in architecture. The research is based on the hypothesis that spatial sustainability is not determined solely by design intentions and technological solutions, but is significantly influenced by project organization models and the decision-making structures established throughout project development. In this context, BIM is understood not merely as a technological platform, but as a collaborative decision-making environment that mediates information exchange, stakeholder interaction, and design coordination. The aim of the study is to identify the mechanisms through which different project delivery models influence architectural decision-making and consequently affect spatial outcomes related to flexibility, adaptability, resource efficiency, and long-term resilience. The research adopts a conceptual and comparative methodology based on a systematic review of literature from the fields of architectural design management, project delivery systems, BIM implementation, and sustainable architecture. Traditional project delivery models are compared with integrated and collaborative approaches to examine their potential impact on spatial sustainability. The paper proposes a conceptual framework linking project organization, BIM-supported collaboration, architectural decision-making, and spatial sustainability outcomes. By positioning project organization as a critical yet often overlooked determinant of architectural form and long-term spatial performance, the study contributes to ongoing discussions on the digital and green transition of the built environment and provides a theoretical basis for future empirical investigations.

Keywords

Project organization; Building Information Modeling (BIM); Architectural Decision-Making; Spatial Sustainability; Built Environment; Sustainable Architecture.

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1. Introduction

The transformation of contemporary architectural practice is increasingly shaped by the parallel demands of sustainable development and digital integration. While sustainability has traditionally been approached through environmental performance, energy efficiency, and technological optimization, recent research emphasizes the importance of the processes through which architectural decisions are generated. The quality and long-term performance of built space depend not only on final design solutions, but also on the organizational structures, communication patterns, and collaborative mechanisms established during project development [1,2]. Building Information Modeling (BIM) has significantly influenced architectural workflows by enabling integrated information management, multidisciplinary coordination, and improved decision-making throughout the building lifecycle. Although BIM is frequently associated with digital modeling, visualization, and technical coordination, its broader value lies in its ability to create a collaborative environment where knowledge from different disciplines can be combined and evaluated during the design process [3]. However, the implementation of BIM alone does not necessarily lead to improved architectural outcomes, as its effectiveness depends on the organizational context, project delivery model, and level of interdisciplinary integration [4]. In complex architectural projects, spatial sustainability emerges through a sequence of interconnected decisions related to spatial organization, adaptability, material strategies, technical systems, and future usability. These decisions are strongly influenced by the timing and quality of collaboration between architects, engineers, contractors, and other stakeholders. Therefore, project organization can be considered a hidden determinant of spatial sustainability, as it establishes the conditions under which design knowledge is exchanged and transformed into architectural space.

This research is based on the hypothesis that integrated project organization supported by BIM enables more sustainable spatial outcomes by improving collaborative decision-making processes. The aim of the study is to examine the relationship between project organization, BIMmediated collaboration, architectural decision-making, and spatial sustainability. The research adopts a conceptual and comparative methodology, combining literature analysis with case-based evaluation of BIM-supported architectural projects. The paper proposes a framework in which BIM is understood not merely as a technological tool, but as a mediating mechanism that connects organizational processes with spatial outcomes. By shifting the focus from the final building product toward the processes through which architectural space is produced, this research contributes to a broader understanding of sustainable architecture as an integrated organizational and design practice.

2. Project Organization, BIM and Spatial Sustainability

Spatial sustainability in architecture extends beyond environmental performance and refers to the ability of built space to remain functional, adaptable, and valuable throughout its lifecycle. While sustainable design is often associated with energy efficiency, material optimization, and reduction of environmental impacts, contemporary approaches increasingly recognize that spatial quality depends on early architectural decisions related to configuration, flexibility, usability, and future transformation potential [5]. Therefore, sustainability should be considered not only as a technical characteristic of a building but also as an outcome of design processes that determine how spaces respond to changing social, functional, and environmental conditions. Architectural projects are developed through continuous interaction between multiple disciplines, where decisions concerning spatial organization, structural systems, building services, and operational performance

influence each other. Consequently, project organization plays an important role in determining how effectively this knowledge is integrated. Traditional delivery models based on sequential phases often separate design activities from construction expertise, limiting opportunities for early interdisciplinary coordination. In contrast, integrated approaches emphasize collaboration, shared responsibility, and early involvement of project participants, enabling a more comprehensive evaluation of design alternatives [6]. Within this context, Building Information Modeling (BIM) represents a significant shift from isolated digital documentation toward integrated informationbased design processes. BIM enables project participants to work within a shared information environment where architectural, technical, and operational requirements can be coordinated throughout the project lifecycle [2]. Its contribution is therefore not limited to creating threedimensional models, but extends to supporting communication, reducing information fragmentation, and improving the transparency of decision-making. The relationship between BIM and sustainability is consequently mediated by the organizational conditions in which BIM is implemented. A digital model alone cannot ensure sustainable architectural outcomes; rather, sustainability emerges when BIM supports collaborative processes that allow different forms of expertise to influence design decisions at the appropriate stages. In this sense, BIM becomes an organizational mechanism through which project knowledge is transformed into architectural solutions with greater adaptability, efficiency, and long-term resilience [3,4]. Therefore, spatial sustainability can be understood as the result of a connected process in which project organization establishes the framework for collaboration, BIM enables information integration, and architectural decision-making translates this knowledge into spatial outcomes.

3. BIM as Mediator of Architectural Decision-Making

Architectural design is fundamentally a decision-making process in which spatial, functional, structural, environmental, and economic requirements are integrated into a coherent solution. The most influential decisions are established during the early design phases, when spatial organization, building systems, and long-term performance are defined. At this stage, the quality of interdisciplinary collaboration and access to reliable information significantly influence the final spatial outcome [7]. Since contemporary architectural projects involve multiple disciplines, decisions related to form, materials, structural systems, energy performance, and adaptability must be evaluated as interconnected aspects of a single spatial system rather than as isolated solutions [8]. Within this context, BIM functions as a mediator between project organization and architectural outcomes. By providing a shared information environment, BIM enables architects, engineers, contractors, and clients to evaluate design alternatives within a coordinated framework. This shifts the design process from sequential information exchange toward integrated decision-making, allowing potential conflicts and performance issues to be addressed during the early stages of development [2]. Therefore, the contribution of BIM extends beyond digital representation, as it creates conditions for informed decisions based on multidisciplinary knowledge. When supported by collaborative organizational structures, BIM enables teams to optimize spatial solutions according to flexibility, resource efficiency, constructability, and lifecycle performance criteria [3]. Consequently, spatial sustainability is shaped not only by design intentions or technical strategies, but also by the way information, expertise, and responsibilities are organized throughout the project lifecycle. In this sense, architectural space can be understood as the result of a coordinated decisionmaking process in which organizational structures influence how sustainable design principles are translated into long-term spatial value.

4. Comparative Analysis of Project Delivery Models

Project delivery models define the organizational structure through which architectural knowledge is developed, coordinated, and transformed into built outcomes. They determine the distribution of responsibilities, timing of stakeholder involvement, communication patterns, and the mechanisms through which design decisions are produced. Since spatial sustainability depends on decisions made throughout the design process, the selected delivery model significantly influences the potential for achieving adaptable, efficient, and resilient architectural solutions [6]. Traditional project delivery models, particularly Design–Bid–Build (DBB), are characterized by a sequential separation between design and construction phases. Although this approach provides clear contractual responsibilities and established workflows, it often limits the involvement of technical specialists and contractors during early design development. As a result, important information related to construction methods, building systems, lifecycle performance, and operational requirements may become available after major architectural decisions have already been established. This can lead to late modifications and reduced opportunities to optimize spatial solutions [9]. In contrast, integrated project delivery approaches supported by BIM reorganize the design process around early collaboration, shared responsibility, and continuous information exchange. Within these models, architects, engineers, contractors, and clients participate in the development of solutions from earlier project stages, allowing spatial and technical requirements to be evaluated simultaneously. BIM provides the information infrastructure that supports this integration by enabling coordinated models, improved communication, and evidence-based comparison of design alternatives [2,10]. The difference between these approaches is therefore not only technological but organizational. Traditional workflows often treat coordination as a corrective activity after individual decisions have been made, while BIM-supported integrated processes establish coordination as a continuous design activity. This shift allows project teams to address potential conflicts earlier and incorporate environmental, technical, and functional considerations into architectural decisions before they become irreversible. The principal differences between traditional and BIM-supported integrated delivery models, together with their implications for spatial sustainability, are summarized in Table 1. From the perspective of spatial sustainability, the value of integrated delivery lies in its ability to connect short-term design choices with long-term spatial performance. Flexibility, adaptability, and lifecycle efficiency are strongly influenced by early decisions regarding spatial configuration, structural systems, and building services. Therefore, the organizational conditions under which these decisions are made become an important factor in determining the future quality of architectural space.

Table 1 *– Project Delivery Models and Spatial Outcomes*

Criterion	**Traditional delivery (DBB)**	**BIM-supported integrated delivery**
Stakeholder involvement	Sequential participation	Early and continuous collaboration
Information flow	Fragmented exchange	Shared information environment
Decision-making	Discipline-based	Integrated and collaborative
Problem identification	Reactive	Proactive
BIM role	Documentation support	Decision-making environment
Spatial sustainability potential	Limited by late coordination	Enhanced through early integration

5. Case-Based Validation

The proposed relationship between project organization, BIM-supported collaboration, and spatial sustainability is further examined through selected complex architectural projects where BIM was implemented as part of an integrated design process. The purpose of this analysis is not to evaluate BIM as a technological product, but to investigate how collaborative organizational structures influence architectural decision-making and contribute to spatial outcomes. The selected cases demonstrate different scales and design challenges, allowing the relationship between information integration, decision processes, and sustainable spatial qualities to be examined.

5.1. The Edge, Amsterdam – Integrated Information for Adaptive Workplace Design

The Edge represents an example where digital coordination and integrated project organization supported the development of a flexible and performance-oriented workplace environment. The complexity of the project required continuous cooperation between architectural, engineering, technological, and operational teams from the early design stages [11]. BIM-supported processes enabled the integration of spatial planning, environmental analysis, building systems, and user requirements within a coordinated information framework. This allowed design teams to evaluate relationships between workplace organization, energy performance, and future operational needs before final decisions were implemented. As a result, sustainability considerations became embedded within spatial development rather than treated as separate technical solutions. From the perspective of this research, the significance of the project lies in the relationship between collaboration and spatial adaptability. The building demonstrates that flexible space is not achieved only through physical design strategies but also through decision-making processes that incorporate changing functional requirements and lifecycle considerations.

5.2. Shanghai Tower – BIM-Based Coordination of Complex Building Systems

Shanghai Tower illustrates the role of BIM-supported collaboration in managing highly complex architectural and engineering relationships. The project required coordination between building geometry, structural systems, façade performance, environmental strategies, and technical infrastructure, making interdisciplinary integration essential [12]. The use of BIM enabled architects and engineers to evaluate design alternatives through coordinated information models, improving communication between disciplines and reducing conflicts during development. This process supported decisions related to building form, façade configuration, structural efficiency, and environmental performance. The case demonstrates that in complex architectural projects, sustainable outcomes emerge through the integration of different types of expertise. BIM functioned as a mediator that transformed distributed knowledge into coordinated spatial decisions, enabling the development of a high-performance architectural system.

5.3. Cross-Case Analysis

The analysis of the selected cases indicates a consistent relationship between integrated project organization, BIM-enabled collaboration, and spatial sustainability outcomes. In both projects, BIM achieved its greatest value when implemented within organizational structures based on early stakeholder involvement, transparent information exchange, and continuous interdisciplinary coordination. Several common mechanisms can

be identified. First, early collaboration enabled architectural decisions to incorporate technical and environmental considerations before design solutions became fixed. Second, shared information environments reduced uncertainty and improved the ability to resolve conflicts proactively. Third, the integration of multidisciplinary knowledge supported spatial qualities related to adaptability, efficiency, and long-term performance. These cases support the central hypothesis of the research: spatial sustainability is influenced by the organizational processes through which architectural decisions are produced. BIM does not directly generate sustainable space; instead, it mediates the relationship between project organization and spatial outcomes by enabling coordinated knowledge exchange and integrated decision-making.

6. Proposed Conceptual Framework

Based on the theoretical analysis and case-based validation, this research proposes a conceptual framework explaining the relationship between project organization, BIM-supported collaboration, architectural decision-making, and spatial sustainability, as illustrated in Figure 1. The framework is based on the assumption that sustainable spatial outcomes are generated through a sequence of interconnected processes rather than through isolated design interventions or technological solutions. Within the proposed model, project organization represents the initial condition that determines the structure of collaboration, distribution of responsibilities, and accessibility of knowledge throughout the project lifecycle. Different organizational approaches influence the extent to which multidisciplinary expertise can contribute to architectural development, particularly during early design phases when spatial decisions have the greatest longterm impact [6]. BIM functions as the mediating mechanism between organizational processes and architectural outcomes. By providing a shared information environment, BIM enables disciplines to exchange, evaluate, and integrate knowledge within a coordinated framework. Its role therefore extends beyond digital representation to supporting collaborative decision-making and strengthening the connection between design intentions and technical requirements [2,3]. The central transformation occurs through architectural decision-making, where integrated information is translated into spatial strategies. Decisions related to spatial configuration, adaptability, material systems, environmental performance, and functional organization are shaped by the quality and timing of available knowledge. When developed through integrated collaboration, these decisions increase the potential for long-term flexibility, efficiency, and resilience. The final outcome is spatial sustainability, understood as an emergent quality of the built environment reflected in the ability of architectural space to accommodate changing requirements, optimize resources, and maintain functional value throughout its lifecycle. The proposed framework therefore demonstrates that spatial sustainability emerges from the integration of project organization, BIM-supported collaboration, and architectural decision-making rather than from technological solutions alone.

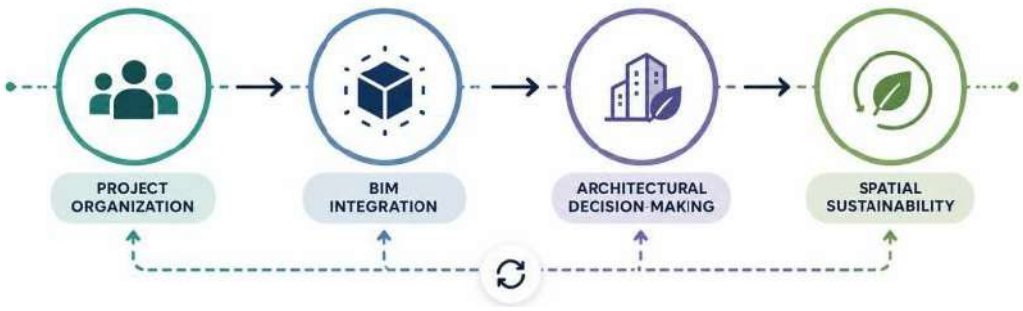


Figure 1 *– BIM-Mediated Framework for Spatial Sustainability*

7. Discussion

The findings of this research indicate that spatial sustainability should be understood as an outcome of the processes through which architectural decisions are developed, rather than solely as a result of environmental technologies or final design solutions. The analysis demonstrates that project organization influences the quality of spatial outcomes by determining how knowledge is exchanged, how different disciplines collaborate, and when critical decisions are evaluated. The comparison of project delivery approaches confirms that the main difference between traditional and BIM-supported integrated models lies in the structure of decision-making processes. While traditional workflows often separate professional contributions into sequential phases, integrated approaches enable continuous interaction between architectural, technical, and operational requirements. This shift allows design teams to consider long-term spatial consequences at the stages when changes are most effective and least costly. The research further emphasizes that BIM should be interpreted as a mediator of architectural intelligence rather than merely a digital modeling tool. Its contribution depends on the organizational environment in which it is applied. When combined with collaborative workflows, BIM supports the transformation of distributed knowledge into coordinated design decisions, improving the potential for adaptable, efficient, and resilient spatial solutions. The case-based validation supports this interpretation by showing that successful BIM implementation is closely related to early collaboration, information transparency, and integrated evaluation of alternatives. In the examined projects, sustainable spatial qualities emerged through coordinated processes in which architectural and technical knowledge were continuously aligned. Therefore, the proposed framework extends the understanding of sustainable architecture by shifting attention from the performance of the final building toward the mechanisms that produce architectural decisions. This perspective highlights that future sustainable practice depends not only on advanced digital tools, but also on organizational models capable of integrating knowledge throughout the design process.

8. Conclusion

This research examined the relationship between project organization, BIM-supported collaboration, architectural decision-making, and spatial sustainability, demonstrating that sustainable architectural outcomes are strongly influenced by the processes through which design knowledge is organized and transformed into spatial solutions. The findings confirm that project organization is a key determinant of spatial sustainability because it shapes collaboration, information exchange, and the integration of multidisciplinary expertise. While traditional delivery models often limit early coordination, BIM-supported integrated approaches enable architects, engineers, contractors, and clients to evaluate architectural, technical, and environmental aspects simultaneously [13]. A key contribution of this research is the repositioning of BIM from a technological tool to an organizational mediator within architectural practice. Rather than directly producing sustainable outcomes, BIM supports the collaborative processes through which informed and sustainable architectural decisions are made. Accordingly, spatial quality depends on the effective integration of digital capabilities, project organization, and decision-making throughout the design process. The proposed conceptual framework demonstrates that flexibility, adaptability, resource efficiency, and long-term resilience emerge through the integration of project organization, BIM-enabled information exchange, and architectural decision-making. The case-based analysis supports the assumption that spatial sustainability is not only a property of the completed building but also a consequence of the organizational processes through which it is conceived. This study is limited by its reliance on theoretical synthesis and qualitative case

analysis rather than large-scale empirical validation. Therefore, the proposed relationships should be interpreted as conceptual rather than universally generalizable. Future research should examine measurable relationships between BIM maturity, project delivery models, and spatial sustainability indicators across different architectural typologies to further validate the proposed framework [14].

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The Role of Digital Forensics in the Development of Digital and Green Education in the Era of Artificial Intelligence

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Abstract

The digital transformation of education and global trends in sustainable development have led to the intensive application of information and communication technologies, artificial intelligence and digital platforms in the learning process. At the same time, the amount of digital data, electronic evidence and security incidents that require the application of digital forensics methods is increasing. Modern educational institutions are increasingly using cloud environments, online learning systems, generative artificial intelligence and digital identities, which raises new issues of data protection, academic integrity and cyber security. Digital forensics is becoming a key tool for identifying, collecting, analyzing and preserving digital evidence in cases of information system misuse, plagiarism, deepfake content and cyber attacks on educational institutions. A special challenge is the harmonization of digital development with the principles of green education and sustainability. The application of forensic technologies must be efficient, energy-optimized and aimed at reducing the negative impact of digital infrastructure on the environment. In this context, the concept of "green digital forensics " is gaining increasing importance as a combination of digital security, responsible use of resources and sustainable development. The paper analyzes the role of digital forensics in the modern educational environment, the impact of artificial intelligence on the process of collecting and analyzing digital evidence, as well as the possibilities of developing the competencies of teachers and students through the integration of digital and green skills. Special attention is paid to the challenges of privacy protection, ethical aspects of the use of artificial intelligence and the need to develop new educational programs that integrate cybersecurity, digital forensics and sustainability.

Keywords

Digital forensics, digital education, green education, artificial intelligence, cybersecurity, digital evidence, sustainable development, data protection, green digital transformation.

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1. Introduction

Modern society is undergoing an intense digital transformation that is significantly changing the way we work, communicate, and educate. The development of information and communication technologies, artificial intelligence (AI), cloud services, and digital platforms has led to the creation of new learning models based on digital content, online environments, and automated systems to support the educational process [1]. At the same time, global challenges related to climate change, energy efficiency, and sustainable development have imposed the need to develop the concept of green education, which involves acquiring knowledge, skills, and competencies aimed at preserving the environment and responsible use of resources [2]. Digital and green education today represent two interconnected processes that play a key role in achieving sustainable development goals. The European Union, through the Digital Education Action Plan 2021–2027 and the European Green Deal, particularly emphasizes the importance of developing digital and green skills as key competencies for the future [3]. Educational institutions are becoming carriers of the digital and green transition, but at the same time they are increasingly targets of cyber attacks, data theft, and various forms of digital fraud [4]. In parallel with the growth of digitalization of education, the amount of electronic data and digital traces generated by the use of information systems, mobile devices, distance learning platforms and artificial intelligence-based systems is increasing. This is precisely why digital forensics is gaining an increasingly important role in the modern educational environment. Its main purpose is to identify, collect, preserve, analyze and present digital evidence in a way that ensures its credibility, integrity and usability in disciplinary, administrative or judicial proceedings [5]. A special challenge is posed by new generative AI technologies that enable the creation of texts, images, audio and video content, including deepfake materials. Such technologies, in addition to numerous advantages for education, raise issues of academic integrity, content authenticity, personal data protection and digital security [6]. In such an environment, digital forensics becomes one of the key mechanisms for detecting abuse, verifying the authenticity of digital content and protecting educational institutions from cyber threats. The aim of this paper is to analyze the role of digital forensics in the development of digital and green education in the era of artificial intelligence, identify key challenges and risks arising from the intensive digitalization of the education sector, and point out the possibilities for improving digital and green competencies through the integration of cybersecurity, data protection, and digital forensics principles into educational processes.

2. Digital and Green Education as the Foundation of Sustainable Development

Digital transformation and sustainable development represent two key strategic directions of modern society. In recent years, education systems around the world have been faced with the need to adapt to accelerated technological development, but also to the demands arising from global environmental challenges. In response to these changes, the concepts of digital and green education have been developed, the main goal of which is to develop the competencies necessary for living and working in a digital and sustainable society [1]. Digital education involves the application of information and communication technologies in the process of learning, teaching and managing educational institutions. It includes the use of learning management systems, cloud platforms, artificial intelligence, virtual laboratories and other digital tools that enable more efficient acquisition of knowledge and the development of digital competencies [3]. Modern education systems are increasingly moving from traditional teaching models to hybrid and online models that enable greater

accessibility of education, flexibility and personalization of the learning process. Green education is an educational approach aimed at developing awareness of environmental protection, sustainable use of natural resources and responsible behavior towards future generations. Its goal is not only to acquire knowledge about ecology, but also to develop competencies that enable sustainable decision-making in professional and private life [2]. In this sense, green education is becoming an important instrument for achieving the sustainable development goals defined by the United Nations 2030 Agenda. The connection between digital and green education is particularly evident through the concept of digital sustainability. The application of digital technologies enables the reduction of paper consumption, the optimization of administrative processes, the reduction of the need for physical travel and a more rational use of resources. However, digital transformation simultaneously creates new challenges related to electricity consumption, electronic waste and the security of information systems [7]. As already noted, EU digital and green education policy frameworks place particular emphasis on these competencies; accordingly, educational institutions are expected to enable students and pupils to acquire knowledge in the fields of digital technologies, cybersecurity, artificial intelligence, data protection and sustainable development [8]. Such an approach contributes to the creation of experts capable of responding to the challenges of a modern digital society and a green economy. In the context of digital forensics, digital and green education represent an important framework for the development of new competencies that combine technological knowledge, security requirements and sustainability principles . Future experts must be able to understand how digital systems function, recognize security threats, protect digital data and at the same time apply the principles of energy efficiency and responsible use of digital resources. This is precisely why digital forensics is becoming an important segment of the development of modern digital and green competencies. Today, digital and green education are no longer separate concepts, but interconnected elements of sustainable digital transformation. Their integration represents the basis for the development of a safe, innovative and sustainable education system that can respond to the challenges of artificial intelligence, cyber threats and accelerated technological development.

Recent peer-reviewed literature reinforces this institutional framing. Comprehensive reviews of green and sustainable computing highlight energy-efficient algorithms, low-carbon data management and lifecycle-aware infrastructure design as core mechanisms through which the ICT sector can reduce its environmental footprint [23], while studies of cybersecurity curriculum design show that structured, competency-based educational approaches, rather than ad hoc awareness campaigns, are needed to close persistent workforce and skills gaps [22]. Evidence-based frameworks for cybersecurity education design, such as intervention-mapping approaches that translate theoretical models into concrete learning outcomes, further indicate that digital and green competencies are most effectively developed when curricula are built around identified stakeholder needs rather than generic content delivery [24].

3. The Role of Digital Forensics in Digital and Green Education

The development of digital education has led to a significant increase in the amount of data generated and processed within educational institutions. Learning management systems, electronic diaries, online teaching platforms, cloud services, mobile applications and tools based on artificial intelligence generate large amounts of digital records every day. Such an environment requires the application of appropriate security mechanisms, but also the development of capabilities for identifying, collecting, analyzing and preserving digital evidence in the event of security incidents. It is in this segment that digital forensics plays a key role [9]. Digital forensics is a scientific discipline that encompasses methods and

procedures for collecting, preserving, analyzing and presenting digital evidence in a way that ensures its integrity, authenticity and admissibility in administrative, disciplinary and judicial proceedings [5]. Its application in the education sector is becoming increasingly important due to the increase in cyber threats, misuse of information systems and the growing use of artificial intelligence in the learning process. One of the most important roles of digital forensics in education is related to the protection of academic integrity. The development of generative AI tools has enabled students and pupils to create seminar, research and other papers with minimal human involvement. At the same time, new forms of plagiarism, content manipulation and concealment of real authorship are emerging. Digital forensics enables the identification of digital traces that can indicate the way a particular document was created, its authenticity and possible content manipulation [10]. In addition to protecting academic integrity, digital forensics plays an important role in protecting the information systems of educational institutions. Universities, schools and research centers often have large amounts of personal data of pupils, students and employees, which is why they represent attractive targets for cybercriminals. Security incidents such as unauthorized access to systems, data theft, ransomware attacks and compromise of user accounts require forensic investigations to determine the cause of the incident, identify perpetrators and collect relevant evidence [11]. Special attention should be paid to protecting the digital identity of users of educational systems. Digital identity today represents the basis for access to educational platforms, electronic libraries, cloud services and other digital resources. Compromise of user accounts can lead to data theft, identity theft or manipulation of educational content. Digital forensics enables the reconstruction of user activities, analysis of access logs and identification of compromised accounts, thereby contributing to improving the security of the educational environment. The development of digital and green education also includes responsible management of digital resources. In this context, digital forensics contributes to sustainability by extending the life of information systems, properly managing digital data and optimizing the process of preserving electronic evidence. The application of forensic procedures allows organizations to use existing infrastructure more efficiently, reduce unnecessary duplication of data and improve the management of digital resources, which indirectly contributes to the achievement of the goals of green education. The additional importance of digital forensics is reflected in the education of future experts. The development of digital and green competencies requires the integration of content in the fields of cybersecurity, data protection, digital forensics and artificial intelligence into curricula. Students who acquire knowledge in these areas become capable of recognizing security threats, protecting digital systems and responsibly managing information in accordance with the principles of sustainable development. It can be concluded that digital forensics represents one of the key elements of modern digital and green education. Its role is no longer limited to conducting investigations after an incident, but includes preventive action, protecting digital identities, preserving academic integrity, protecting personal data, and developing digital competencies necessary for a safe and sustainable digital society.

4. Artificial Intelligence, Digital Evidence and New Forensic Challenges

The rapid development of artificial intelligence (AI) represents one of the most significant technological changes in modern society. The application of AI systems is now present in almost all areas, including education, science, business, public administration and security. In the education sector, artificial intelligence enables personalized learning, automation of administrative processes, analysis of educational data and development of intelligent learning support systems. At the same time, its widespread application opens up new issues related to the authenticity of digital content, data protection, academic integrity and digital security [12]. One of the greatest challenges for digital forensics is the emergence of generative artificial intelligence, which enables the creation of texts, photos, audio and

video content that are often difficult to distinguish from the original materials. Tools based on large language models and generative networks allow the creation of convincing content without the need for advanced technical knowledge. As a result, the risk of information manipulation, the spread of disinformation and the creation of false digital evidence is increased [13]. Deepfake technologies that use artificial intelligence to generate or modify audio and video content pose a particular threat. Such content can show people saying words or performing actions that never happened. In an educational environment, deepfake content can be used to damage the reputation of teachers, students, or educational institutions, as well as to carry out various forms of fraud and manipulation. Therefore, digital forensics is developing new methods for identifying and analyzing AI-generated content to determine its authenticity [6]. A recent systematic survey of digital forensic methods for multimodal deepfake identification confirms that detection increasingly relies on combining visual, audio and metadata cues, and that no single technique yet offers reliable, generalisable identification across manipulation types [25], which underscores the need for the kind of applied digital literacy training highlighted later in this paper's survey results. In addition to the problem of content authenticity, artificial intelligence creates new challenges in the field of digital evidence. Traditional methods of forensic analysis were based on the assumption that digital data represents a reliable record of a certain event. However, the development of AI systems allows for the automatic generation of a large number of fake documents, photographs, and other digital artifacts that can make it difficult to establish facts during a forensic investigation. Therefore, modern digital forensics increasingly relies on metadata analysis, multimedia forensics, data source verification, and the application of manipulation detection algorithms. At the same time, artificial intelligence can significantly improve digital forensics processes. The application of AI algorithms enables the automatic analysis of large amounts of data, the recognition of behavioral patterns, the identification of anomalies and the rapid discovery of digital traces relevant to the investigation. Such systems can help forensic experts in processing large data sets, identifying compromised systems and reconstructing events preceding a security incident [14]. In the context of digital and green education, the development of competencies for the critical use of artificial intelligence is of particular importance. Pupils, students and teachers must be able to recognize potential misuses of AI technologies, assess the credibility of digital content and understand the basic principles of data protection and digital evidence. Such competencies represent an important element of digital literacy and contribute to the creation of a safer and more responsible digital environment. The future development of artificial intelligence will undoubtedly further increase the complexity of digital investigations. Therefore, cooperation between experts in the fields of artificial intelligence, cybersecurity, data protection and digital forensics will become one of the key factors for maintaining trust in digital systems and educational institutions. Digital forensics will play an increasingly important role in confirming the authenticity of digital content, protecting academic integrity, and maintaining the security of the digital educational environment.

5. Green Digital Forensics and Sustainability of Information Systems

The concept of sustainable development has become an integral part of all segments of society in recent years, including information technology, cybersecurity and education. In this context, the concept of green digital forensics is also being developed, which involves the application of forensic methods and technologies while reducing the negative impact of information systems on the environment. The goal of this approach is to establish a balance between the needs for efficient digital investigations and the principles of sustainability, energy efficiency and responsible management of digital resources [15]. Modern digital forensics is faced with a constant increase in the amount of data that needs to be collected, analyzed and stored in the long term. Cloud infrastructure, the Internet of Things (IoT),

artificial intelligence and online education systems generate huge amounts of digital records every day. Processing and storing such data requires significant computing resources and electricity consumption, which directly affects the increase in the carbon footprint of information systems [16]. Green digital forensics seeks to optimize the processes of collecting and analyzing digital evidence through the application of energy-efficient algorithms, intelligent data filtering methods and automation of forensic procedures. Instead of collecting the complete contents of information systems, modern approaches increasingly use targeted collection of relevant data, which reduces the requirements for storage, processing and long-term preservation of digital evidence. Such an approach allows for more efficient use of resources while maintaining the required level of forensic reliability. Green digital forensics is of particular importance in the education sector, where online learning systems, digital libraries, electronic repositories and platforms based on artificial intelligence are used daily. Efficient management of digital data contributes to reducing paper consumption, more rational use of information resources and reducing the need for physical infrastructure. At the same time, proper management of digital evidence enables the protection of academic integrity, personal data and the security of information systems. The development of green digital competencies also includes understanding the impact of digital technologies on the environment. Future experts in the fields of cybersecurity, digital forensics and information technologies must be able to assess the energy efficiency of systems, optimize data processing processes and apply the principles of sustainable management of digital infrastructure. Such an approach contributes to achieving the goals of green education and sustainable development. The application of artificial intelligence in the optimization of forensic processes is an added value. AI systems can automatically classify and filter large amounts of data, identify relevant digital traces, and reduce the need for unnecessary information processing. In this way, it is possible to significantly reduce the consumption of computing resources, analysis time, and the overall environmental impact of digital investigations [17]. In the long term, green digital forensics represents an important step towards establishing sustainable models for managing digital evidence and information systems. Its application allows for the simultaneous achievement of security goals, protection of digital data, and responsible use of technological resources. For this reason, the concept of green digital forensics is becoming an important element of the development of digital and green education in the era of artificial intelligence.

6. Recommendations for the Development of Digital And Green Competences in Education

Successful integration of digital forensics into the concept of digital and green education requires a systemic approach that includes educational institutions, policymakers, cybersecurity experts and the business sector. The development of digital and green competencies must be a continuous process aligned with technological changes and the requirements of sustainable development. First of all, it is necessary to improve curricula by including content in the fields of digital forensics, cybersecurity, data protection, artificial intelligence and sustainable information systems management. Such content should be adapted to different levels of education so that students acquire the knowledge necessary for the safe and responsible use of digital technologies. Educational institutions should develop laboratories and practical environments for simulating cyber incidents, analyzing digital evidence and applying forensic tools. Practical teaching allows students to acquire concrete skills that are increasingly in demand on the labor market, especially in the areas of digital forensics, cybersecurity and protection of critical information infrastructure. Special attention should be paid to the education of teaching staff. Teachers must continuously improve their digital competences in order to be able to use modern technologies effectively,

recognize security threats and apply the principles of data protection and digital evidence in the educational process. At the same time, it is necessary to develop awareness of the sustainable use of digital technologies. Pupils and students should be encouraged to responsibly manage digital resources, reduce digital waste, rationally use cloud services and apply energy-efficient technological solutions. In this way, digital competences become directly linked to the goals of green education and sustainable development. Of additional importance is the establishment of cooperation between universities, research institutions, government agencies and the economy. Such cooperation enables the exchange of knowledge, the development of joint projects and the faster transfer of innovations in the field of artificial intelligence, digital forensics and cybersecurity into the educational system. By applying the above recommendations, it is possible to create an educational environment that simultaneously develops digital and green competences, improves the security of information systems and contributes to the sustainable development of society as a whole.

7. Research on Students' Perception of the Role of Digital Forensics in Digital and Green Education

7.1. Research methodology

For the purpose of the research, an anonymous online survey was conducted among students of FINRA University Tuzla during May 2026, using a non-probability convenience sampling procedure. The survey link was distributed through the university's official e-learning platform and student communication channels, and participation was voluntary and anonymous. Because the questionnaire was distributed through open, university-wide channels rather than to a closed list of named invitees, an exact response rate relative to the full student population could not be calculated; 126 completed responses from students across different study programs were obtained and treated as the effective analytical sample. This non-probability approach is consistent with similar exploratory studies of digital literacy and cybersecurity awareness in higher education [22], [24]. The aim of the research was to determine the level of knowledge of digital forensics, the perception of cyber security threats in education, and students' attitudes about the importance of digital and green competencies in the modern educational process. A structured questionnaire consisting of 15 closed-ended items was used to collect data; the items were organized into thematic clusters addressing (i) the perceived impact of artificial intelligence on education, (ii) awareness of cybersecurity and data-protection risks, (iii) knowledge of digital forensics concepts, (iv) self-assessed ability to recognize AI-generated and deepfake content, and (v) attitudes toward the integration of digital and green competencies into curricula. Item wording was adapted from constructs used in comparable studies on digital forensics and cybersecurity education [22], [25], which supports the content validity of the instrument. In line with the anonymous, closed-response design adopted to protect respondent privacy, study program was recorded as the only demographic variable, and no further personal identifiers (age, gender) were collected; this is reported here as a limitation of the sampling design rather than an omission of the analysis. The results obtained were analyzed using descriptive statistics.

7.2. Research results

The results of the survey showed that 84% of respondents believe that artificial intelligence will significantly impact the future of education, while 79% believe that it will also

increase the risk of misuse of digital content. As many as 88% of students believe that basic knowledge of digital forensics should be an integral part of higher education, while 91% of respondents believe that cybersecurity and data protection are key competencies of future experts. When asked about the ability to recognize deepfake content, only 27% of respondents said that they could independently recognize most of such content, which indicates the need for additional education in this area. The survey showed that 86% of respondents support the integration of digital and green competencies into curricula, while 82% believe that digital technologies can contribute to sustainable development by reducing the consumption of paper, energy and other resources.

7.2.1. Percentage Calculation of Respondents

$$\boldsymbol{P = \frac{f}{N} \times 100} \quad (1)$$

$$\boldsymbol{P = \frac{115}{126} \times 100 = 91.27\%} \quad (2)$$

Percentage Calculation of Respondents

where:

P – percentage of respondents (%)

f – number of respondents who selected a particular answer

N – total number of respondents (126)

Although the arithmetic mean and standard deviation are commonly reported alongside percentage results, computing them across the seven items summarized in Table 1 would not be statistically appropriate. Each item corresponds to a distinct survey question addressing a conceptually different construct (e.g., the perceived impact of artificial intelligence, self-assessed ability to recognize deepfake content, or support for curriculum change), rather than repeated measurements of a single underlying variable. Averaging percentages drawn from such heterogeneous items would produce a summary value without a clear substantive interpretation, and the accompanying dispersion measure would reflect differences between unrelated survey questions rather than sampling variability within a single measured attribute. For this reason, the results are reported and interpreted item-by-item, as presented in Table 1, rather than as a single aggregate mean and standard deviation.

The percentage of affirmative responses ranged from 27% (self-assessed ability to recognize deepfake content) to 91% (cybersecurity as a key competency of the future). This range indicates that while students' awareness of the importance of digital forensics, cybersecurity and green digital competencies is consistently high, their practical competency in identifying AI-generated manipulation remains comparatively low, which points to a gap between perceived importance and applied skill that educational programs should address.

7.3. Discussion

The results obtained confirm the growing awareness of students about the importance of digital forensics, cybersecurity and data protection in modern education. At the same time, the results indicate an insufficient level of practical knowledge related to the recognition of manipulated digital content and the misuse of artificial intelligence. The research results confirm the need to integrate content from the field of digital forensics into digital and green

education programs so that future experts are trained for the safe, responsible and sustainable use of modern technologies.

Table 1 *– Research results*

Question	YES (%)
AI will significantly impact education	84
AI increases the risk of content abuse	79
Digital forensics should be part of study programs	88
Cyber security is a key competency of the future	91
I can recognize deepfake content	27
I support the integration of digital and green competencies	86
Digital technologies contribute to sustainability	82

Figure 1 shows the results of a survey conducted among 126 students at FINRA University Tuzla in May 2026. The results show a high level of awareness of the importance of cybersecurity (91%), digital forensics (88%), and the integration of digital and green competencies (86%) into educational programs. At the same time, only 27% of respondents believe that they can reliably recognize deepfake content, which indicates the need for additional education in the areas of digital forensics, artificial intelligence, and digital evidence protection.

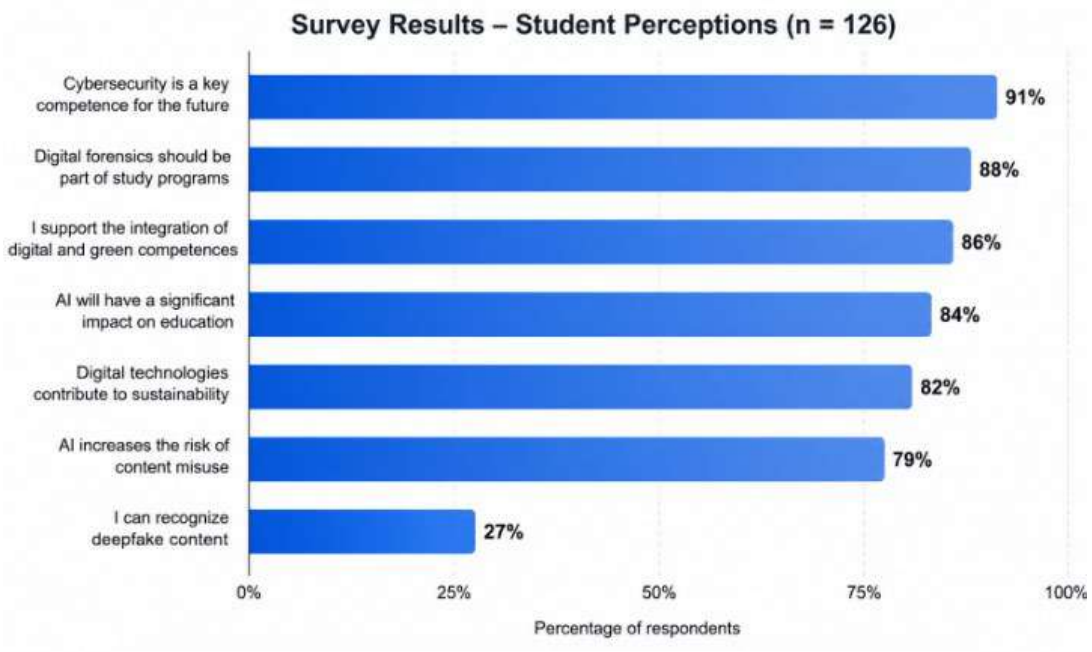


Figure 1 *– Students' views on digital forensics, artificial intelligence and green education, Source Authors*

8. Conclusion

The digital transformation of society and the rapid development of artificial intelligence create new opportunities for improving educational processes, but at the same time generate

new security challenges. Digital and green education are becoming key elements of sustainable development, where the development of digital competencies must be accompanied by the responsible use of technologies, data protection and preservation of digital security. In such an environment, digital forensics occupies an important place as a discipline that enables the identification, collection, analysis and preservation of digital evidence, and contributes to the protection of the integrity of information systems and digital content. The results of a survey conducted among students of FINRA University Tuzla showed a high level of awareness of the importance of cybersecurity, digital forensics and data protection in modern education. The majority of respondents believe that digital forensics should be an integral part of educational programs, while at the same time there is a pronounced need for additional knowledge in the field of recognizing deepfake content and other abuses based on artificial intelligence. The results obtained confirm that there is a real need for the systemic development of digital and green competencies at all levels of education. The analysis showed that artificial intelligence brings significant benefits to the educational process through the personalization of learning, automation and increased availability of educational content. However, the development of generative AI systems, deepfake technologies and automated creation of digital content simultaneously increases the risks associated with the authenticity of information, academic integrity and protection of personal data. Therefore, digital forensics is becoming one of the key mechanisms for verifying the authenticity of digital content and maintaining trust in the digital educational environment. A special contribution of the paper is reflected in the connection of the concept of digital forensics with the principles of green education and sustainable development. The concept of green digital forensics indicates the possibility of establishing a balance between the requirements for the security of digital systems and the need for rational use of technological resources. The application of energy-efficient solutions, optimization of data processing processes and responsible management of digital infrastructure represent an important contribution to the achievement of sustainable development goals. It can be concluded that digital forensics is an important factor in the development of a secure, sustainable and innovative education system. Its integration into the processes of digital and green education enables strengthening cybersecurity, protection of digital evidence, improvement of academic integrity and development of competencies necessary for successful functioning in a digital society. In the era of artificial intelligence, the synergy of digital forensics, cybersecurity, data protection, and sustainable development will represent one of the key prerequisites for building a resilient and competitive education system of the future.

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T05

Green Skills, Climate Resilience & Disaster Risk Management

Digital Approaches to Climate Resilience: Assessing Wildfire Response Capacity in Vojvodina

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Abstract

Climate change is increasingly influencing the frequency, intensity, and spatial distribution of wildfires, creating new challenges for local communities and emergency response systems. Rising temperatures, prolonged drought periods, and more frequent extreme weather events contribute to elevated wildfire risk, particularly in regions characterized by extensive agricultural land and open landscapes. In this context, strengthening climate resilience requires not only adequate response capacities but also the application of digital approaches that support informed decision-making and resource planning.

This paper examines wildfire response capacity in the Autonomous Province of Vojvodina, Serbia, using the South Bačka District as a case study area, with a particular focus on the spatial relationship between wildfire occurrence and the distribution of firefighting resources. The study integrates georeferenced data on wildfire locations, professional fire-rescue units, and volunteer fire brigades to evaluate territorial coverage and identify areas potentially exposed to delayed response. The analysis is based on wildfire events recorded during an extreme fire year and examines the contribution of local firefighting capacities to the overall resilience of the emergency management system. The findings indicate significant territorial differences in the accessibility of firefighting resources, particularly between urban and rural areas. The results further highlight the importance of volunteer fire brigades in strengthening local response capabilities and improving coverage in areas located farther from professional units. By combining digital data management, spatial assessment, and climate resilience perspectives, the study demonstrates how digital approaches can support evidence-based planning, enhance preparedness, and contribute to more resilient wildfire risk management at the local and regional levels.

Keywords

Climate resilience, Digitalization, Wildfires, Emergency response, Volunteer fire brigades, Disaster risk management.

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1. Introduction

Climate change has emerged as one of the most significant drivers of natural hazards worldwide, affecting the frequency, intensity, and spatial distribution of extreme events. Among these hazards, wildfires have gained increasing attention due to their growing occurrence, environmental consequences, and socioeconomic impacts. Rising temperatures, prolonged drought periods, and more frequent heat waves create favorable conditions for wildfire ignition and rapid fire spread, particularly in regions characterized by extensive agricultural land and open landscapes [1,2].

The concept of climate resilience refers to the ability of communities, institutions, and systems to anticipate, withstand, adapt to, and recover from climate-related hazards while maintaining essential functions [3]. In the context of wildfire risk, resilience depends not only on preventive measures and risk awareness but also on the effectiveness of emergency response capacities. Rapid detection, timely intervention, and adequate territorial coverage of firefighting resources play a critical role in limiting wildfire spread and reducing potential losses. Consequently, assessing the availability and accessibility of response capacities represents an important component of climate adaptation and disaster risk reduction strategies.

Digitalization is increasingly transforming disaster risk management by enabling the collection, integration, and analysis of large volumes of spatial and operational data. The availability of digital records, georeferenced information, and analytical tools supports evidence-based decision-making and facilitates a better understanding of territorial vulnerabilities and resource distribution [4,5]. Digital approaches can therefore contribute to improved preparedness, more efficient allocation of resources, and enhanced resilience to climate-related hazards.

The Autonomous Province of Vojvodina represents a particularly relevant area for studying wildfire response capacity. The region is characterized by extensive agricultural production, large open spaces, dispersed rural settlements, and significant areas of vegetation that may become vulnerable during periods of drought and elevated temperatures. Furthermore, climate adaptation policies at the European level emphasize the importance of strengthening local capacities and improving risk-informed decision-making in response to increasing climate-related threats [6].

This paper examines wildfire response capacity in the Autonomous Province of Vojvodina through a case study of the South Bačka District. The study analyzes the spatial relationship between wildfire occurrence and the distribution of firefighting resources, including professional fire-rescue units and volunteer fire brigades. The objective is to identify areas with limited accessibility to response capacities, assess the contribution of volunteer firefighting organizations to territorial coverage, and demonstrate how digital approaches can support climate resilience planning and disaster risk reduction.

2. Materials and Methods

2.1. Study Area

The Autonomous Province of Vojvodina is located in northern Serbia and represents one of the country's most important agricultural regions. Characterized by extensive arable land, open landscapes, dispersed rural settlements, and relatively low terrain elevation, the province is exposed to wildfire risks associated with agricultural activities, vegetation burning,

prolonged droughts, and extreme weather conditions. These characteristics make Vojvodina a suitable area for assessing the relationship between wildfire occurrence, emergency response capacity, and climate resilience.

This study focuses on the South Bačka District as a case study area. Located in the central part of Vojvodina, the district includes the City of Novi Sad and the municipalities of Bač, Bačka Palanka, Bački Petrovac, Beočin, Srbobran, Temerin, Titel, Vrbas, and Žabalj. The district combines densely populated urban areas with extensive agricultural and rural zones, creating diverse conditions for wildfire occurrence and emergency response. Due to its demographic, economic, and territorial significance, South Bačka represents a relevant case for examining the effectiveness of wildfire response capacities and identifying opportunities for strengthening local climate resilience.

2.2. Data Sources

The analysis was based on digital spatial datasets describing wildfire occurrence and the distribution of firefighting resources within the study area. Wildfire data were derived from records of open-space fires registered on state-owned land during 2012, a year characterized by extreme temperatures and prolonged drought conditions that resulted in an exceptionally high number of wildfire events. A total of 1,189 wildfire locations were identified within the South Bačka District. The year 2012 was selected because it represents one of the most severe wildfire seasons recorded in Serbia during the last two decades. Exceptionally high temperatures, prolonged drought, and widespread fire occurrence created conditions that clearly exposed the spatial distribution of wildfire risk and the functioning of available response capacities. Analysing an extreme fire year enables a more robust assessment of territorial coverage under high-demand conditions and provides valuable insights for climate resilience planning in the context of increasingly frequent extreme weather events.

Data on firefighting resources included the locations of professional fire-rescue units and volunteer fire brigades operating within the district. Additional datasets included administrative boundaries and spatial reference layers necessary for territorial analysis. All datasets were georeferenced and integrated into a digital spatial database to enable further analysis and visualization.

2.3. Analytical Framework

The research applies a digital approach to the assessment of wildfire response capacity by integrating multiple spatial datasets within a unified analytical framework. The analysis examines the spatial relationship between wildfire occurrence and the territorial distribution of firefighting resources in order to evaluate response capacity and identify areas potentially exposed to limited accessibility.

The analytical process consisted of four main steps:

- compilation and preparation of digital spatial data,
- mapping of wildfire locations and firefighting resources,
- assessment of territorial coverage and spatial accessibility, and
- identification of areas requiring enhanced response capacities.

Territorial coverage was assessed by analysing the spatial proximity between recorded wildfire locations and the distribution of professional fire-rescue units and volunteer fire brigades. The evaluation was based on the assumption that shorter spatial distances indicate greater potential accessibility and faster initial response. Areas with a high concentration of wildfire events and a relatively low density of firefighting resources were identified as

potentially under-served. Conversely, areas where volunteer fire brigades complemented the territorial distribution of professional units were considered to have improved response coverage. The assessment was intended to provide a comparative spatial evaluation of territorial accessibility rather than a simulation of actual intervention times or operational performance.

Particular attention was given to the potential contribution of volunteer fire brigades in improving territorial coverage and supporting first-response activities in rural areas.

By combining digital data integration, spatial assessment, and climate resilience perspectives, the proposed framework enables the identification of territorial vulnerabilities and supports evidence-based decision-making for disaster risk reduction and climate adaptation planning.

3. Results

The South Bačka District represents one of the most important and functionally complex territorial units within the Autonomous Province of Vojvodina. The area is characterized by a heterogeneous land-use structure, intensive agricultural production, a developed settlement network, significant population concentration, and extensive transport infrastructure. Urban, suburban, and rural environments coexist within a relatively limited geographical area, creating diverse conditions that influence both wildfire occurrence and emergency response capacity.

According to available records, a total of 1,189 open-space fires were registered on state-owned land within the South Bačka District during 2012. This year was characterized by prolonged drought periods, exceptionally high temperatures, and reduced vegetation moisture, creating favorable conditions for wildfire ignition and rapid fire spread. The combination of climatic conditions, dry biomass, and anthropogenic activities contributed to a significant increase in wildfire occurrence throughout the district.

Figure 1 presents the spatial distribution of recorded wildfire events together with the locations of professional fire-rescue units and volunteer fire brigades. The analysis reveals that wildfire occurrence was not evenly distributed across the district. Instead, the recorded events exhibit both broad spatial dispersion and localized concentrations associated with areas of intensive agricultural activity, developed settlement networks, and increased human presence.

Particularly high concentrations of wildfire events can be observed in the wider Novi Sad area and in municipalities characterized by extensive agricultural land use. This pattern suggests a strong relationship between wildfire occurrence and anthropogenic factors, including agricultural practices, infrastructure density, and the intensity of land use. At the same time, territorial differences among municipalities indicate that wildfire occurrence is influenced by a combination of environmental, infrastructural, and socioeconomic factors.

The structure of recorded events further highlights the predominance of vegetation-related fires, including grassland, reed, and low-vegetation fires. Such events are typical of open-space environments and are especially common during periods of drought and elevated temperatures. The prevalence of these fire types confirms the importance of climatic conditions in shaping wildfire risk and emphasizes the vulnerability of agricultural and semi-natural landscapes to fire occurrence.

The spatial distribution of wildfire events also demonstrates a noticeable association with agricultural fields, canal networks, unmanaged vegetation areas, and other open landscapes. These locations are often characterized by increased exposure to wind and favorable conditions for rapid horizontal fire spread. Consequently, the proximity and

availability of firefighting resources become critical factors influencing the effectiveness of emergency response.

Figure 1 also illustrates the territorial distribution of professional fire-rescue units and volunteer fire brigades within the district. Professional units are primarily concentrated in major urban centers, while volunteer fire brigades are more broadly distributed across smaller settlements and rural communities. A total of 44 volunteer fire brigades were identified within the study area, indicating a significant potential for local response and community-based support during wildfire events.

The analysis suggests that volunteer fire brigades may play an important role in strengthening local resilience by improving territorial coverage and supporting initial response activities, particularly in areas located farther from professional fire-rescue units. Although the spatial presence of firefighting resources does not necessarily reflect their operational readiness, equipment level, or personnel capacity, the observed distribution indicates that volunteer organizations represent an important component of the overall response system.

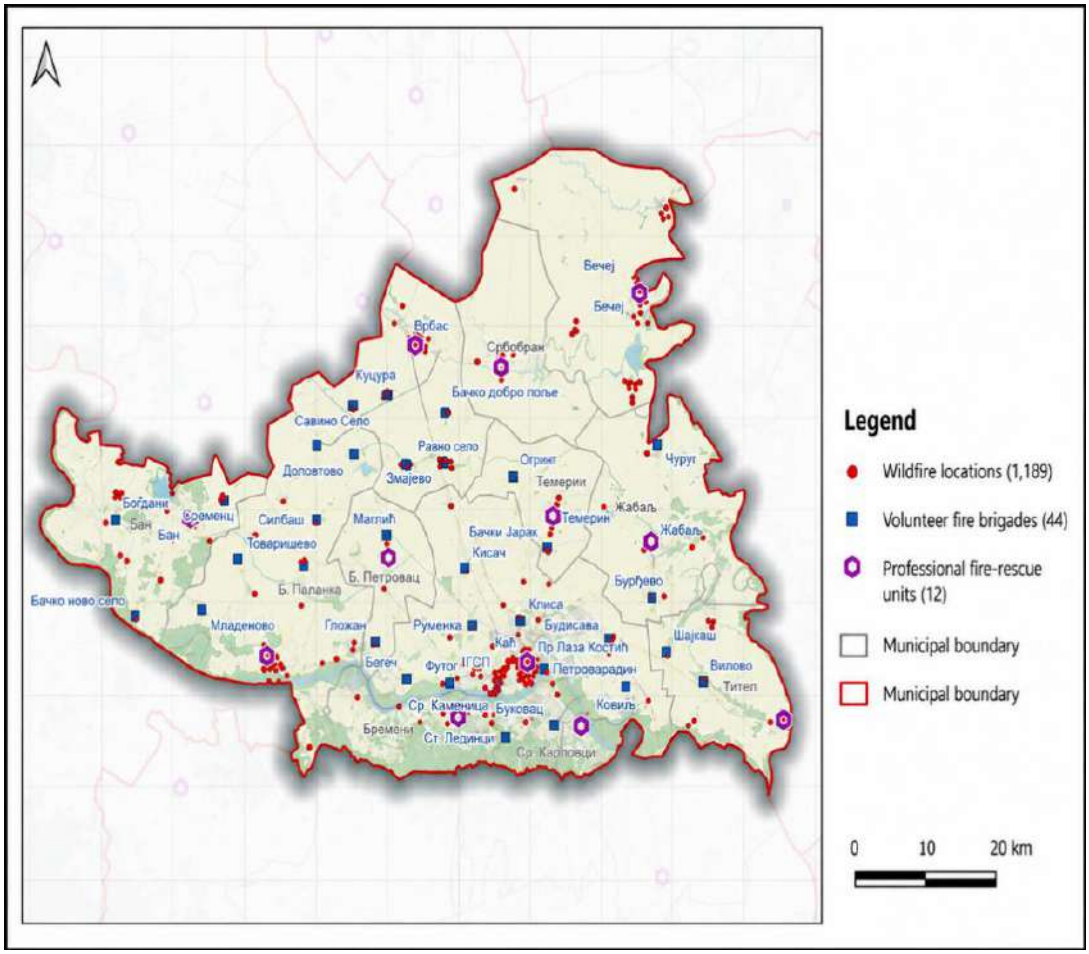


Figure 1 *– Spatial distribution of wildfire events and response capacities in the South Bačka District*

From the perspective of climate resilience, the results demonstrate that wildfire risk and response capacity are both strongly influenced by spatial factors. The integration of wildfire records and firefighting resource data within a digital analytical environment enables the identification of territorial vulnerabilities and supports evidence-based planning. Such digital approaches can assist decision-makers in improving preparedness, prioritizing investments, and strengthening local capacities for responding to climate-related hazards.

4. Discussion

The spatial analysis conducted in this study highlights the importance of integrating prevention, local response capacities, professional intervention mechanisms, and post-event evaluation into a unified wildfire risk management framework. Based on the findings, a conceptual model for strengthening wildfire response capacity is proposed (Figure 2).

The model consists of four interconnected phases supported by a transversal digital information layer. The first phase focuses on prevention and risk management activities, including vegetation management, control of agricultural practices, public awareness raising, and early warning mechanisms. These activities aim to reduce wildfire occurrence and minimize the exposure of vulnerable areas.

The second phase represents the initial response at the local level. In this stage, volunteer fire brigades play a critical role due to their territorial proximity and ability to react rapidly during the early stages of wildfire development. Their contribution is particularly important in rural areas where response times may significantly influence fire spread and overall intervention effectiveness.

The third phase includes professional emergency response conducted by fire-rescue units. Professional responders assume operational command, deploy specialized equipment and personnel, and coordinate activities with other institutions involved in emergency management. This phase represents the core operational component of wildfire suppression and protection activities.

The fourth phase focuses on recovery, evaluation, and learning. Activities include incident documentation, damage assessment, performance evaluation, analysis of response times, and incorporation of lessons learned into future planning processes. Continuous evaluation contributes to the improvement of operational procedures and supports long-term resilience building.

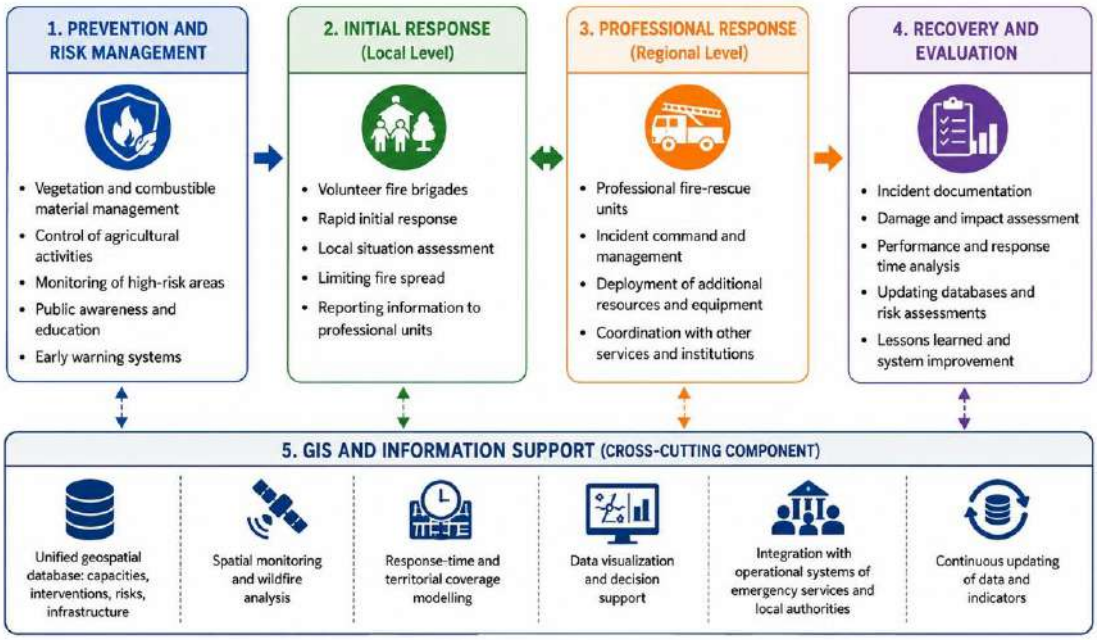


Figure 2 *– Digital framework for wildfire risk management and climate resilience enhancement*

A key feature of the model is the integration of digital information and spatial data across all phases. Digital databases, spatial monitoring, territorial analyses, response-time assessments, and decision-support tools provide the information necessary for effective planning and resource allocation. By linking prevention, response, recovery, and digital

information management, the model supports a comprehensive approach to climate resilience and wildfire risk reduction.

The proposed framework emphasizes that climate resilience is not solely determined by the availability of firefighting resources, but also by the ability to collect, integrate, analyze, and continuously utilize digital information throughout the entire wildfire management cycle.

5. Conclusion

Climate change is expected to increase the frequency and intensity of wildfire-prone conditions, creating additional challenges for emergency management systems and local communities. In regions characterized by extensive agricultural land and open landscapes, such as Vojvodina, strengthening response capacities represents an important component of climate resilience and disaster risk reduction.

Using the South Bačka District as a case study, this research examined the spatial distribution of wildfire events and firefighting resources in order to assess territorial response capacity. The results indicate that wildfire occurrence is not evenly distributed across the district and is strongly influenced by the interaction of climatic conditions, land-use characteristics, and human activities. The analysis also revealed noticeable territorial differences in the accessibility of firefighting resources.

Particular importance was identified in the role of volunteer fire brigades, whose widespread territorial presence complements the operational capacities of professional fire-rescue units. Although their operational readiness may vary, volunteer brigades represent an important local resource that can contribute to faster initial intervention, especially in rural areas and locations situated farther from professional response centers.

The study further demonstrates the value of digital approaches for understanding wildfire risk and supporting evidence-based decision-making. The integration of spatial wildfire records and firefighting resource data enables the identification of territorial vulnerabilities, supports resource allocation, and provides a foundation for improving preparedness and response planning.

Based on the findings, a conceptual framework for wildfire risk management and response capacity enhancement was proposed. The framework emphasizes the integration of prevention, local response, professional intervention, recovery activities, and digital information support as mutually reinforcing components of climate resilience. Such an approach can support more effective wildfire risk management and contribute to the development of resilient communities capable of adapting to increasing climate-related hazards.

Future research should expand the analysis to other districts of Vojvodina and incorporate additional operational indicators, including response times, intervention outcomes, and capacity performance data, in order to support more comprehensive assessments of wildfire resilience at the regional level.

Acknowledgment

This research was supported by the Provincial Secretariat for Higher Education and Scientific Research through the project **"***Assessment of Emergency Management Capacity for Wildfires in Vojvodina".*

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Influence Of Solar Radiation, Façade Orientation and Diural Ambient Temperature Variations on the Transient Thermal Behaviour of External Walls

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Abstract

Building envelopes are continuously exposed to transient climatic conditions characterized by diurnal ambient temperature variations and solar radiation. These environmental actions produce time-dependent temperature fields that cannot be accurately represented using conventional steady-state analytical methods.

This study investigates the influence of solar radiation, façade orientation, and diurnal ambient temperature variations on the transient thermal behaviour of multilayer external walls using the Finite Element Method (FEM). Two-dimensional transient analyses were performed for masonry wall assemblies with and without external thermal insulation under representative summer and winter climatic conditions for North Macedonia.

The numerical model incorporates realistic daily temperature cycles, solar radiation intensity, and façade orientation to evaluate their combined influence on heat transfer through the building envelope. The results show that solar radiation substantially increases external surface temperatures and modifies the temperature distribution within the wall, particularly during summer. West-facing façades exhibit the highest thermal loading because peak solar radiation coincides with maximum ambient air temperatures. Thermal inertia causes delayed heat transfer through the wall, while external insulation effectively attenuates temperature fluctuations and stabilizes the internal surface temperature.

The study demonstrates that transient finite element analysis provides a more realistic assessment of wall thermal performance than conventional steady-state methods and represents an effective tool for the design of energy-efficient building envelopes under realistic climatic conditions.

Keywords

Transient heat transfer, building envelope, external wall, solar radiation, diural temperature variation, finite element method, thermal insulation.

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1. Introduction

Improving the thermal performance of building envelopes is a major objective of modern building design because it directly influences energy consumption, indoor thermal comfort, and the durability of construction materials. External walls represent a significant part of the building envelope and therefore play a key role in heat exchange between indoor and outdoor environments.

In engineering practice, thermal performance is commonly evaluated using steady-state analytical methods, such as those defined in EN ISO 6946. Although these methods provide reliable estimates of thermal transmittance under constant boundary conditions, they cannot accurately represent real climatic conditions, where ambient temperature and solar radiation vary continuously throughout the day. Consequently, the temperature distribution within external walls becomes a transient phenomenon governed by heat storage, attenuation of temperature fluctuations, and phase shift caused by the thermal inertia of construction materials.

The present study investigates the combined influence of solar radiation, façade orientation, and diurnal ambient temperature variations on the transient thermal behaviour of multilayer external walls using two-dimensional finite element analysis. Masonry wall assemblies with and without external thermal insulation are analysed under representative summer and winter climatic conditions. The results provide insight into heat storage, delayed heat transfer, and the contribution of external insulation to the thermal performance of building envelopes under realistic environmental loading.

2. Numerical Model

2.1. Governing Heat Transfer Equation

Heat transfer through the wall was analysed as a two-dimensional transient conduction problem using the Finite Element Method (FEM). The wall materials were assumed to be homogeneous, isotropic, and characterized by constant thermophysical properties. The transient heat conduction process is governed by Fourier's equation:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) \quad (1)$$

where: T is the temperature, t is time, ρ is the material density, c_p is the specific heat capacity, λ is the thermal conductivity.

The governing equation was solved using the transient heat transfer module implemented in the numerical software.

2.2. Wall Configuration

Two representative multilayer external wall assemblies commonly used in residential buildings were analysed. The first configuration W1 consisted of a masonry wall without additional thermal insulation, while the second configuration W2 incorporated an external thermal insulation layer of only 5 cm expanded polystyrene (EPS) to improve the thermal performance of the building envelope. The geometrical dimensions and thermophysical properties adopted in the numerical model are summarized in Table 1.

Table 1 *– Wall configurations analysed in the numerical simulations.*

Configuration	***Wall assembly (inside → outside)***	**Thickness (mm)**
W1	*Internal plaster (25 mm) + Clay block masonry (250 mm) + External plaster (25 mm)*	*300*
W2	*Internal plaster (25 mm) + Clay block masonry (250 mm) + Expanded polystyrene (EPS) insulation (50 mm) + External plaster (25 mm)*	*400*

Table 2 *– Thermophysical properties of materials used in the numerical model.*

Configuration	***Thermal conductivity, λ (W·m⁻¹·K⁻¹)***	**Density, ρ (kg·m⁻³)**	**Specific heat capacity, cp (J·kg⁻¹·K⁻¹)**
Lime–cement plaster	0.99	1800	840
Clay block masonry	0.52	1000	840
Expanded polystyrene (EPS)	0.040	20	1450

The comparison of insulated and non-insulated wall assemblies enables assessment of the influence of thermal insulation on the transient temperature distribution and heat propagation through the building envelope.

2.3. Finite Element Model and Model Assumptions

A two-dimensional finite element model was developed to simulate transient heat transfer through the wall cross-section. The computational domain was discretized using quadrilateral finite elements with mesh refinement near the external surface to accurately capture steep temperature gradients. Transient analyses were performed using an implicit time integration scheme. Simulations were repeated over successive daily cycles until periodic thermal conditions were achieved, eliminating the influence of the initial temperature field.

The numerical model assumes homogeneous, isotropic, and temperature-independent material properties, conductive heat transfer only, perfect thermal contact between adjacent layers, constant indoor temperature, and neglects moisture transport, latent heat effects, internal heat gains, and thermal bridges.

2.4. Boundary Conditions

The external wall surfaces were subjected to realistic climatic loading consisting of time-dependent ambient air temperature and incident solar radiation representative of summer and winter conditions. The outdoor temperature varied continuously during the day according to measured climatic data (Table 1), while the intensity of solar radiation depended on the façade orientation and the position of the sun (Figure 1).

Convective heat transfer between the wall surface and the surrounding air was considered through appropriate external surface heat transfer coefficients. Solar radiation was introduced as an additional heat flux acting on the exposed external surface. On the internal side of the wall, a constant indoor air temperature representative of conditioned building spaces was prescribed throughout the simulations. Internal surface heat transfer was modelled using standard convective boundary conditions. This combination of boundary conditions enables realistic simulation of the transient thermal behaviour of external walls subjected to changing environmental conditions.

***Table 3** – Boundary conditions adopted in the transient numerical simulations.*

Parameter	Summer	Winter
Indoor air temperature, Ti	25 °C	21 °C
Maximum outdoor air temperature	40 °C	-4 °C
Minimum outdoor air temperature	20 °C	-20 °C
Max. solar radiation (Fig.1)	1100 $W \cdot m^{-2}$	Neglected / low intensity
External convection coefficient	25 $W \cdot m^{-2} \cdot K^{-1}$	25 $W \cdot m^{-2} \cdot K^{-1}$
Internal convection coefficient	4 $W \cdot m^{-2} \cdot K^{-1}$	4 $W \cdot m^{-2} \cdot K^{-1}$
Façade orientation	East / West	East / West

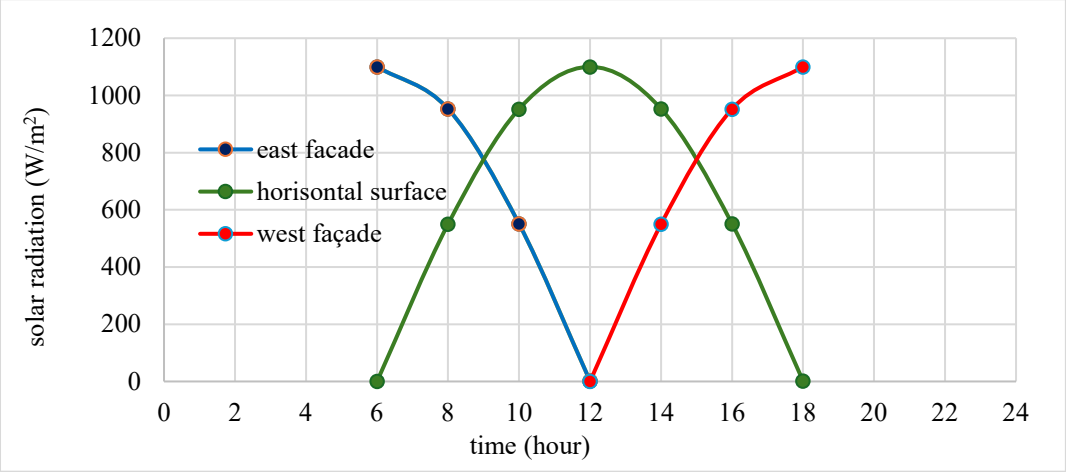


***Figure 1** – Intensity of sun radiation on building envelope in summer, in 24 hours*

3. Results and Discussion

3.1. Effect of Daily Ambient Temperature Variations

The transient numerical simulations show that the temperature distribution within the wall continuously changes in response to diurnal ambient temperature variations. Unlike steady-state conditions, transient climatic loading produces a dynamic temperature field that evolves as heat propagates through the different wall layers.

Figure 2 presents the temperature profiles across Configuration W1 for representative times during a summer day. The external surface responds rapidly to changes in outdoor temperature, whereas the internal layers exhibit a delayed response due to the thermal inertia of the construction materials. Consequently, the temperature field depends not only on the instantaneous outdoor conditions but also on the previous thermal history of the wall.

Temperature fluctuations gradually decrease through the wall thickness as heat is stored within the masonry. The resulting attenuation of the thermal wave and the associated

phase shift delay heat transfer toward the interior, improving thermal stability. These transient effects cannot be represented by conventional steady-state analytical methods.

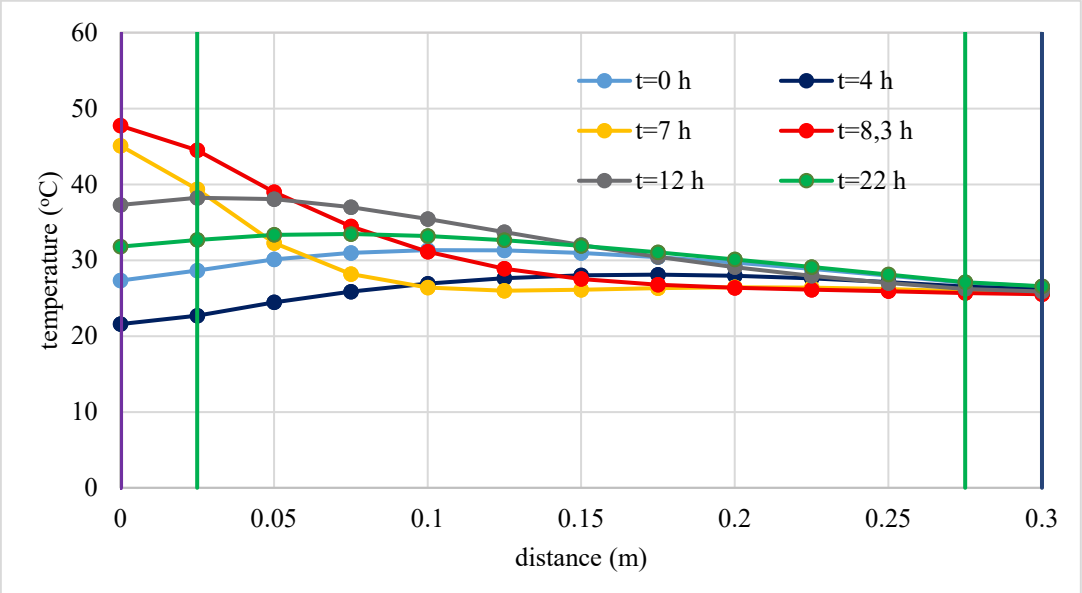


***Figure 2** – Time dependent temperature profiles across Configuration W1 oriented on east, under daily summer temperature variations and solar radiation*

3.2. Influence of Solar Radiation

Solar radiation significantly increases the thermal load acting on the external wall by introducing an additional heat flux at the exposed façade surface. Figure 3 presents the temperature profiles for Configuration W1 under summer conditions. During periods of maximum solar exposure, the external surface temperature exceeds the ambient air temperature, increasing both the temperature gradient and heat penetration into the masonry.

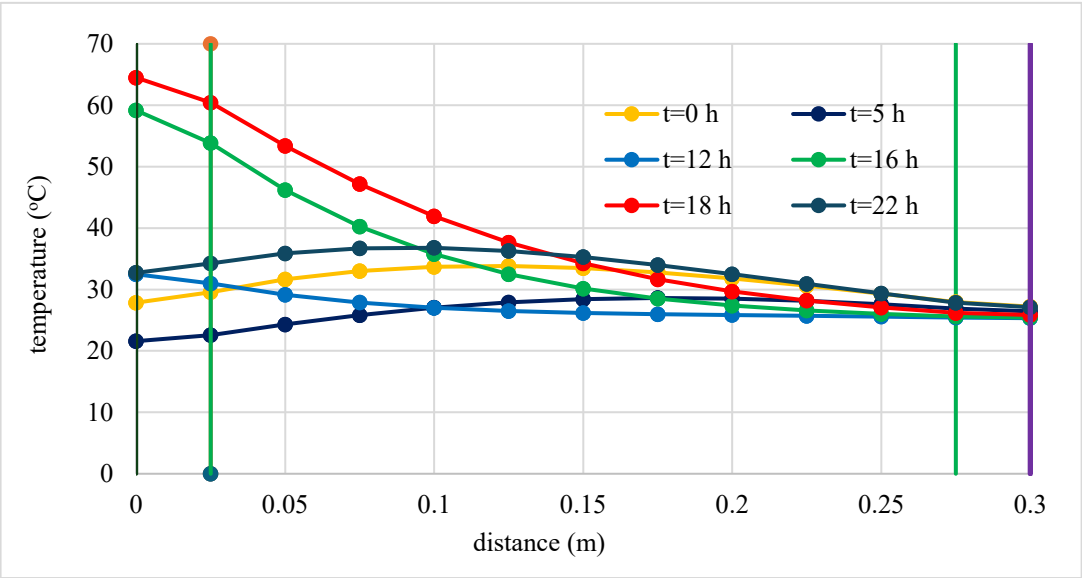


***Figure 3** – Temperature profiles across Configuration W1 oriented on west, under daily summer temperature variations and solar radiation, over a 24-hour period*

The absorbed solar energy is gradually stored within the wall and released over time because of the thermal inertia of the masonry. As a result, elevated wall temperatures persist after solar radiation decreases, delaying heat transfer toward the interior and increasing cooling demand during the evening.

Compared with simulations neglecting solar radiation, the numerical results demonstrate considerably higher wall temperatures throughout the daytime. These findings confirm that transient finite element analysis is required to capture the coupled effects of solar radiation, heat storage, and conductive heat transfer under realistic climatic conditions.

3.3. Influence of Façade Orientation

The orientation of the external wall strongly influences its transient thermal behaviour because it determines both the magnitude and timing of incident solar radiation. Figures 2 and 3 compare the temperature distributions for east- and west-facing façades subjected to identical ambient temperature variations.

The east-facing façade receives maximum solar radiation during the cooler morning hours, resulting in moderate thermal loading. In contrast, the west-facing façade is exposed to peak solar radiation when ambient air temperatures are highest, producing the greatest heat storage within the wall and the highest external surface temperatures.

Due to thermal inertia, the additional heat stored in the west-facing wall is released gradually during the evening, extending heat transfer toward the indoor environment. These results demonstrate that façade orientation should be considered together with thermal insulation and shading when designing energy-efficient building envelopes.

3.4. Effect of External Thermal Insulation

External thermal insulation significantly modifies the transient thermal response of the wall by reducing heat penetration and attenuating temperature fluctuations. Figures 3 and 4 compare the uninsulated (W1) and insulated (W2) wall configurations under identical summer climatic conditions.

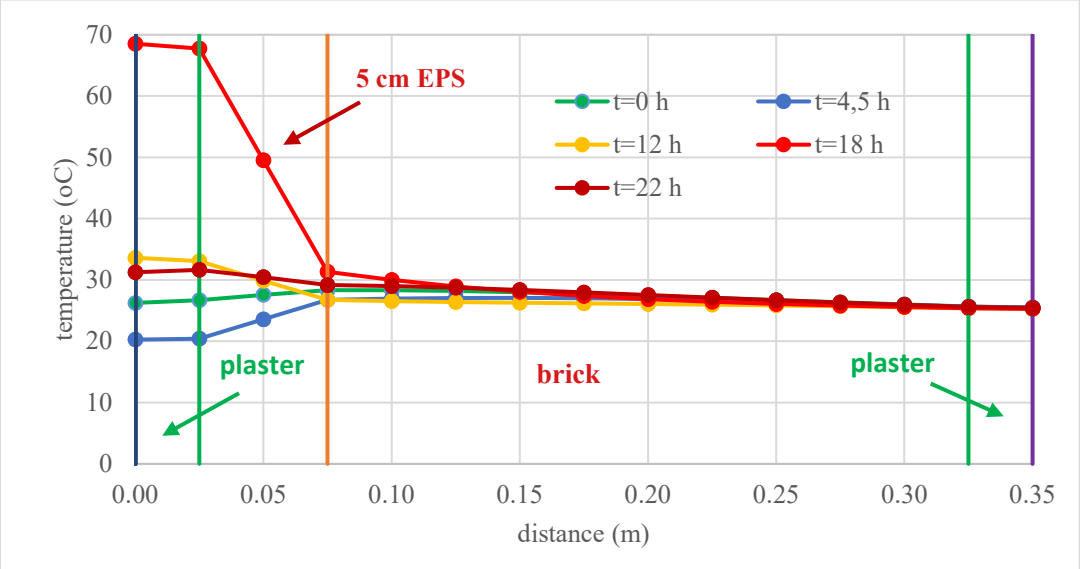


***Figure 4** – Temperature profiles across Configuration W2 oriented on west, under daily summer temperature variations and solar radiation, over a 24-hour period*

In Configuration W1, solar energy penetrates directly into the masonry, producing larger temperature fluctuations and delayed heat transfer toward the interior. In contrast, the EPS insulation in Configuration W2 limits heat penetration, maintains the masonry at more uniform temperatures, and stabilizes the internal surface temperature throughout the daily cycle. The insulation layer also relocates the principal temperature gradient from the masonry to the insulation, reducing thermal stresses and improving the dynamic thermal performance of the wall.

In winter, to obtain the most unfavourable impact, solar radiation is not included in the analysis. The temperature profiles across Configuration W2, for different periods of the day, are presented in Figure 5.

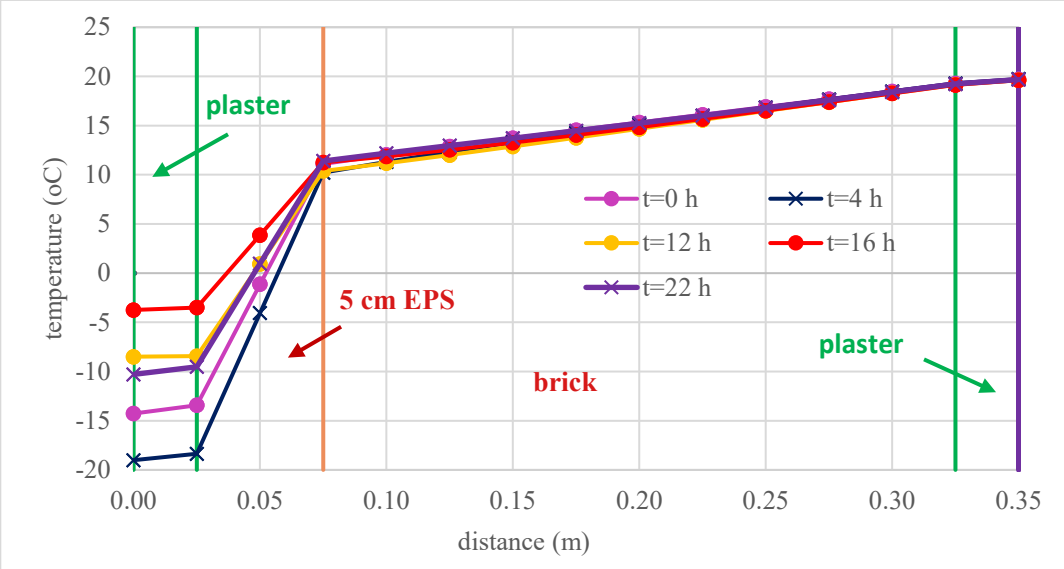


***Figure 5** – Temperature profiles across Configuration W2, under daily winter temperature variations, over a 24-hour period*

Due to the thermal resistance of the insulation, the external wall surface temperatures under winter conditions are slightly lower than those without insulation. However, over a 24-hour period, the masonry wall exhibits an approximately constant temperature that is significantly higher than that of a non-insulated wall.

For this reason, the energy consumption for heating is expected to be significantly lower than in the case of a non-insulated wall. The positive effect of insulation cannot be adequately represented when an approximate method recommended in MKS EN 1991-1-5 is used to define the temperature profile.

4. Conclusions

This study investigated the influence of solar radiation and daily ambient temperature variations on the transient thermal behaviour of external walls using the finite element method. The numerical simulations considered realistic climatic loading, façade orientation, and the presence of external thermal insulation. Based on the obtained results, the following conclusions can be drawn:

Transient climatic conditions significantly influence the temperature distribution within external walls. Daily variations in ambient temperature produce continuously evolving temperature fields that cannot be adequately represented using conventional steady-state heat transfer methods.

Solar radiation substantially increases the thermal load acting on building envelopes during summer conditions. The absorbed solar energy elevates external surface temperatures and promotes heat storage within the wall, resulting in delayed heat transfer toward the indoor environment.

Façade orientation plays an important role in the dynamic thermal response of external walls. West-facing façades experience the most severe thermal loading because maximum solar radiation coincides with the highest outdoor air temperatures, leading to greater heat storage and increased evening heat gains.

External thermal insulation effectively attenuates temperature fluctuations and stabilizes the internal thermal conditions of the wall. By reducing heat penetration into the masonry, insulation decreases the amplitude of temperature variations, limits delayed heat transfer, and improves the overall thermal performance of the building envelope.

Transient finite element analysis provides a realistic framework for evaluating building envelope performance under actual environmental conditions. The numerical model captures the coupled effects of heat conduction, thermal inertia, cyclic ambient temperatures, and solar radiation, enabling a more comprehensive assessment of energy efficiency and thermal behaviour than is possible with steady-state approaches.

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Interaction Between Reinforced Concrete Frames and Masonry Infill Walls in the Context of Seismic Performance and Sustainable Construction

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Abstract

The interaction between reinforced concrete (RC) frames and masonry infill walls significantly affects the seismic response of multi-story buildings, where masonry walls are less prevalent at the ground floor than at the upper stories due to functional requirements. This paper compares two three-dimensional structural models: one with bonded infill walls and one with structurally isolated infill walls. Differences in global stiffness, natural vibration periods, seismic force distribution, lateral displacements, and reinforcement demand are evaluated. The results show that bonded infill walls reduce vibration periods, increase seismic forces, and concentrate deformations and internal forces at the ground floor, increasing the risk of soft-story formation and torsional effects. In contrast, structural separation of infill walls from the load-bearing system provides a more predictable response and reduces earthquake-induced damage. Limiting infill–frame interaction improves seismic performance, extends service life, and increases the potential for material reuse, supporting sustainable construction and circular economy principles.

Keywords

Reinforced concrete (RC) frames, masonry infill walls, seismic response, soft story, reliability, sustainable construction.

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1. Introduction

Multi-story reinforced concrete (RC) buildings in regional construction practice are most commonly designed as monolithic frame structures, while frame infill is typically constructed using traditional masonry techniques. In such buildings, the presence of masonry walls at the ground floor is significantly lower than on the upper stories, primarily due to functional space requirements (Figure 1). Although these walls are often considered only as dead load in structural analysis, in the completed structure they frequently remain in direct interaction with the RC frame. This interaction alters the dynamic characteristics of the system and the distribution of internal forces, particularly during the initial stage of seismic action, when the stiffness of the infill walls remains high [1–6]. Observations from past earthquakes and numerous research studies indicate that such interaction may be beneficial in terms of reducing overall displacements and dissipating seismic energy through infill wall damage, but it may also have highly unfavorable consequences due to the occurrence of short-column effects, soft-story mechanisms, local concentrations of shear stresses, torsional effects, and out-of-plane failure of infill walls [7–15].



***Figure 1** – Typical buildings with infilled upper stories and an open ground floor*

In addition to the requirements for life safety and structural integrity, modern seismic design is increasingly being viewed through the principles of sustainable construction and the circular economy [16]. Structures that sustain less damage during earthquakes require fewer repair interventions, lower consumption of new materials and energy for rehabilitation, and generally achieve a longer service life. Consequently, proper consideration of the influence of non-structural elements, including masonry infill walls and the possibility of their structural separation from the load-bearing system, is important not only from the perspective of seismic safety but also in terms of sustainable management of the built environment.

Based on these considerations, this study examines how the assessment of seismic response differs when the same building is modeled with structurally isolated and with bonded masonry infill walls. Particular attention is given to the common structural configuration consisting of a more open ground floor and infilled upper stories, since such a stiffness distribution represents a frequent and unfavorable example in regional building practice. In this context, the objective of the paper is not to demonstrate the need for increasingly sophisticated nonlinear analyses, but rather to evaluate the extent to which the structural modeling concept itself influences the assessment of safety. The underlying

hypothesis is that the greatest source of uncertainty does not arise from software limitations, but from the discrepancy between the assumptions adopted in the structural analysis and the conditions actually realized during construction.

2. Analytical Models

The analysis was conducted on a building with a plan measuring 15.0 × 15.5 m, consisting of a basement, ground floor, and eight upper stories, with a total height of H = 32.6 m (Figure 2). The basement is partially embedded and enclosed by rigid reinforced concrete (RC) perimeter walls, while the upper levels comprise an RC frame structure with masonry infill walls and façade openings. The building is founded on a rigid foundation slab resting on soil with favorable geotechnical properties. Consistent with local construction practice, the ground floor is relatively open, whereas the upper stories contain a significantly higher proportion of masonry infill walls.

The numerical analysis was performed using the software package Tower. Material properties were adopted from the original study: C30/37 concrete with E_m = 33 GPa and masonry infill with E_m = 2.3 GPa. To simulate cracked behavior, stiffness reduction factors were introduced in the seismic analysis. For concrete, k = 0.6 was adopted for flexure and shear, while for masonry infill, k = 0.001 was used for out-of-plane bending stiffness and k = 0.6 for in-plane behavior.

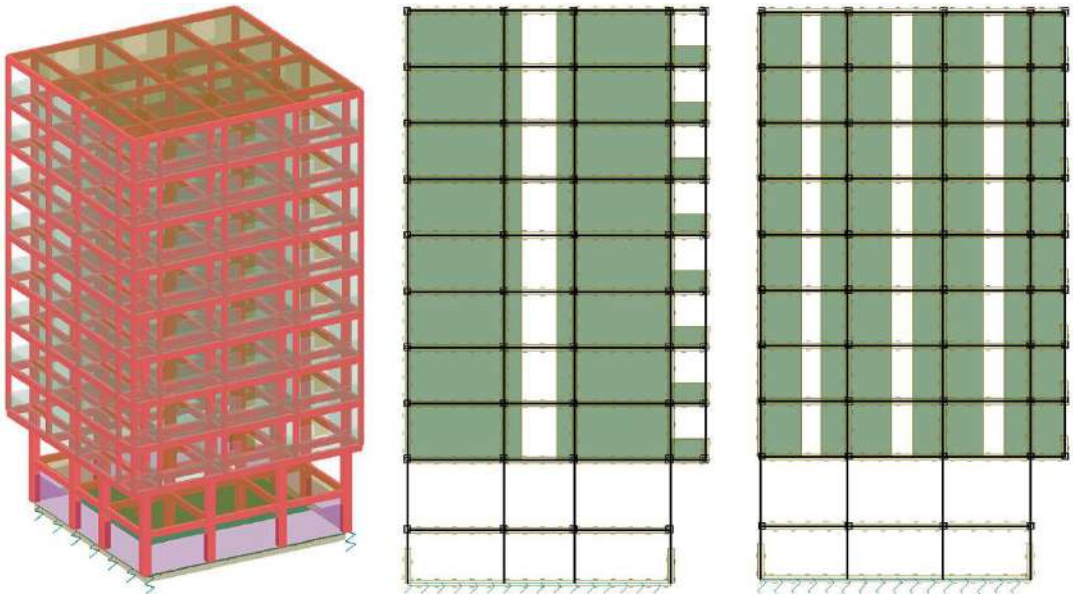


Figure 2 *– Three-dimensional analytical model and representative frame layouts*

Two three-dimensional structural models were compared. The first model represents a structure with bonded masonry infill walls, allowing active frame–infill interaction during the initial stage of seismic response. The second model represents a structure with structurally isolated infill walls, where the infill does not contribute to the global lateral stiffness of the system. Seismic analysis was performed in accordance with Eurocode 8 (EC8) for agR = 0.25g, Ground Type B, and Importance Class II. Behavior factors of q = 3.0 and q = 4.0 were adopted for the bonded and isolated infill models, respectively. For both models, natural vibration periods, total seismic forces in the principal directions, distributions of internal actions and lateral displacements, and required column reinforcement were analyzed in order to quantify the influence of the selected modeling approach on the global and local structural response.

The interpretation of masonry infill behavior is based on the well-established compressed diagonal strut mechanism, through which infill walls may temporarily increase the global stiffness of the structure while simultaneously transferring higher forces to contact regions, particularly in systems with irregular distributions of infill walls over the building height and plan. Within the broader research framework, the literature distinguishes between macro-models, in which infill walls are commonly idealized as equivalent diagonal compression struts, and more detailed micro-models that provide a more accurate representation of material behavior and interface interactions [9–15]. However, since the objective of this study is the practical comparison of two design-relevant scenarios, a simplified global approach was adopted using two conceptual limit cases: one with active infill participation and one with structurally isolated infill walls. Although this idealization does not provide a complete nonlinear description of infill degradation, it clearly demonstrates the sensitivity of structural performance to the fundamental design decision regarding the treatment of masonry infill walls.

2.1. Analysis Results

In the model with bonded infill walls, the obtained periods were T_1 = 1.25 s, T_2 = 1.20 s, and T_3 = 1.04 s, whereas in the model with isolated infill walls, the corresponding values were T_1 = 1.90 s, T_2 = 1.87 s, and T_3 = 1.60 s. Thus, the inclusion of bonded infill walls significantly increases the initial stiffness of the system and reduces the vibration periods by approximately 35%. At the same time, the total seismic forces also increase: for the bonded infill model, ΣS_x = 5582 kN and ΣS_y = 5277 kN, while for the isolated infill model, $\Sigma S_x = \Sigma S_y$ = 2669 kN, representing an approximately twofold increase. Regarding the vibration modes, the isolated infill model exhibits the expected separation of translational and torsional modes, whereas in the bonded infill model torsional behavior appears already within the first two modes.

Figure 3 shows the internal actions in a selected column from the three-dimensional model of the frame structure under seismic forces S_x. The distribution of axial forces (N_1) in the column is of particular interest. The isolated infill model shows a stepwise variation in axial force at floor levels, with its magnitude increasing from the top of the building toward the foundation, while remaining approximately constant within each story. This distribution is characteristic of “pure” frame systems subjected to lateral forces. This behavior is also reflected in the diagrams of transverse forces (V_2) and bending moments (M_3). The transverse force exhibits a stepwise distribution along the column height, with approximately constant values within individual stories and abrupt changes at slab levels, while its magnitude decreases from the ground floor toward the top of the building without a change in sign. The bending moments show a linear distribution within each story and a change in sign along the column height, with characteristic breaks in the diagram at the frame joints. This diagram shape corresponds to the expected behavior of a frame structure subjected to horizontal seismic loading. The lateral displacement diagram (u_2) also confirms behavior typical of a frame system, with a continuous increase in lateral displacements toward the top of the building.

Figure 4 shows the internal actions in the same column of the three-dimensional model with bonded masonry infill walls under seismic forces S_x. Unlike the isolated infill model, the axial force distribution (N_1) shows more pronounced variations over the building height, as well as higher axial force values in the upper stories. This indicates the active participation of masonry infill walls in transferring lateral loads and a change in the internal force path within the structure. As a result, the load distribution becomes less uniform, with more pronounced variation of axial forces along the column height.

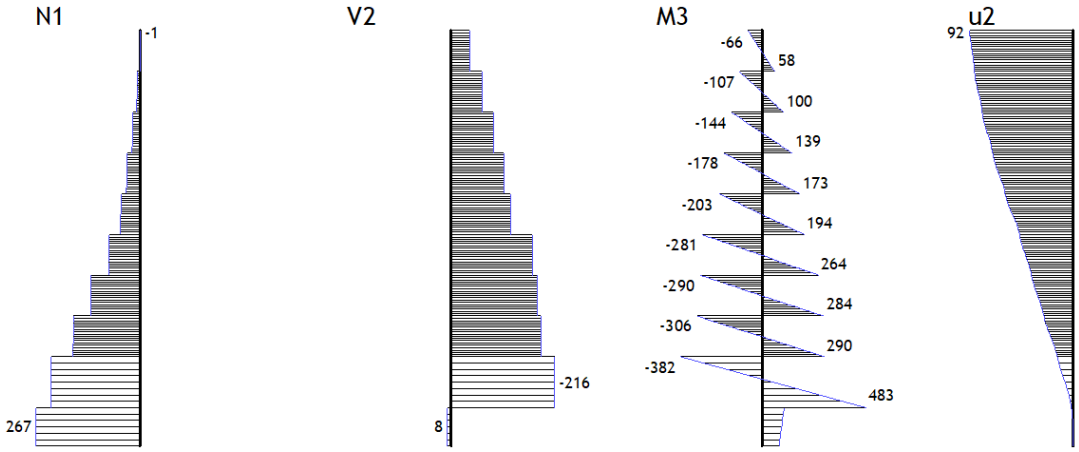


Figure 3 *– Internal actions in the column due to Sx for the model with isolated infill walls*

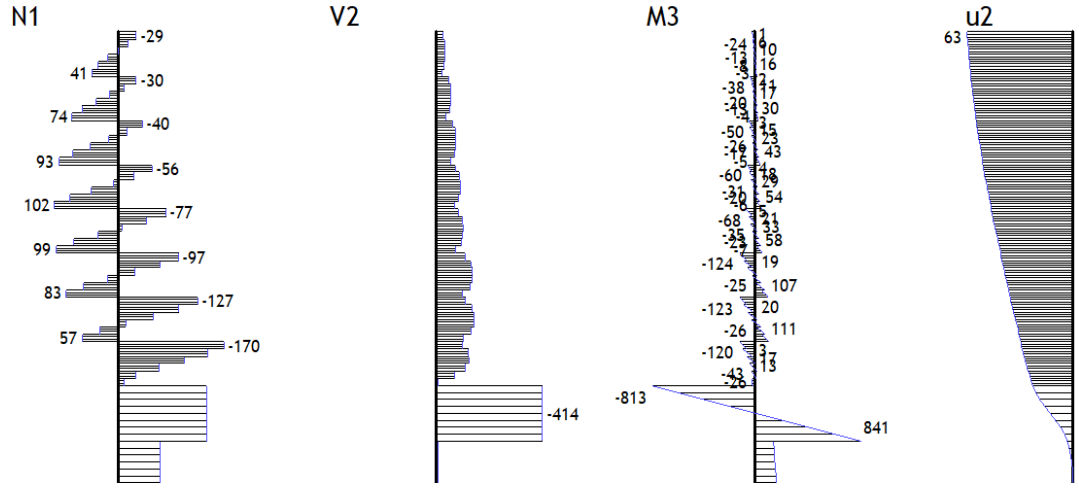


Figure 4 *– Internal actions in the column due to Sx for the model with bonded infill walls*

Similar differences can be observed in the transverse forces (V2) and bending moments (M3). Although the diagrams retain the general shape characteristic of a frame system, the values of transverse forces and bending moments are noticeably lower in the infilled stories and significantly higher at the open ground floor compared with the model with isolated infill walls. Due to the abrupt change in stiffness between the open ground-floor and the infilled upper stories, a pronounced concentration of internal forces occurs in the ground-floor and basement zones. This distribution confirms the development of a soft-story effect, whereby the majority of seismic demands are transferred to the columns of the lowest stories.

The lateral displacement diagram (u2) also indicates the formation of a soft-story mechanism. While the slope of the displacement curve is considerably reduced in the upper stories due to the increased stiffness provided by the masonry infill walls, a sudden change in slope and a concentration of interstory drifts can be observed at the open ground-floor level. Although the displacements of the upper stories are lower than those obtained for the isolated infill model, the ground floor displacement is greater, further confirming the concentration of deformations in the lowest story.

The obtained diagrams confirm that bonded masonry infill walls do not act merely as additional mass but significantly influence the distribution of stiffness and seismic forces within the structure. As a result, the expected response of a “pure” frame system is altered, increasing the structure's susceptibility to local stress concentrations and deformation demands in the lower stories.

The change in global stiffness is also directly reflected in the required amount of reinforcement in the vertical structural elements (Figures 5 and 6). The model with bonded

infill walls requires approximately twice as much longitudinal and transverse reinforcement in the ground-floor columns, whereas the model with isolated infill walls results in a more uniform distribution of reinforcement demand over the building height and a greater proportion of reinforcement in the columns of the upper stories.

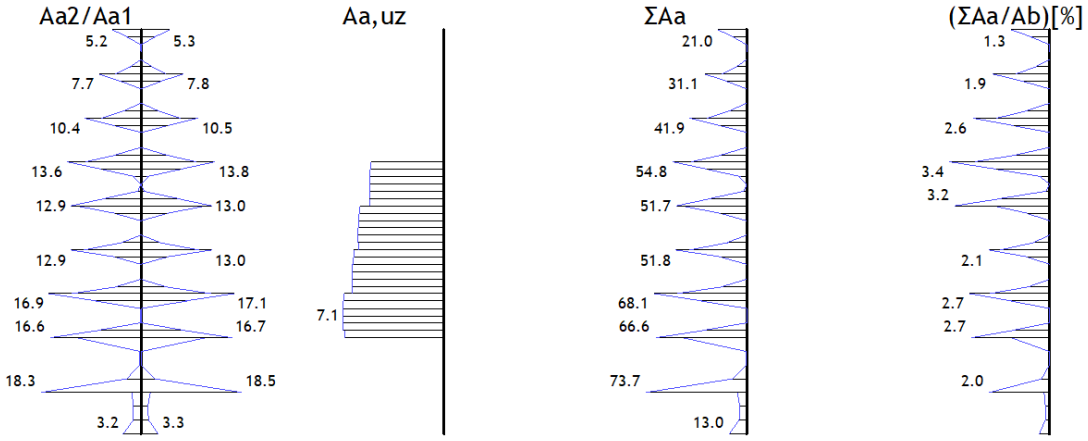


Figure 5 *– Required column reinforcement for the model with isolated infill walls*

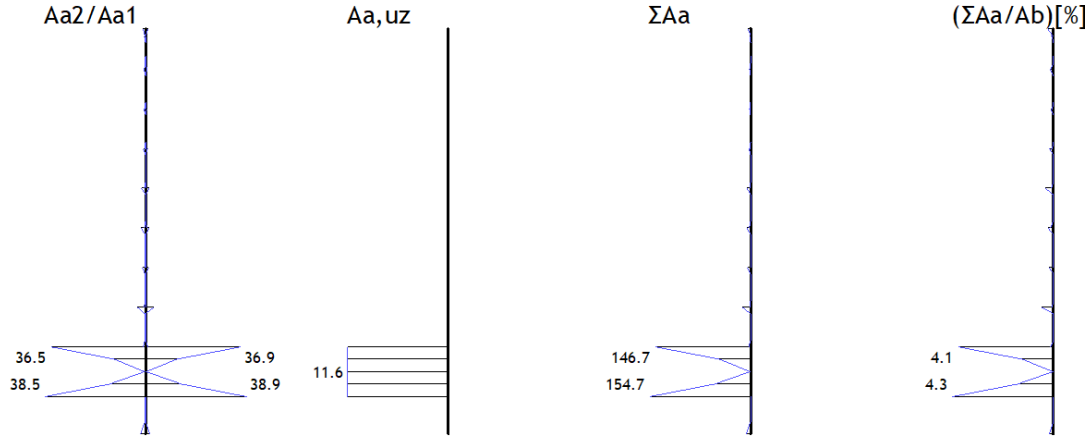


Figure 6 *– Required column reinforcement for the model with bonded infill walls*

2.2. Discussion of Results

The obtained results confirm that the modeling approach adopted for masonry infill walls is not merely a numerical issue but primarily a conceptual one. In the initial stage of response, bonded infill walls appear to improve structural performance by reducing overall displacements; however, they simultaneously increase seismic forces and concentrate deformations and reinforcement demands at the ground-floor level. In buildings with an open ground floor, this creates an unfavorable soft-story mechanism, where the RC columns of the ground floor may become critically loaded before significant degradation of the infill walls occurs in the upper stories.

It is important to emphasize that the linear model with bonded infill walls represents the initial tangent stiffness of the system and therefore does not capture the full nonlinear degradation of masonry walls under cyclic loading. Conversely, the model with isolated infill walls may underestimate the initial forces if the completed structure does not provide actual structural separation between the infill walls and the RC frame. Consequently, the issue cannot be reduced to the selection of a more sophisticated analysis procedure; the key requirement is consistency between the design concept, the adopted analytical model, and

the actual construction practice. If isolated infill walls are specified in the design, their separation from the frame and out-of-plane stability must be ensured through appropriate detailing and construction. Otherwise, the influence of bonded infill walls should be considered, at least approximately, in the assessment of seismic response.

From a design perspective, the results suggest a practical conclusion: verification of a "pure" frame system alone is insufficient for buildings in which continuous and rigid masonry infill walls are expected under actual service conditions, particularly when the ground floor is open, and the upper stories are densely infilled. In such cases, even a simple comparative analysis of two models can provide a useful estimate of the possible range of structural response and support decisions regarding ground-floor column detailing, selection of behavior factors, and the need for systematic infill isolation. This approach offers a practical decision-making framework without requiring complex nonlinear time-history analyses, making it well suited to engineering practice. At the same time, solutions that limit unfavorable interaction between infill walls and the structural system can reduce seismic damage, repair requirements, and the amount of construction waste generated after earthquakes. In this way, seismic design gains an additional sustainability dimension by extending the service life of buildings and reducing resource consumption throughout their life cycle, in accordance with the principles of sustainable construction.

3. Conclusion

The study demonstrates that neglecting masonry infill walls in seismic analysis while allowing their rigid interaction with the structural system in the completed building represents a significant conceptual inconsistency. In the analyzed case, bonded infill walls reduced the vibration periods, approximately doubled the total seismic forces, increased torsional sensitivity, and concentrated deformations and reinforcement demands in the ground-floor and basement levels. In contrast, the model with isolated infill walls produced a more uniform distribution of displacements, but such an approach is appropriate only when structural separation is effectively implemented through detailing and construction.

The main practical recommendation of this study is that the design of RC frame buildings should either consistently incorporate systematic infill isolation while ensuring adequate out-of-plane stability, or, in the case of non-isolated infill walls, include an additional assessment of their influence on seismic response, particularly for buildings with open ground floors. Furthermore, construction details should be consistent with the assumptions adopted in the analytical model. Such an approach contributes not only to greater reliability of seismic design but also to reduced earthquake-induced damage, lower rehabilitation requirements, and improved preservation of the materials incorporated in the infill walls. Physical separation of infill walls from the structural system facilitates selective dismantling and increases the potential for reuse and recycling of construction materials at the end of the building's service life or following possible damage. This extends the life cycle of resources, reduces waste generation, and supports the principles of sustainable construction and the circular economy.

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Modeling Sediment Deposition and its Impact on the Drin River Downstream of the Vau i Dejes Dam Using a Conceptual HEC-RAS Model

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Abstract

Sediment transport and deposition are fundamental processes that directly influence riverbed morphology and the long-term performance of hydro technical structures, particularly dams and hydropower plants. The presence of a dam interrupts the natural continuity of sediment transport, typically inducing pronounced deposition within the reservoir and a corresponding sediment deficit downstream, which alters the longitudinal and cross-sectional bed profile and may increase the risk of channel instability, bank erosion, and localized flooding. The Vau i Dejes Dam, the downstream-most structure in the Drin River hydropower cascade, has substantially altered the natural sediment regime of the river since its construction, trapping the majority of incoming bed material within its reservoir and reducing sediment supply to the reach below the dam. Despite the practical relevance of this issue for flood management, channel stability, and the operation of downstream infrastructure, the sediment dynamics of this specific reach remain insufficiently documented in the scientific literature, particularly regarding the spatial distribution and quantification of deposition zones. This study aims to model sediment deposition and its morphological impact on the Drin River segment downstream of the Vau i Dejes Dam using a conceptual HEC-RAS model (Hydrologic Engineering Center). Due to the lack of accessible high-resolution bathymetric data, a schematic geometric model was developed based on typical gravel-bed river characteristics and satellite imagery estimations. By isolating the imbalance between the clear-water transport capacity of dam releases and the negligible sediment supply from local tributaries, the model successfully verifies the "hungry water" hypothesis. The findings provide a quantitative basis for understanding the morphological evolution of this reach under altered sediment supply conditions, offering a scientific foundation for sediment management strategies, flood risk mitigation, and the design and maintenance of hydro technical infrastructure along the lower Drin River system.

Keywords

Sediment, reservoir sedimentation, HEC-RAS conceptual model, downstream erosion.

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1. Description of the Vau i Dejes Hydropower Plant

Vau i Dejes hydropower plant is located approximately 18 km upstream from the city of Shkoder, and is located in the lower part of the Drin Cascade comprising of Fierze, Koman and Vau i Dejes dams. The reservoir required the construction of three large dams, which ensure effective reservoir management and energy production [1], [7]. The HPP comprises of three separate dams, Qyrsaq, Zadeja and Ragam. Ragam dam is zoned rockfill embankment dam same as the Zadeja dam. Qyrsaq dam is zoned rockfill embankment dam with adjacent concrete gravity dam. Water tightness of the dam's foundations is achieved by clay core and grout curtain [7].

The maximum height above foundation of the Ragam, Zadeja and Qyrsaq dams are 21m, 59,5 m and 46,5 m respectively, while crest length 240, 380 and 375 m respectively. The crest elevation is at 79 m asl and the maximum water level in the reservoir is at 76.2 as well as maximum operation water level [1], [7].

Minimum foundation level of Ragam, Zadeja and Qyrsaq dams are 58 m, 19.5 m, and 32.6 m respectively. The dam volumes are 0.11 mil, 3.2 mil and 1.2 mil m3. The average annual inflow into the reservoir is 9.650 million m3. The reservoir total storage is 560 million m3 and the active storage volume is 310 million m3 [1], [7]. The spillway is used to pass flood flows and consists at the Zadeja Dam of two intakes with radial gates and adjacent outlet tunnel and on Qyrsaq of three intakes with radial gates and adjacent chute [7].

Additional releases can be made through the power plant which has five submerged intakes. Crest level of Qyrsaq spillway is at 61.7 m asl while of Zadeja spillway is at 59 m asl. At maximum level Qyrsaq spillway has total discharge capacity of 3*1400 m3/s and Zajeda spillway 2*1200 m3/s. The powerhouse is located at a downstream toe of the dam and has five units with a total generation capacity of 5*50 MW. The powerhouse discharge capacity is 4×113 m³/s. Nominal net head is 54 m. Annual mean energy output is 880 GWh and plant factor is 40% [1]. Figure 1 presents layout of the Vau i Dejes reservoir (1 – Qyrsaq dam; 2 – Zadeja dam; 3 – Ragam dam; 4 – reservoir; 5 – Drin river; 6 – Drin river; 7 –Gjadrit river; 8– Consiqes river; 9 – Drin Canal.)

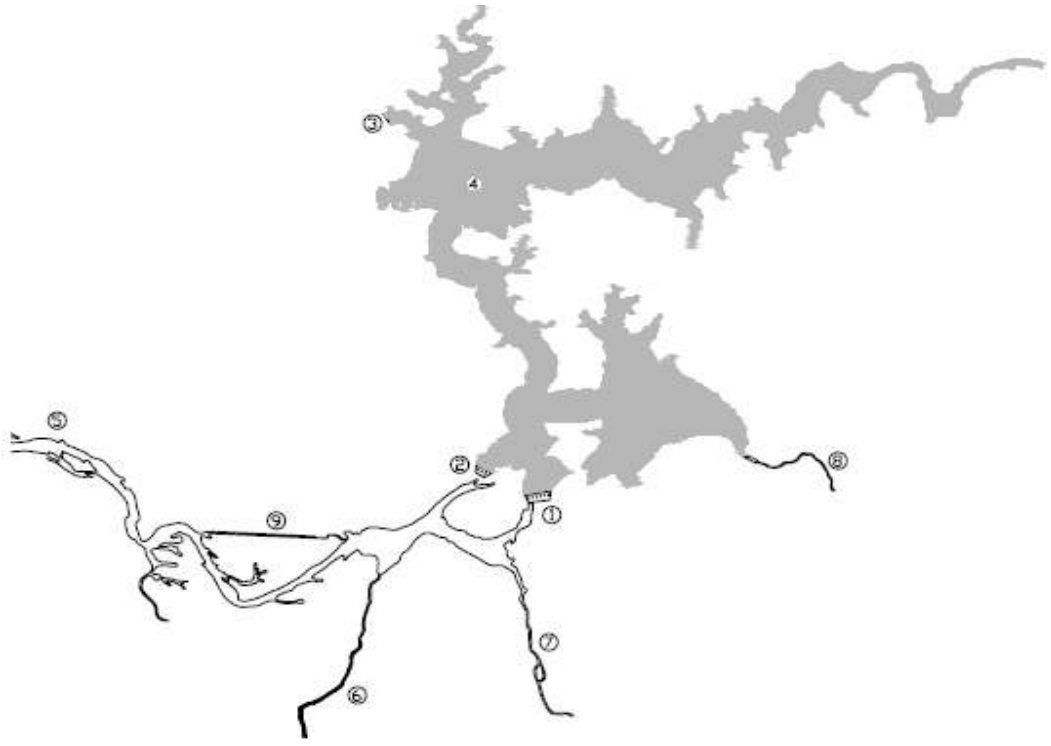


Figure 1 *– Layout of Vau i Dejes reservoir HPP*

2. Sediment Regime Changes in the Vau I Dejes Reach of the Drin River

The Drin River, together with its tributaries the Gjader and Kiri, historically transported large quantities of sediment that were mainly deposited in the Vau i Dejes-Bahçallek area. Coarser material was deposited immediately after entering this reach, while progressively finer sediments were transported further downstream toward the Buna River. Prior to dam construction, the solid sediment load at the Vau i Dejes outlet was estimated at approximately 520,000 m³/year [7].

The construction of the Fierza, Komani, and Vau i Dejes hydropower plants, completed before 1980, fundamentally altered the river's hydrological and sediment regime. Sediment transport downstream of Vau i Dejes was almost completely interrupted, as the reservoirs act as effective sediment traps. Currently, sediment supply in this reach is mainly provided by the Gjader River (~30,000 m³/year) and the Kiri River [7], representing only a small fraction of the historical sediment load. This has led to channel narrowing, bed incision, and both vertical and lateral erosion, particularly in the Vau i Dejes–Kosmaç segment. Since the 1990's, uncontrolled gravel and sand extraction from the riverbed for construction purposes has further accelerated erosional processes, intensifying the impacts of sediment starvation caused by the upstream dams.

2.1. Effect of Dams Have on Sediment Transport

Dams are structures that directly intervene in the natural continuity of sediment transport. When a dam is constructed, flow velocities decrease within the reservoir, leading to significant sediment accumulation [2], [6]. This process triggers profound consequences downstream, altering river morphology and linked ecosystems.

Sediment Trapping: Reservoirs act as absolute "sediment traps," accumulating both fine and coarse materials. In the case of the HPP Vau i Dejes complex, the system of dams (Qyrsaq, Zadeja, Rragam, and Gjocaj) creates a massive reservoir with a capacity of approximately 580 million m³, where substantial volumes of historical sediment load are permanently deposited [2], [7].



Figure 2 *– View of the study area at Vau i Dejes*

2.1.1. Methodology: A Conceptual 1D HEC-RAS Approach

HEC-RAS (Hydrologic Engineering Centre – River Analysis System) is a software package developed by the United States Army Corps of Engineers (USACE) and is widely used for hydraulic analysis and sediment transport modelling in river systems. The software provides capabilities for one-dimensional hydraulic computations and simulations of sediment transport processes and mobile-bed morphological changes [4], [5].

To analyze the morphological changes in the Drin River segment downstream of the Vau i Dejes Dam, the HEC-RAS (Hydrologic Engineering Centre's River Analysis System) software was selected, specifically the 1D sediment transport module coupled with unsteady flow hydraulic computations (Unsteady Flow Sediment Transport). The primary objective of the model was to quantitatively verify the "sediment starvation" hypothesis and to predict the general trend of riverbed incision.

Given the absence of high-resolution, contemporary bathymetric data for this specific reach, this study adopts a conceptual modelling approach. Rather than attempting to precisely replicate the exact topographical geometry, the model is designed as a numerical laboratory to isolate and quantify the physical drivers of the "hungry water" effect.

It should be emphasized that the present HEC-RAS model is conceptual rather than predictive. The objective was not to reproduce the exact morphology of the downstream Drin River, but to isolate the dominant physical processes controlling sediment transport under sediment-starved conditions. Consequently, the model is intended to demonstrate the general trends of riverbed response to sediment deficit rather than to predict absolute bed elevations or local scour depths.

2.1.2. Model Limitation

The model was not calibrated against measured water levels, sediment transport rates, or repeated bathymetric surveys because such datasets are currently unavailable for the investigated reach. Consequently, the results should be interpreted qualitatively rather than as precise quantitative predictions. In addition, the simplified one-dimensional representation cannot capture complex three-dimensional flow structures, local scour around hydraulic structures, or detailed lateral sediment redistribution. Nevertheless, the model provides a robust first-order assessment of the dominant morphological response associated with sediment starvation downstream of the Vau i Dejes Dam.

2.1.3. Hydraulic and Sediment Boundary Conditions

The model consisted of a 10 km reach, subdivided into six cross-sections. Boundary conditions were defined based on actual operational data from KESH and literature observations:

Upstream Boundary (Cross-section 10000): An inflow hydrograph was introduced with a base flow of 300 m^3/s and a peak discharge of 2500 m^3/s, simulating the actual hydraulic conditions of dam releases. Downstream Boundary (Cross-section 0): A Normal Depth condition was applied with a slope of 0.0005.

Sediment Inflow: in accordance with the reality of sediment trapping by the reservoir, the sediment load at the upstream boundary was set to zero (0 tons/day). At the mid-reach cross-section (near the confluence of the Gjader and Kiri rivers), a continuous sediment inflow of 130 tons/day was introduced. This value realistically represents the approximate daily equivalent of the documented 30,000 m^3/year tributary supply (assuming a bulk density of 1.6 t/m^3).

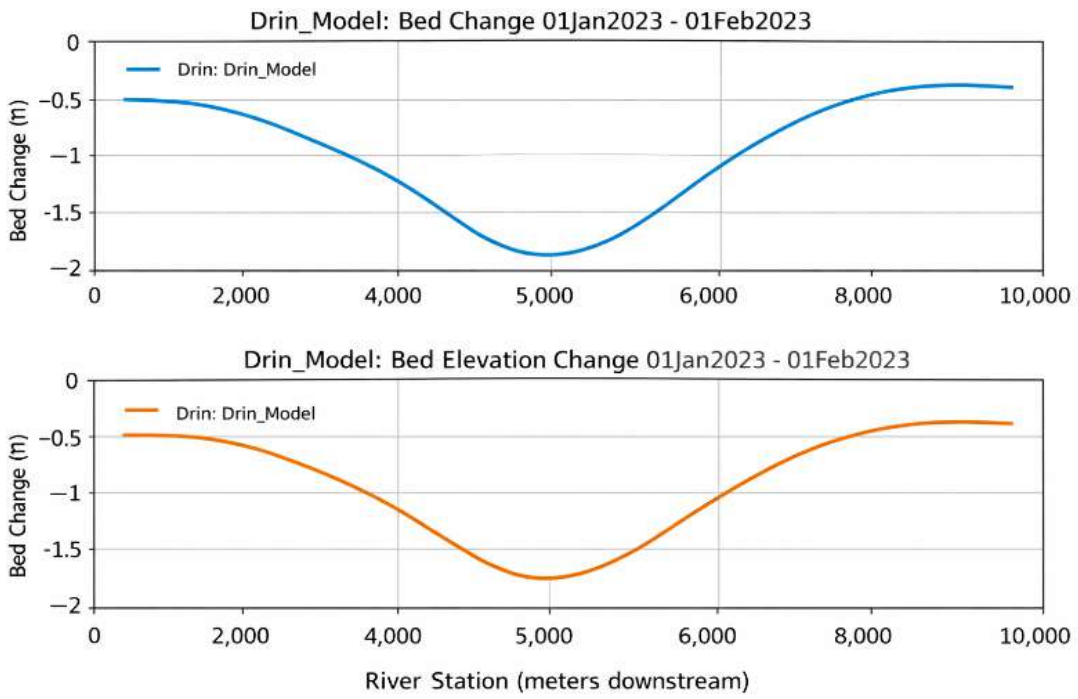


Figure 3 *– Drin Model: Bed Change 01 Jan 2023 – 01 Feb 2023*

Sediment Parameters: the Meyer-Peter Müller transport function was selected [3], which is the most suitable formula for gravel-bed Rivers such as Drin River. The bed gradation was defined as 80% gravel and 20% sand.

The execution of the Unsteady Sediment model yielded results that clearly confirm the phenomenon of riverbed incision as a consequence of sediment interruption. Analysis of the bed change plot reveals a consistent erosion pattern along the entire reach.

The above plot presents the bed elevation change over a one-month simulation period. Negative values indicate material removal (erosion). A significant observation is the distinct "U" shape of this erosion profile. In the initial cross-sections near the dam (10000 m), the erosion rate is relatively lower. This is explained by the fact that the flow has just exited the dam structure and is adjusting to the width of the free-flowing river. In the mid-reach segment (around 5000 m), erosion reaches its maximum negative value. Here, the river has achieved maximum velocity and turbulence; due to the complete absence of incoming material from the vicinity of the dam, the attractive forces of the water act directly on the existing bed. At the downstream end of the reach (near 0 m), the erosion rate slightly decreases.

This phenomenon is attributed to the inflow from tributary rivers (Gjader and Kiri), as the model demonstrates this 130 tons/day sediment supply is profoundly insufficient to compensate for the transport capacity of the main stem and therefore cannot prevent continued channel degradation. The computational reach was represented by six cross-sections, which were considered sufficient for this conceptual analysis. The objective was to capture the longitudinal evolution of sediment transport and riverbed changes rather than detailed local hydraulic conditions. A limited number of representative cross-sections reduce geometric uncertainty arising from the lack of recent bathymetric surveys while preserving the principal hydraulic gradients and sediment transport processes governing the reach.

3. Conclusions

This study demonstrated the application of a 1D conceptual modelling approach in HEC-RAS to assess the long-term impact of hydraulic structures on the morphology of the Drin River [2], [6], [7]. By isolating the primary physical variables-specifically the severe imbalance between transport capacity and sediment supply-the model provided a robust quantitative foundation for understanding the lower Drin River's evolution. Based on the obtained results, the following conclusions are drawn:

- System Transformation: The construction and operation of the Vau i Dejes hydropower cascade has caused a total sediment deficit in the downstream reach, permanently transforming the river from a historically dynamic, depositional system into a highly erosion environment.
- Verification of the "Hungry Water" Effect: The HEC-RAS model quantitatively confirmed that "sediment starvation" is the primary driving force behind riverbed incision. The distinct "U" shaped erosion profile validates the theory that maximum scour occurs not immediately at the dam outlet, but further downstream where flow dynamics fully develop.
- Inadequacy of Tributary Supply: The contribution of lateral tributaries (Gjader and Kiri) is negligible in comparison to the transport capacity of the main stem. While they create micro-zones of reduced erosion, they completely fail to restore the morphological equilibrium required for long-term channel stability.
- Methodological Value: The study proves that even schematic 1D models, when calibrated with accurate boundary conditions (zero inflow from dam, realistic grain size distribution), are highly effective screening tools for understanding macroscopic morphological trends where detailed bathymetric data is lacking.
- Management Implications: These results underscore the urgent need for basin-wide sediment management strategies. To mitigate the severe erosion pressure and protect downstream infrastructure operational modifications-such as periodic sediment flushing from upstream reservoirs during high-flow events-must be technically and economically evaluated by energy authorities.

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Regional Climate Modeling and Adaptation Planning in Albania Using the SimCLIM Software

[Blerina Beqaj][1], [Oltion Marko][2], [Besjana Mazari][3]

Abstract

Global climate change is no longer a theoretical projection of the future, but a tangible reality that is rapidly transforming environmental, social, and economic structures across the planet. This research focuses on climate modelling and the evaluation of environmental policies as critical instruments for adaptation to these changes, using the Municipality of Pogradec and the transboundary Ohrid lake region as a case study. The significance of this study becomes even more urgent in light of the extreme events of the current year, 2026, during which the intensification of the El Niño phenomenon has caused unprecedented thermal anomalies on a global scale, resulting in prolonged heatwaves, severe droughts, and massive wildfires, followed by destructive and unexpected flooding in various regions. Within this context of environmental instability, Albania is positioned as one of the most vulnerable and at-risk countries in the Western Balkans region. The recent deterioration of atmospheric conditions within the country, accompanied by severe flooding caused by concentrated precipitation events and prolonged periods of drought that threaten water reserves, highlights the immediate need for accurate scientific risk management tools. Using the advanced climate simulation software SimCLIM AR6 and the integration of Albanian spatial datasets, this study provides a detailed analysis of the different Shared Socioeconomic Pathway (SSP) scenarios, ranging from the sustainable and low-emissions SSP1-1.9 scenario to the extreme high-emissions SSP5-8.5 scenario. This modelling aims to characterize the behaviour of key climate indicators, such as mean temperatures and precipitation distribution, at the local scale. Focusing specifically on the Pogradec area, the research analyses the direct impacts that these scenarios have on the fragile ecosystem of Ohrid lake and on critical environmental infrastructure. Ultimately, this research seeks to establish a link between quantitative hydrological science and the development of institutional environmental policies in Albania, while providing concrete recommendations for governmental institutions regarding how adaptation strategies should be revised in order to build long-term resilience against the climate challenges of the XXI century.

Keywords

Climate change, modelling, SimCLIM, climate adaptation, Ohrid lake, local adaptation plan.

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1. Introduction

Climate change is increasingly affecting environmental, economic, and social systems worldwide through rising temperatures, changing precipitation patterns, and more frequent extreme weather events [7]. These impacts are particularly significant at the local level, where regional climate modelling provides essential information for understanding future climate conditions and supporting evidence-based adaptation planning [4, 7]. Climate projections are therefore becoming an important component of sustainable environmental management and long-term policy development. Recent studies have identified the Western Balkans as one of the European regions highly vulnerable to climate change, with projected increases in temperature, more frequent heatwaves, prolonged droughts, and a greater risk of flooding. These changes are expected to affect water resources, biodiversity, agriculture, tourism, and public health, highlighting the need for effective adaptation strategies based on reliable climate projections [2, 5]. In the Lake Ohrid basin, previous research has emphasized the ecological importance of this unique transboundary ecosystem and its sensitivity to climatic and hydrological changes [1, 5]. This study applies the SimCLIM AR6 modelling platform to assess future climate conditions in the Municipality of Pogradec under different Shared Socioeconomic Pathway (SSP) scenarios. The research evaluates projected changes in temperature and extreme climate events and discusses their implications for the Lake Ohrid ecosystem and local adaptation planning, providing scientific evidence to support climate-resilient decision-making in Albania [2,4].

2. Multi-Sectoral Importance of Studying the Ohrid Lake Ecosystem

Ohrid lake catchment basin holds critical local, regional, and transboundary importance, carrying immense environmental, socio-economic, and scientific value. It is one of the four oldest lakes in the world, about 2-4 million years old and one of the deepest in the Balkans. It has a regular shoreline of 88 km and 358 km^2, of which about 1/3 belongs to Albania and the rest to North Macedonia. The surface of the watershed reaches 1487 km^2 and is located 695 meters above sea level, its average depth is 145 m and the maximum reaches 289 m. The main water supply of the lake is made through underground routes from Prespa lake, located 157 m above, with a total flow of 15m^3/s. Another part of the waters received from the outflow of streams and rivers is estimated at about 26%. Ohrid lake discharges only into the Drin River, with an average flow of 22.2 m^3/s. In fact, the lake acts as a giant thermal regulator, making winters milder and cooler than other inland areas of Albania.

Biodiversity (Flora & Fauna): The lake is renowned for its exceptionally high level of archaic endemism. Benthic fauna includes unique species like the round sponge (*Ochridospongia rotunda*) and a massive variety of endemic gastropods. The fish fauna contains **60**% endemic species (21 native species), highlighted by two highly valuable salmonids: the Ohrid Trout / Koran (*Salmo letnica*) and the Belushka (*Salmothymusohridanus*). Additionally, phytoplankton (such as *Cyclotella ocellata*) and zooplankton serve as highly sensitive biological indicators of water quality.

Agricultural Sector: Due to the region's microclimatic conditions, crop production has historically been a pillar of the local economy. However, the sector is highly sensitive to climate change; irrigation is an absolute necessity during dry years. Abundant water resources and basin streams facilitate irrigation, but the sector remains threatened by land erosion, plot fragmentation, and degraded irrigation canals.

Tourism Sector: Tourism is the main driver of economic growth and seasonal employment in Pogradec. It relies heavily on lake-based and nature tourism, but seamlessly

intertwines with cultural and archaeological tourism (e.g., the paleochristian mosaics in Lin and traditional villages like Tushemisht).

3. Using SimCLIM AR6 Software for Climate Scenario Modeling

The **SimCLIM AR6** system represents advanced software for climate data management and analysis, designed in full compliance with the guidelines of the IPCC Sixth Assessment Report (AR6). It facilitates the transition from raw global simulations to actionable information at the local level. It serves as a bridge between exact hydrological/climate science and environmental policy-making, enabling decision-makers to analyze different scenarios (from the optimistic SSP1-1.9 to the pessimistic SSP5-8.5) to stress-test critical infrastructure. The main components studied in these climate models are wind rose, cloud simulation, heat currents, atmospheric pressures, minimum, maximum and average temperatures, vegetation simulation, snow cover, soil types, surface water network, water biochemistry, water movement, coastal erosion, glacier melt, and absorption of solar radiation.

3.1. Modeling Climate Scenarios of Average Temperature for the Time Period 2030, 2050 and 2070

Only 3 maps are shown because for each year, the visual change of the scenarios is almost the same between them.

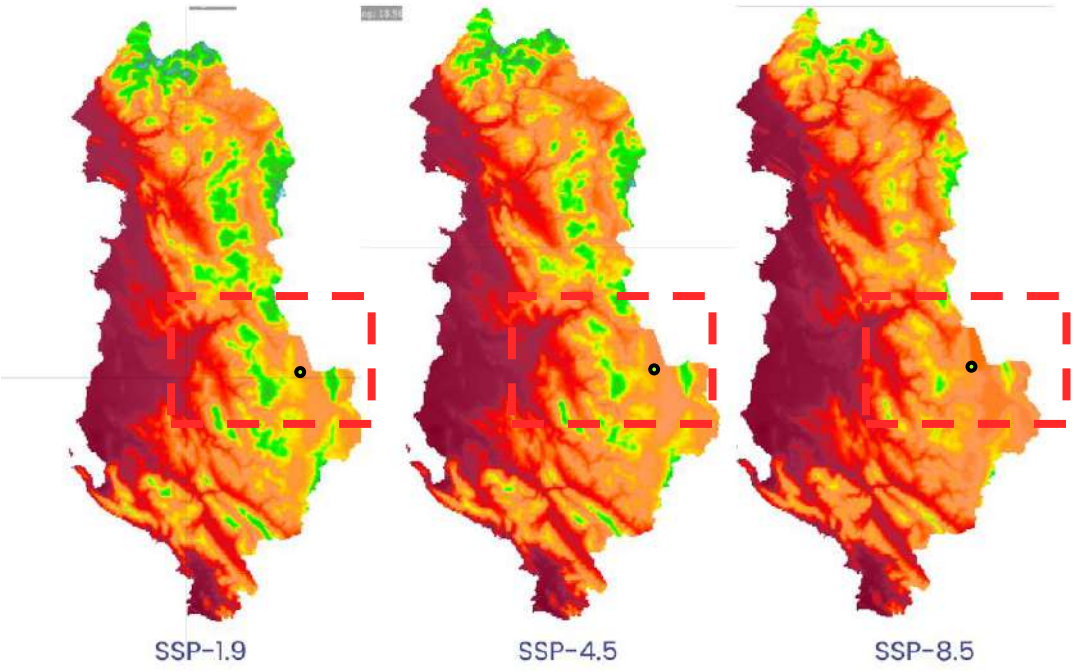


Figure 1 *– Maps of average temperature in the period 2030, 2050 and 2070*

3.1.1. Analyses of Each Modeling Scenario

1. Optimistic scenario SSP - 1.9: For Pogradec, this means that the increase in the average annual temperature remains minimal and controlled. The region maintains its traditional characteristics of paramontane coolness, without suffering major thermal shocks.

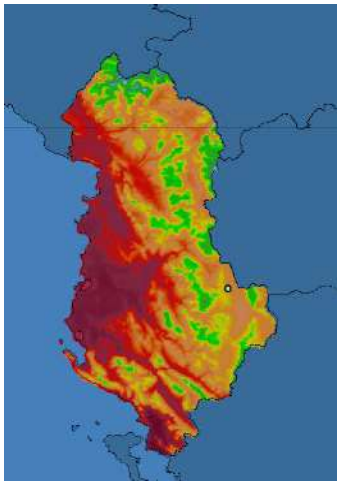


Figure 2 *– Temperature map for Albania with reference point Pogradec in the time period 2050, scenario SSP - 1.9*

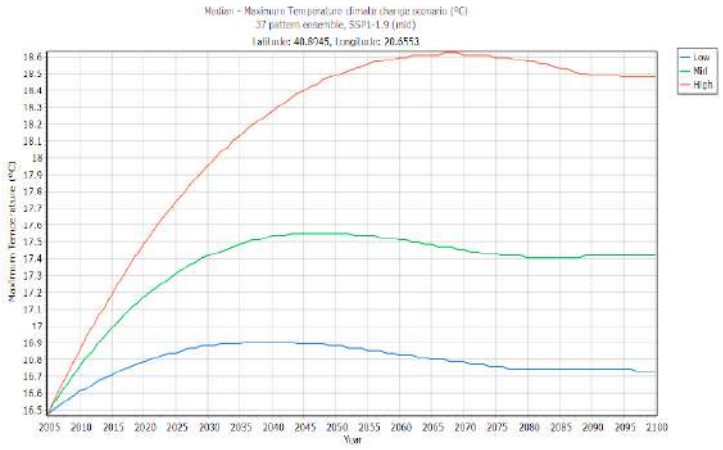


Figure 3 *– Maximum temperature graph for the SSP - 1.9.*

This scenario represents the most optimistic global path (the "Green Scenario"), where the world manages to significantly reduce greenhouse gas emissions, aiming to keep global warming below 1.5°C. The curved shape of the lines (which rise until mid-century and then straighten or fall) demonstrates that the success of global environmental policies would curb further warming of the Pogradec municipality in the second half of the century, largely preserving the existing stable microclimate of the city and the lake.

2. Average scenario SSP-4.5: This scenario reflects a situation where emissions peak around mid-century and then stabilize. For Pogradec, this brings about a significant increase in the average annual temperature. Hot summer days increase and winters become milder (fewer days with snow and frost), slightly changing the stable microclimate that the lake has historically brought.

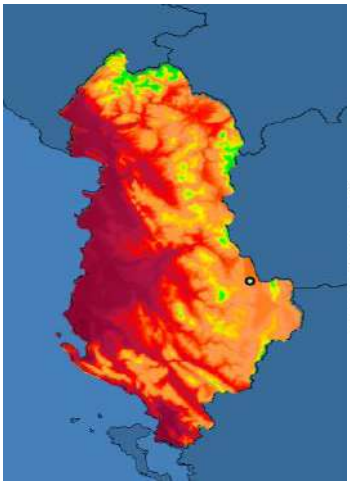


Figure 4 *– Temperature map for Albania with reference point Pogradec in the time period 2050, scenario SSP - 4.5*

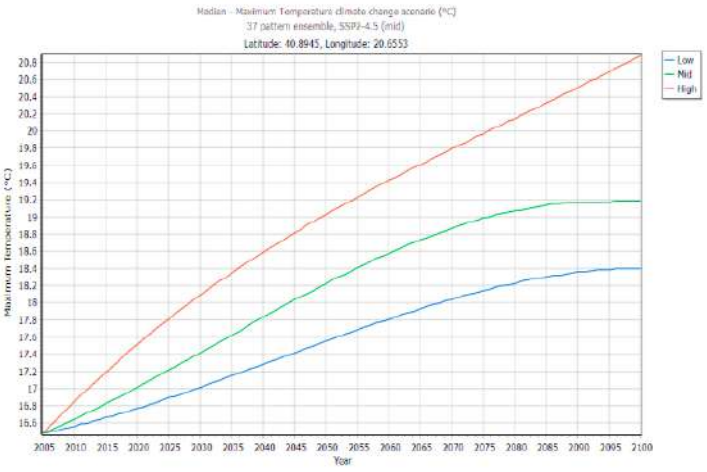


Figure 3 *– Maximum temperature graph for the SSP - 4.9.*

The data in this graph confirm that in the average SSP-4.5 scenario, Pogradec will face a continuous warming without a downward trend. The fact that in 2070 the average maximum temperature reaches 18.87°C (and the minimum is a full 18.04°C, i.e. higher than the average of the optimistic scenario) shows that the city's microclimate will undergo radical changes periods and snow during the winter in the lake region. This constant increase would extend the summer season, increase the days with intense heat and significantly reduce the cold.

3. Pessimistic scenario SSP-8.5: This is the most extreme scenario, where global greenhouse gas emissions continue to increase without any limits. For Pogradec, this scenario predicts a drastic and worrying increase in the average temperature. The moderating influence of Lake Ohrid would be put under great pressure; summer would turn into a season of intense heat (similar to the current lowlands), while winter would almost completely lose its paramontane character. The data in this graph prove that in the average SSP-8.5 scenario, Pogradec will face a continuous warming without a downward trend.If the world follows the path of the extreme SSP-8.5 scenario, the traditional microclimate of Pogradec will be completely destroyed.The fact that in 2070 the average maximum temperature crosses the threshold of 20.21°C indicates that the region would lose its cool paramontane character. Ohrid lake would no longer be able to regulate and remove intense heat waves. Summers in Pogradec would turn into periods of scorching African heat similar to the current low-lying coastal areas, while winters would become completely mild, bringing about the almost total disappearance of snow and frost in the city.

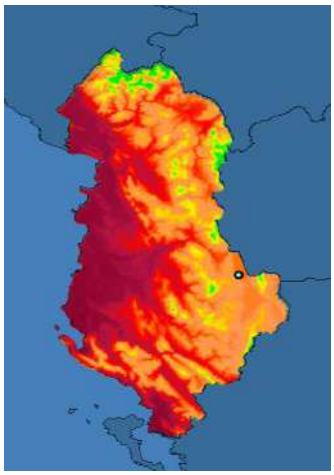


Figure 6 *– Temperature map for Albania with reference point Pogradec in the time period 2050, scenario SSP - 8.5*

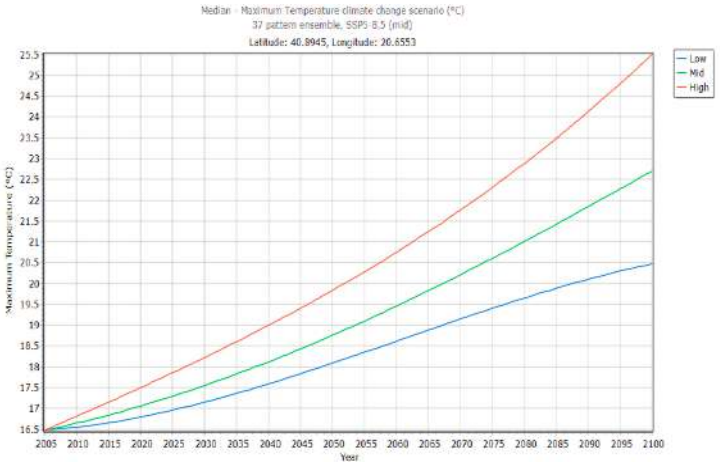


Figure 7 *– Maximum temperature graph for the SSP - 8.5.*

3.1.2. Extreme Events Analysis for 2050

The Extreme Event Analysis option is not based solely on monthly or annual averages, but uses Extreme Value Theory to predict how the frequency and intensity of destructive events will change in the future according to the SSP scenarios analyzed above. Through this SimCLIM option, the change in frequency of an event, the change in intensity, the extraction of extreme value graphs and event change factors can be calculated. In the following graphs for extreme events in the Pogradec area, we can describe the frequency of return of the event for the same maximum temperature or find the temperature for the same frequency of return of the event. Optimistic scenario SSP - 1.9: For Pogradec, this means that the increase in the average annual temperature remains minimal and controlled. The

region maintains its traditional characteristics of paramontane coolness, without suffering major thermal shocks.

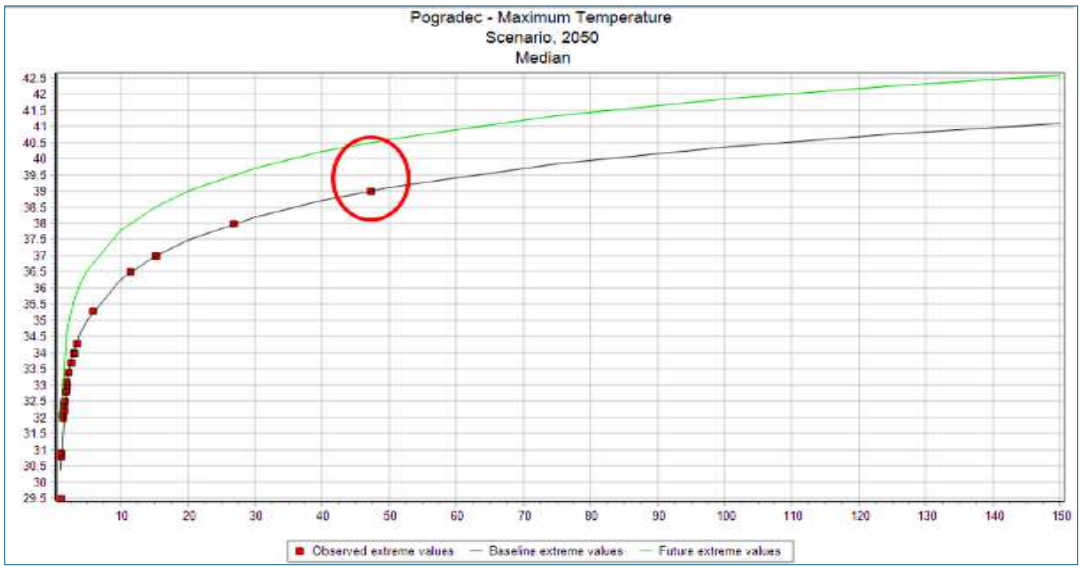


Figure 8 *– Extreme analyses event graph for the SSP –1.9*

SSP – 1.9:

1. According to climate modeling, a **maximum temperature of 39°C**, which had a return period of 48 years during the baseline period, is projected to become significantly more frequent, reaching a return period of 20 years.
2. Climate modeling indicates that for a 20-year return period, the maximum temperature is projected to increase from 37.5°C during the baseline period to 39°C.

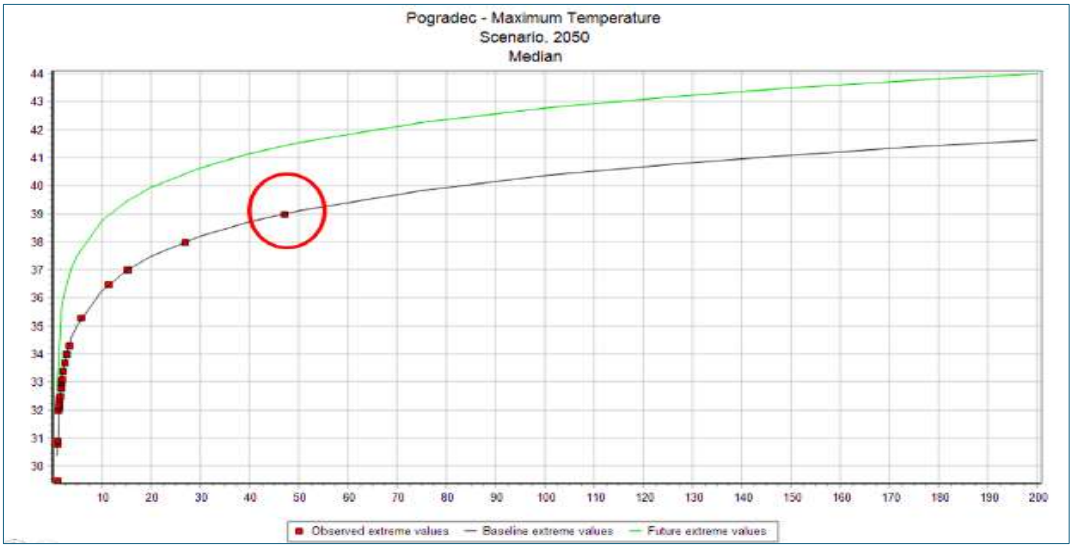


Figure 9 *– Extreme analyses event graph for the SSP –4.5*

SSP – 4.5:

1. According to climate modeling, a **maximum temperature of 39°C**, which had a return period of 48 years during the baseline period, is projected to become significantly more frequent, reaching a return period of 12 years.

2. Climate modeling indicates that for a **20-year return period**, the maximum temperature is projected to increase from 37.5°C during the baseline period to 39.9°C.

SSP – 8.5:

1. According to climate modeling, a **maximum temperature of 39°C**, which had a return period of 48 years during the baseline period, is projected to become significantly more frequent, reaching a return period of 8 years.
2. Climate modeling indicates that for a **20-year return period**, the maximum temperature is projected to increase from 37.5°C during the baseline period to 40.8°C.

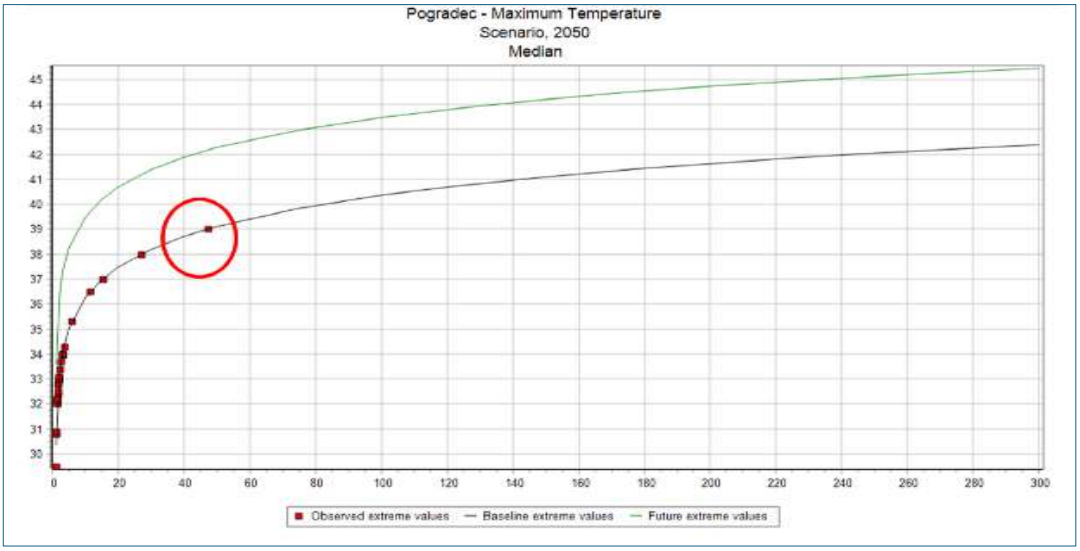


***Figure 10** – Extreme analyses event graph for the SSP –8.5*

4. Measure Recommendations for Climate Change Adaptation Planning

Planning for climate change for 15-25 years is more than appropriate because it coincides with the time scale with which the phenomenon of climate change is expected to significantly affect the environment, economy and local systems of countries. It also corresponds to the planning and lifespan of public investments, such as water supply infrastructure, urban development projects or green spaces. Temperature, precipitation and other extreme weather events become more evident over decades than over a short fraction of years. This interval simultaneously allows municipalities to gradually implement specific adaptation measures, monitoring their effectiveness and constantly reviewing strategies according to new climate data and of course through technologies that advance every day.

In the specific case of Pogradec, this study affects the strengthening of adaptation measures to climate change by protecting the ecological integrity of Ohrid lake, ensuring the continuity of tourism, protecting public health and supporting the lives of local people.

Protection of Water Resources: To ensure long-term water availability and maintain Ohrid's lake water quality, the sector focuses on comprehensive infrastructure and ecological safeguards. This includes reducing widespread water losses by modernizing the existing water supply infrastructure, alongside actively promoting water-saving and recycling technologies across local hotels and households. Additionally, management plans call for more regular and frequent monitoring of the lake's water quality, paired with strict protections for the lake's sensitive coastal zones, discharge areas, and vital feeding systems like minor streams and rivers.

More Climate-Resilient Urban Development: The primary objective for urban areas is reducing localized vulnerability to extreme heat and flooding events. To achieve this, municipalities are prioritizing nature-based solutions, such as expanding urban green spaces and planting trees to counteract the urban heat island effect. Urban planning will also see structural upgrades, specifically through improving stormwater drainage systems to handle heavy downpours, while formally integrating comprehensive climate risk assessments into all future municipal development frameworks.

Preserving Ecosystems and Biodiversity: Protecting the unique, ancient ecosystem of Ohrid lake requires a mixture of active restoration and policy enforcement. Key measures involve rehabilitating degraded lakeshore habitats and strengthening regional legislation dedicated to protecting wetlands, flora, and fauna. To stay ahead of ecological disruptions, the strategy mandates the continuous monitoring of invasive species while simultaneously expanding community-wide environmental awareness programs to foster local stewardship.

Adapting Tourism in a Sustainable Manner: In order to maintain the region's tourist attractiveness amidst changing climate conditions, the tourism sector must diversify and adapt its current infrastructure. This involves developing year-round tourism activities to reduce seasonal strain and promoting eco-tourism initiatives that respect the natural environment. Furthermore, local authorities encourage the construction of climate-resilient infrastructure in hotels and require the strict implementation of the HEATWAVE RESPONSE call during peak tourist seasons.

Public Health and Community Awareness: Protecting residents from climate-related health risks requires a proactive approach to community safety and public infrastructure. A central pillar of this effort is developing robust early warning systems for extreme heat waves, known as the HEATWAVE RESPONSE. Complementing these systems, municipalities intend to increase the availability of public shaded areas, conduct widespread public awareness campaigns regarding climate risks, and continuously improve emergency preparedness protocols for extreme weather events.

Agriculture and Fisheries: Supporting local agriculture and fisheries means steering both industries toward climate-resilient practices that protect the wider basin. This involves actively promoting drought-resistant crop varieties and offering subsidies for highly efficient irrigation systems. Alongside these agricultural updates, the strategy emphasizes regular monitoring of fish populations and general ecosystem health, while providing practical training for local farmers on modern agricultural techniques to mitigate climate impacts.

5. Conclusions

This study demonstrates the value of regional climate modelling as a scientific tool for supporting climate adaptation planning at the municipal level. Using SimCLIM AR6 and IPCC Sixth Assessment Report (AR6) climate scenarios, future changes in temperature and extreme climatic events were analysed for the Municipality of Pogradec and the transboundary Lake Ohrid basin under SSP1-1.9, SSP2-4.5, and SSP5-8.5 emission pathways. The modelling results consistently indicate progressive warming throughout the twenty-first century, with substantially greater temperature increases and more frequent extreme heat events under higher-emission scenarios. While the moderating influence of Lake Ohrid is expected to persist under low-emission pathways, its capacity to buffer regional climate conditions is projected to decline considerably under SSP5-8.5, leading to profound changes in the area's traditional microclimate.

These projected climatic changes have significant implications for biodiversity conservation, water resource management, agriculture, tourism, public health, and urban infrastructure. Increasing temperatures, altered hydrological regimes, and more frequent

climate extremes are likely to intensify pressures on the unique Lake Ohrid ecosystem, emphasizing the need for proactive adaptation measures that integrate ecosystem protection with sustainable socio-economic development. The adaptation measures proposed in this study-including improved water resource management, climate-resilient urban planning, ecosystem restoration, sustainable tourism, enhanced public health preparedness, and climate-smart agricultural practices-provide a practical framework for strengthening local resilience. Incorporating regional climate projections into municipal planning and investment decisions will enable authorities to reduce future climate risks while supporting sustainable development objectives.

Overall, this research highlights the importance of combining regional climate modelling with local environmental planning to support evidence-based decision-making in Albania. The methodological framework developed for Pogradec can also serve as a transferable approach for other municipalities in the Western Balkans facing similar climate-related challenges. Future research should further improve local-scale projections by incorporating higher-resolution regional climate models, expanded observational datasets, hydrological simulations, and continuous monitoring to refine adaptation strategies under evolving climatic conditions.

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T06

Circular Economy

Circular Economy and Construction Products in Montenegro: Regulatory, Digital and Material Pathways

[Goran Gorašević][1]

Abstract

The circular economy has become a practical framework for transforming the construction sector from a linear chain of extraction, production, use and disposal into a system that preserves the value of materials and products over the entire life cycle of buildings and infrastructure. This paper focuses on construction products in Montenegro and examines how their design, documentation, market placement, use, maintenance, removal and possible reuse can support a gradual circular transition. The paper combines the national development context for the Montenegrin construction sector with recent European policy directions, especially the revised Construction Products Regulation, the Circular Economy Action Plan, Level(s), and the emerging role of digital product passports. The analysis shows that the key issue is not only the recycling of construction and demolition waste, but the creation of a reliable product system in which safety, declared performance, environmental data, traceability and end-of-life options are treated together. Montenegro has a strong need to reduce dependence on imported construction materials, improve control over mineral resource extraction, develop secondary raw material markets and introduce digital instruments that can link product data with design, public procurement and waste management. The proposed approach is based on four mutually connected directions: circular product design, selective demolition and pre-demolition audits, quality-controlled production of recycled and secondary materials, and digital documentation through BIM-compatible material passports. The paper concludes that circular construction products should be developed through pilot projects, updated technical rules, public procurement criteria, education of engineers and gradual establishment of testing and certification capacity. In this way, circularity can become a quality and competitiveness criterion, not only an environmental obligation.

Keywords – Style: 03_Abstract Heading, Arial Bold (10 pt)

Circular economy, construction products, recycled materials, material passports, Montenegro.

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1. Introduction

Construction products are usually discussed as market goods that must satisfy technical and safety requirements. In a circular economy, however, they also become carriers of material value, environmental information and future reuse potential. A concrete block, a steel profile, a timber panel, a façade element or insulation board is not only a component placed into a building; it is also a temporary material stock that should remain useful after maintenance, renovation or deconstruction. This change of perspective is important for Montenegro, where construction has a visible role in investment, tourism, housing and infrastructure, while the reuse of construction and demolition waste is still limited [1,2].

The subject of this paper is therefore the circular economy of construction products, with emphasis on the conditions under which recycled, reused or remanufactured products can be safely and economically applied. The aim is to define a development model that connects product compliance, resource efficiency, digital documentation and local market needs. The paper is not limited to recycling as a waste-management measure; it treats circularity as a design, production, procurement and documentation principle. The methodology is based on a qualitative review of national programme documents, local presentations on circular and digital construction, and European policy documents and standards [1-10].

2. Construction Products as Circular Value Carriers

A construction product may be understood as a material, element, component or system intended for permanent incorporation in construction works. In the Montenegrin development framework, construction products are connected with the Law on Planning of Space, Law on Construction of Structures, the Law on Construction Products and the Law on Waste Management, while the national approach is broadly aligned with the European logic of performance declaration and market surveillance [1]. This is important because circular products cannot be introduced by ignoring technical requirements. A recycled aggregate, reused brick, timber element or secondary raw material must be assessed according to its intended use and must provide reliable information to designers, contractors, authorities and users.

The circular value of a construction product can be observed through three loops. The first loop is longevity: the product is designed and installed so that it performs for a long time, can be maintained and does not cause premature replacement. The second loop is reuse: the product or component can be removed without losing its function and can be incorporated into another project after inspection. The third loop is recycling: the material is processed into a secondary raw material or new construction product when direct reuse is no longer realistic. The highest circular value is normally achieved by keeping the product close to its original function, while recycling is necessary when safety, geometry, contamination or market demand prevent reuse.

This hierarchy means that circular design should begin before construction, not at the landfill. Product selection should consider durability, adaptability, disassembly, availability of spare parts, reparability, content of hazardous substances, potential for selective removal and availability of product documentation. The same logic is visible in circular design principles promoted by international practice: waste is treated as a design failure, materials should circulate at their highest value, and systems should reduce pressure on natural resources [9].

3. European Policy Direction and Product Compliance

European policy increasingly links construction products with climate, resource efficiency and digitalisation. The 2020 Circular Economy Action Plan identifies the need to address the entire life cycle of products and to keep used resources in the economy for as long as possible [4]. For buildings and construction, the European Commission highlights the sector's demand for materials and its contribution to waste generation, and promotes durability, adaptability, digital building logbooks, life-cycle assessment and possible recycled-content requirements [6].

The revised Construction Products Regulation, Regulation (EU) 2024/3110, is particularly relevant because it moves construction products beyond traditional technical performance. It establishes the basis for declaring environmental sustainability performance, including life-cycle information, while keeping the internal market logic of harmonised rules and reliable product information [5]. It also introduces the construction digital product passport, which is intended to contain performance and conformity information, product instructions, technical documentation, unique identifiers and data carriers, with improved traceability along the value chain [5].

For Montenegro, the practical importance of this European direction is twofold. First, the country will need to approximate its product rules and market practices to EU requirements as part of the broader integration process. Second, construction companies and producers can use the same logic to create competitive advantages even before full regulatory obligation. A product that has verified performance, environmental information and clear end-of-life instructions will be easier to use in public procurement, energy renovation and infrastructure projects. Circularity therefore becomes part of product quality, not a separate environmental label.

4. Montenegro: Baseline Conditions and Barriers

The Montenegrin construction sector has significant investment dynamics and remains important for the national economy, but the market is predominantly domestic and project management is still mostly traditional [2]. The same source notes that digital tools are applied to a limited extent and that the reuse of construction and demolition waste is minimal [2]. These findings are consistent with the broader Programme for the Development of Construction in Montenegro, which identifies the construction materials industry, mineral resources, labour skills, technical regulation and circular economy as development areas [1].

The main barriers are not only technological. They include the absence of a developed secondary materials market, limited recycling and processing facilities, insufficient logistics for separate collection, lack of pre-demolition audits, uncertain demand from investors, and limited data on product composition. Another barrier is trust. Designers and supervising engineers will not specify recycled or reused products unless performance, durability, fire behaviour, structural suitability and environmental safety are documented. Contractors will not use secondary materials if supply is irregular or if responsibility for failures is unclear. Public authorities will not promote reuse without traceability and inspection procedures.

At the same time, Montenegro has opportunities. Existing mineral resources, construction activity, renovation needs, underused industrial capacities and local academic initiatives can support new material loops. The Programme for the Development of Construction proposes support for revitalising production capacities and using modern technologies in accordance with green and circular economy principles [1]. Local initiatives such as Mock-up/Junk Lab and O5 Lab show that waste streams can become the basis for

new material experiments and design culture [3]. The challenge is to move from creative prototypes to construction products that can be tested, documented, certified and used in buildings.

5. Circular Design Criteria for Construction Products

A circular construction product should satisfy the same basic expectations as any other construction product: it must be safe, fit for purpose, durable and clearly documented. Its circular advantage should then be demonstrated through additional criteria: reduced use of primary raw materials, recycled or reused content, lower life-cycle impact, design for disassembly, absence or control of hazardous substances, and a realistic scenario for reuse, remanufacturing or recycling at the end of use. The key is to avoid a false conflict between circularity and quality. Circular products must not be perceived as inferior substitutes, but as technically verified products with better resource performance.

Four product groups are particularly relevant for Montenegro. The first group includes mineral-based products such as aggregates, concrete products, blocks, paving elements and road layers, where controlled use of recycled aggregates or industrial by-products can reduce pressure on quarries and river materials. The second group includes metals and timber, where reuse and high-quality recycling can preserve material value. The third group includes façade, interior and modular components, where design for disassembly can make future renovation easier. The fourth group includes experimental composite materials from plastic, rubber, glass or textile waste, where innovation must be combined with testing and clear limits of application.

In all cases, the product should be evaluated through a product file containing: source of raw material, percentage and type of secondary input, test results, intended use, limitations, installation instructions, expected service life, maintenance instructions and end-of-life route. For products intended for structural or fire-sensitive applications, additional caution and independent verification are necessary. For non-structural applications, pilot projects can create demand and confidence more quickly, especially in urban furniture, paving, partitions, landscape elements and temporary structures.

6. Digital Tools and Market Instruments

Circular construction products require information continuity. Without data, a product becomes anonymous waste when the building is renovated or demolished. Digital tools can therefore connect the product with the building life cycle. The local Zero Waste Montenegro presentation identifies BIM, digital twins, IoT, AI and big data, material passports, 3D printing and blockchain as technologies that can support material tracking, disassembly and resource optimisation [2]. At the product level, the most practical starting point is a simple material passport connected to the bill of quantities and the BIM model.

A material passport should not be treated as a complex software project at the beginning. It can start as a standardised digital sheet containing product identity, manufacturer, declared performance, dimensions, mass, material composition, recycled content, hazardous substance information, expected service life, maintenance requirements, disassembly instructions and recovery route. Later, this information can be integrated into BIM objects, public procurement databases and digital product passports aligned with European requirements [5].

Public procurement can create the first stable demand for circular products. Instead of choosing only the lowest initial price, tenders for selected public works can include criteria

such as documented recycled content, life-cycle cost, possibility of disassembly, local availability of secondary materials, environmental product declaration or material passport. The criteria should be proportional: they must not exclude the market before testing capacity exists, but they should reward verified circular performance. Pilot projects can be implemented first in road works, public landscaping, schools, administrative buildings and renovation projects.

7. Proposed Implementation Pathway for Montenegro

A realistic transition should be gradual. The first step is to create a national typology of construction and demolition material flows, including concrete, asphalt, brick, stone, metals, timber, glass, plastics, gypsum and insulation. The second step is to introduce pre-demolition and renovation audits for larger projects, so that reusable products, hazardous materials and recyclable fractions are identified before works begin. The third step is to establish quality protocols for secondary raw materials and recycled construction products. The fourth step is to connect product data with BIM and material passports, beginning with public projects. The fifth step is to use public procurement and professional education to create demand and competence.

Table 1 *– Proposed implementation pathway for circular construction products in Montenegro*

Step	Product focus	Circular effect	First action
Material-flow mapping	Concrete, asphalt, brick, metals, timber and plastics	Identifies realistic reuse and recycling quantities	Create a baseline inventory by municipality and project type
Pre-demolition audit	Reusable components and recyclable fractions	Prevents contamination and increases recovery value	Require audits for larger demolition and renovation projects
Product quality protocol	Recycled aggregates, blocks, paving, panels and composites	Builds trust in secondary products	Define testing, declarations and limits of application
Digital passport pilot	Selected products in public projects	Keeps product data available for maintenance and future reuse	Use BIM-compatible material sheets in pilot procurements

This pathway is intentionally incremental. It begins with information and quality control, because circular markets cannot function without reliable data, predictable supply and clear responsibility for performance.

8. Conclusions

Circular economy in construction products is not a single technology or recycling campaign. It is a product-system transition that requires reliable performance information, better design, selective demolition, quality control, digital documentation and market demand. For Montenegro, this transition is important because it can reduce pressure on natural resources, lower dependence on imported construction materials, create new business opportunities and improve alignment with EU policy directions.

The most important conclusion is that circularity must be connected with safety and declared performance. Reused and recycled products can enter construction practice only if

designers, contractors and authorities trust their quality. Therefore, Montenegro should focus on pilot projects, pre-demolition audits, testing capacity, BIM-compatible material passports and procurement criteria that reward verified circular performance. Local creative and academic initiatives can provide strong inspiration, but the next development phase must transform experiments into documented products and repeatable market models.

By treating buildings as material banks and construction products as traceable value carriers, Montenegro can move from waste disposal towards a circular construction economy. The proposed approach does not require waiting for a fully developed market. It can begin with selected product groups, public-sector pilot projects and clear technical documentation, and then expand as capacity, regulation and demand mature.

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Development of Sustainable Concrete for the Marine Environment by Implementation of Fluidized Bed Fly Ash

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Abstract

The development strategies of the European Union (EU) until 2050, as well as those of many developed countries, are aimed at promoting practices that are considered to ensure sustainable construction and decarbonization of the construction sector. On one hand, this includes diverting waste from landfills through separation, recycling, and resource recovery, with the aim of reducing the consumption of natural resources and protecting the environment. On the other hand, this involves technologies and processes for reducing CO_2 emissions through reducing energy demands and consumption, incorporating low-carbon technologies and renewable energy sources, as well as 'capturing' and storing CO_2 in order to slow down global warming. Moreover, the current geopolitical situation in the world has highlighted the need to establish a robust supply chain for raw materials. In this regard, it is extremely important to focus on the use of locally available raw materials and on strengthening the national construction material production industry. In this way, both economic and ecological savings are achieved simultaneously.

For many years now ground granulated blast furnace slag and pulverised coal fly ash were main supplementary cementitious materials used in cement. Today sources of slag are becoming less available and pulverized coal combustion technology is being replaced by combustion in a circulating fluidized bed, which is characterized by lower energy consumption. This paper investigates possibility of using circulating fluidized bed coal fly ash as a cement replacement material in concrete with a special focus of its performance in the marine environment where corrosion of reinforcement caused by the action of chlorides is undoubtedly one of the most common factors that adversely affect the service life of reinforced concrete structures.

Keywords

Fluidized bed fly ash, marine environment, cement replacement, concrete industry.

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1. Introduction

Concern for sustainability constantly brings new challenges in resource management that are also present in the cement and concrete industries. The drive to reduce energy consumption in construction and the production of building materials necessitates the most efficient possible use of raw materials [1, 2]. Consequently, it is essential to encourage the use of locally available materials and to reduce the proportion of Portland cement in concrete by substituting a portion of it with industrial by-products. Utilizing by-products from other industries simultaneously protects the environment by reducing the volume of landfilled material and lowering the risk of environmental pollution emissions [3]. Implementing these practices in the construction of structures located near the sea poses additional challenge since marine environment is one of the most aggressive and complex. Degradation mechanisms in such an environment are numerous, and their intensity and interaction depend on the local specifics of a particular region.

When designing concrete resistant to marine environment exposure, a prescriptive approach is still predominantly used today, specifying limits for the water-cement (w/c) ratio and minimum cement content. According to standard EN 206 when concrete is intended for placement near the sea coastline where salts from the sea can reach the concrete surface, exposure condition designated XS are applied [4]. In addition, a minimum concrete compressive strength class and a recommended concrete cover thickness are usually specified. Corrosion of reinforcement caused by the action of chlorides is undoubtedly one of the most common factors that adversely affect the service life of reinforced concrete structures in the marine environment. The process of chloride penetration is one of the most important parameters when designing concrete structures, as well as planning remedial measures and maintenance. The water content in the pores of concrete, but also in the environment that surrounds it, largely affects transport mechanisms and degradation phenomena in concrete [5]. The prediction of chloride penetration into concrete is complex since it depends on different transport mechanisms or their interdependent combination. For simplification, diffusion is usually taken as the main mechanism of chloride transport and the rate of diffusion is controlled by diffusion coefficient [6]. Therefore, knowing a diffusion coefficient is significant for reliable estimation of service life and was implemented as additional requirement for concrete durability in the Croatian national requirements to standard EN 206:2021 [7].

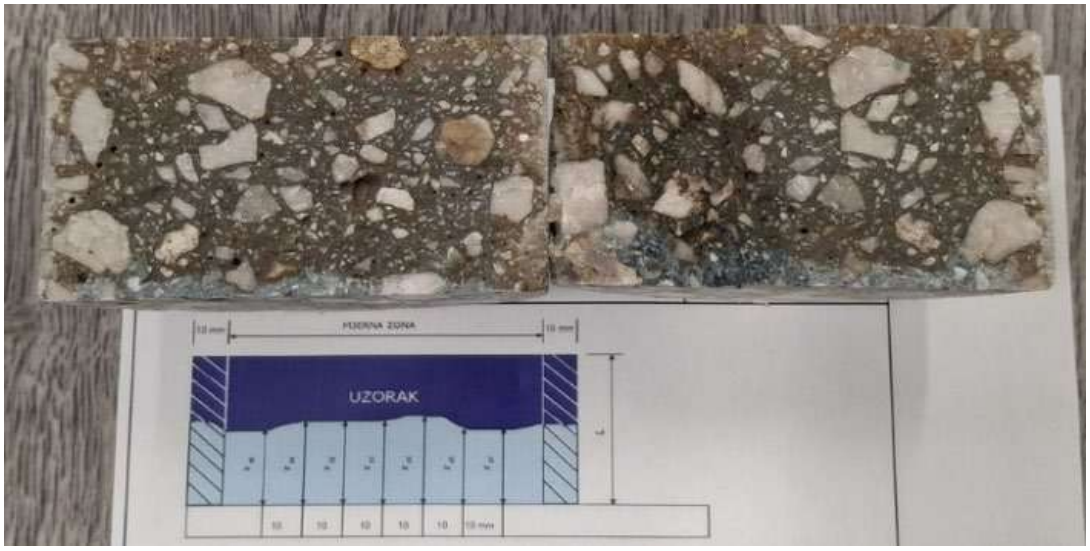
There are different methods developed for estimation of diffusion coefficients assuming either steady-state or non-steady-state flow [8]. In the past natural diffusion test methods were used but nowadays accelerated chloride migration tests are dominantly used which provide estimate of the rate of chloride ingress into concrete at a much shorter time period [9]. Arguably, most widely accepted test today is a method given in the Nordtest standard NT BUILD 492 [10]. Method given in standard NT BUILD 492 is a non-steady migration test where external electrical field is used to increase the rate of chloride penetration. Test is performed on cylindrical sample with a length of 50 mm and diameter of 100 mm sliced from a cast cylinder or from a core. After testing, the chloride penetration front is determined on the split sample (Figure 1). In Croatia, standard HRN 1128:2023 limits the chloride migration coefficient determined according to NT BUILD 492 at concrete age of 90 days to be $\leq 12\times10^{-12}$ m^2/s for exposure class XS1, $\leq 9\times10^{-12}$ m^2/s for exposure class XS2, $\leq 6\times10^{-12}$ m^2/s for exposure class XS3 [7].

It was shown that the use of cements containing ground granulated blast furnace slag (GGBFS) or pulverized coal fly ash (PCFA) reduce the rate of chloride ingress into concrete. For example, Dutch standards recommend the use of cements type CEM II/B-V, CEM III/A (with > 50% GGBFS) and CEM III/B, designated according to European standard EN 197-1:2011, for the exposure class XS [11]. Croatian standard HRN 1128:2023 doesn't provide guidance on cement types most appropriate for marine environment however since

contribution of pozzolanic reactions becomes significant after 28 days of hydration, testing of diffusion at the age of 90 days goes in favour of cements that react more slowly i.e. cements containing fly ash or slag.



a)



b)

Figure 1 *– Measurement chloride migration coefficient according to NT BUILD 492:1999: a) measuring cells; b) evaluation of chloride penetration front (grey area)*

Today sources of slag are becoming less available and pulverized coal combustion technology is being replaced by combustion in a circulating fluidized bed, which is characterized by lower energy consumption [12]. Unlike PCFA circulating fluidized bed fly ash has irregular particles and poses self-cementitious properties [13]. When used as cement replacement material circulating fluidized bed fly ash usually increases water demand and decreases strength but also reduces permeability and improved durability of concrete [14-16]. This paper investigates possibility of using circulating fluidized bed coal fly ash as a cement replacement material in concrete with a special focus of its performance in transport of chlorides.

2. Experimental Work

Influence of CFBFA on the concrete permeability was analysed on eight concrete mixes whose composition is given in Table 1. Cement used was ordinary portland cement type CEM I 52,5 N (CEM I) containing > 95% of portland cement clinker. As a filler material limestone quarry dust (LQD) was used which is a fine powder material containing > 85 % of particles passing the 0,063 mm sieve. Physical properties of CEM I and LQD can be found in [17]. Circulating fluidized bed fly ash (FA) originated from thermal power plant Stanari located in the central part of Bosnia and Hercegovina. Power plant uses lignite coal as a fuel which is incinerated at ≈ 850 °C. FA is a fine powder of median particle size of 18,8 μm and a density of 2,39 g/cm^3. Chemical and physical properties of FA used in this experiment can be found in [17] and [18]. Aggregate used was crushed limestone with three size fractions 0/4 mm, 4/8 mm and 8/16 mm and the average density of 2,68 kg/dm^3.

***Table 1** – Concrete mix composition (quantities per 1 m^3 of concrete)*

Mix Designation	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**
CEM I (kg)	400	355	320	400	350	400	350	300
Water (kg)	160	160	160	196	196	221	221	221
Superplasticizer (kg)	8,5	10,3	11,0	12,0	13,8	10,2	9,8	9,8
LQD (kg)	180	225	260	90	90	90	90	90
FA (kg)	-	-	-	90	140	90	140	190
CEM I+LQD+FA (kg)	580	580	580	580	580	580	580	580
Water/cement ratio	0,40	0,45	0,50	0,49	0,56	0,55	0,63	0,74
Water/binder ratio	0,40	0,45	0,50	0,40	0,40	0,45	0,45	0,45
Water/powder ratio	0,28	0,28	0,28	0,34	0,34	0,38	0,38	0,38
Aggregate 0-4 mm (kg)	941	941	941	877	872	843	838	833
Aggregate 4-8 mm (kg)	342	342	342	319	317	307	305	303
Aggregate 8-16 mm (kg)	428	428	428	399	397	383	381	378
Concrete properties								
Fresh concrete density (kg/m^3)	2420	2430	2410	2350	2365	2343	2310	2310
28-day compressive strength (MPa)	80,2	80,4	69,3	78,7	80,9	68,7	68,7	68
90-day compressive strength (MPa)	86,8	90,7	78,6	87,8	87,3	75,6	72,1	76,9

Mixes M1-M8 are designed with the same powder content (CEM I+LQD+FA) of 580 kg per 1 m^3. Mixes can be divided into three groups based on their water/powder (w/p) ratio. Mix M1 was selected as a reference mixture and was made without FA. In mixes M2 and M3 part of the cement was replaced by LQD. In mix M4 50% of LQD was replaced with FA while in mix M5 50kg of cement was additionally replaced with fly ash. Water/binder (w/b) ratio given in Table 1 is calculated assuming that both CEM I and FA can be treated as a binder.

To maintain the same w/b ratio of 0,4 as in mix M1 water content in mixes M4 and M5 was increased accordingly. Mixes M6-M8 were made with w/b ratio of 0,45. Compared to mix M6 cement content of 50 kg and 100 kg were replaced by FA in mixes M7 and M8 respectively. Analysis of fresh concrete properties and compressive strength for the mixes given in Table 1 can be found in [17].

Tests of chloride diffusion were made according to the standard NT BUILD 492 at an age of concrete of 28 and 90 days. Tests were performed on the concrete samples cast in the cylindrical moulds of diameter 100 mm and the height of 200 mm. After casting specimens were placed in a water bath at a temperature of 20±2°C. Prior to testing specimens were sawn to the height of 50 mm.

3. Results and Discussion

Measured chloride migration coefficients D_{nssm} are presented in Figure 2. Reduction of D_{nssm} in the period from 28 to 90 days is clearly visible for all mixes. In Figure 3 D_{nssm} is plotted versus cement replacement ratio expressed as mass of cement replaced by LQD or FA divided by cement content. Results for mix M2 and M3 show that replacing cement with LQD is reducing resistance to chloride penetration and changes classification of exposure class from XS2 to XS1. It is interesting that the compressive strength and density of fresh concrete for mix M2 (Table 1) doesn't follow the same trend. Increased compressive strength and density in mix M2 can be attributed to the increased packing density. This shows that increased packing density doesn't necessarily lead to reduced permeability to chlorides.

Replacing 50% of LQD with FA in mix M4 significantly reduced chloride permeability (Figure 2). Additional replacement of cement with FA in mix M5 shows almost the same D_{nssm} as in mix M4. Compressive strength in mixes M4 and M5 is very close to the compressive strength of mix M1 (Table 1) regardless that the binder content being increased from 400 kg to 490 kg per m^3. This implies that the binding ability of FA is lower than that of cement and that filling effects and perhaps chloride absorption effects lead to decreased rate of chloride ingress. Increasing w/b ratio to 0,45 in mix M6 lead to increase in D_{nssm}. This is expected since larger quantity of water increases capillary porosity of the binder paste. Replacing cement with FA in mixes M7 and M8 reduced chloride transport (Figure 3) with the lowest D_{nssm} recorded in mix M8. From compressive strength results (Table 1) it can be seen that replacing cement with FA had almost no effect on the compressive strength in mixes M7 and M8.

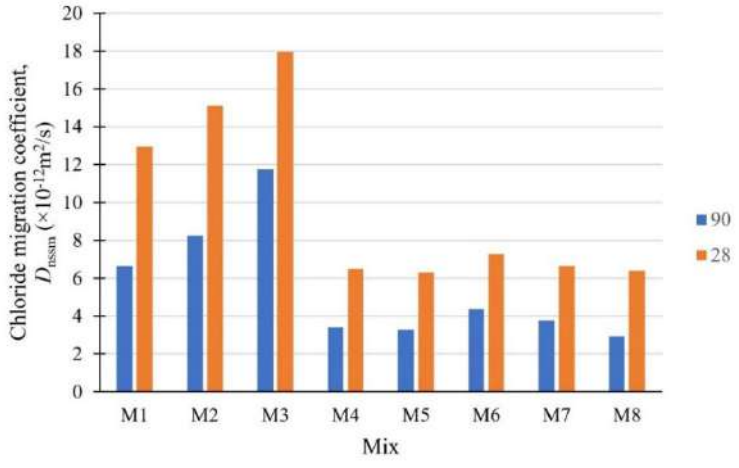


Figure 2 *– Chloride migration coefficient at an age of 28 and 90 days*

Jozwiak-Niedzwiedzka investigated effect of replacing 15% and 30% of cement with circulating fluidized bed fly ash and found that D_{nssm} decreases proportional to the fly ash content [15]. Zahedi et al. found that cement replacement by fluidized bed fly ash led to pore refinement [16]. The same authors also speculate that the increased alumina content of the fluidized bed fly ash can increase chloride binding from pore solution.

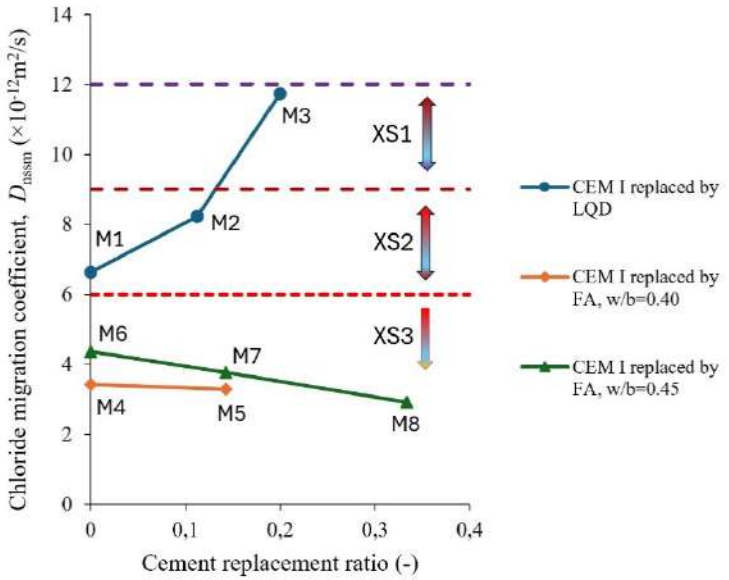


***Figure 3** – Correlation of D_{nssm} coefficient with cement replacement ratio and classification according to exposure classes as defined in standard HRN EN 1128-:2023*

4. Conclusion

The performance of concrete containing fluidized bed fly ash was studied with emphasis on the chloride transport properties. All mixes containing fly ash could be classified as exposure class XS3 which represent most severe marine conditions regarding durability. Results show that the rate of chloride penetration is reduced with the increase in fly ash content. Investigation also shows that that the circulating fluidized bed fly ash is more effective than cement in preventing chlorides from penetrating concrete. Analysis of compressive strength data implies that the mechanisms behind improved chloride resistance are primarily related to the refinement of pore size and not through pozzolanic and hydraulic reactions. Therefore, circulating fluidized bed fly ash could be implemented as a cement replacement material or as a mineral admixture for concrete but there remains the challenge of careful optimization of fly ash content primarily related to the high variability depending on the local source of origin.

Acknowledgement

This study was conducted within the framework of the University of Zagreb Faculty of Civil Engineering Institutional project for enhancing scientific excellence – OPTI-MATE Optimization of materials and technologies for sustainable built environment which was co-financed by funds from the National Recovery and Resilience Plan 2021-2026. Funded by the European Union – NextGenerationEU. The views and opinions expressed are solely those of the author(s) and do not necessarily reflect the official positions of the European

Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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Experimental Investigation of SCC Freeze-Thaw Resistance as a Function of Using Different Types of Recycled Concrete Aggregate

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Abstract

This paper presents an original experimental study on the influence of aggregate type on the freeze-thaw resistance of self-compacting concrete (SCC). Particular emphasis is placed on the effects of coarse recycled concrete aggregate (RCA) derived from crushed waste concrete, specifically comparing RCA of a controlled composition and known origin with RCA of unknown origin sourced from a construction and demolition waste recycling facility. Four SCC mixtures incorporating aggregates of different origins were examined: a control mixture produced entirely with crushed natural limestone, a mixture made with natural river aggregate, and two SCC mixtures containing natural river sand combined with coarse RCA of known and unknown origin, respectively. The freeze-thaw resistance of the investigated concretes was evaluated after 200 freeze-thaw cycles. The results indicate that incorporating RCA of unknown origin had the most pronounced adverse effect on the concrete's durability under cyclic freezethaw action.

Keywords

Recycled Concrete Aggregate of Known Origin (RCA-K), Recycled Concrete Aggregate of Unknown Origin (RCA-U), Freeze-Thaw Resistance, Self-Compacting Concrete (SCC).

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1. Introduction

The durability of concrete structures has become one of the central issues in contemporary civil engineering, due to the widespread use of concrete as the dominant construction material and the growing awareness of deterioration processes induced by environmental actions. Among the various mechanisms responsible for durability loss, freeze-thaw action represents one of the most severe forms of degradation in regions characterised by prolonged periods of sub-zero temperatures. Repeated freezing and thawing may initiate microcracking, increase internal damage, and ultimately impair both the mechanical performance and service life of concrete structures [1–3]. Consequently, the development of durable concrete mixtures capable of resisting freeze-thaw exposure remains an important research challenge.

Particular attention has been directed toward self-compacting concrete (SCC), a highly flowable cementitious composite capable of filling formwork and encapsulating reinforcement without the need for external vibration. Due to its superior characteristics in the fresh state, improved surface quality, and reduced labour requirements, SCC has been increasingly adopted in structural applications and is widely recognised as a viable alternative to conventionally vibrated concrete [4– 10]. However, the growing demand for SCC is accompanied by an increasing consumption of natural raw materials, especially aggregates, which has intensified concerns regarding resource depletion and environmental sustainability.

In parallel with the continuous extraction of natural aggregates, the construction sector generates substantial quantities of construction and demolition waste. The recycling of these materials, particularly waste concrete, offers an opportunity to simultaneously reduce landfill disposal and preserve natural aggregate resources [6, 11–14]. This issue is especially relevant in the Republic of Srpska, where a comprehensive system for the management and recycling of construction waste has not yet been fully established. Large quantities of waste concrete are generated during demolition activities, infrastructure rehabilitation works, and post-disaster reconstruction processes, such as those that followed the severe floods of 2014. In practice, a considerable proportion of this material is still disposed of at municipal dumpsites or uncontrolled disposal facilities, as illustrated in Figure 1, representing both an environmental burden and a loss of potentially valuable secondary raw materials.



***Figure 1** – Examples of illegal construction and demolition waste dumping sites*

Previous studies [13–19] have indicated that construction and demolition waste constitutes one of the largest waste streams worldwide, often exceeding the quantity of municipal solid waste generated annually. In countries characterised by intensive urban development and infrastructure expansion, the volume of construction waste may exceed

several times that of household waste. Accordingly, the production of recycled concrete aggregate (RCA) from waste concrete has emerged as one of the most promising strategies within the framework of sustainable construction and circular economy principles.

The durability performance of concrete incorporating recycled aggregates depends on numerous factors, including aggregate quality, source characteristics, replacement ratio, pore structure, and interfacial transition zone properties [13, 17, 19]. Since freeze-thaw resistance is strongly influenced by moisture movement and the development of hydraulic pressures within the pore system, aggregate selection is a critical parameter in the design of durable concrete mixtures [20–23]. Therefore, the present study investigates the influence of several aggregate types available on the local market, namely natural river aggregate (NRA), natural crushed aggregate (NCA), recycled concrete aggregate of known origin (RCA-K), and recycled concrete aggregate of unknown origin (RCA-U), on the freeze-thaw resistance of SCC.

2. Experimental Investigation

To evaluate the influence of recycled concrete aggregates originating from different sources on the freeze-thaw durability of self-compacting concrete (SCC), an experimental programme comprising four SCC mixtures was conducted. The investigated concretes incorporated aggregates of both natural and recycled origin. Natural aggregates included river aggregate (NRA) and crushed limestone aggregate (NCA), whereas recycled concrete aggregates were classified according to their provenance as recycled aggregate of known origin (RCA-K) and recycled aggregate of unknown origin (RCA-U).

All aggregate blends were designed as a continuously graded three-fraction blend with a maximum nominal aggregate size of 16 mm, thereby ensuring comparable particle size distributions among all investigated concrete mixtures.

The SCC mixtures evaluated in this study were designated as follows:

- SCC_{NCA} – SCC incorporating natural crushed aggregate;
- SCC_{NRA} – SCC produced exclusively with natural river aggregate;
- $SCC_{RCA\text{-}K}$ – SCC containing natural river sand combined with coarse recycled concrete aggregate of known origin; and
- $SCC_{RCA\text{-}U}$ – SCC containing natural river sand combined with coarse recycled concrete aggregate of unknown origin.

A testing programme was carried out on both fresh and hardened concrete specimens.

The properties evaluated in the fresh state included:

- concrete temperature, determined in accordance with EN 12350-1 [24];
- entrapped air content, measured according to EN 12350-7 [25];
- consistency, assessed via the slump-flow method in accordance with EN 12350-8 [26]; and
- concrete density, determined in accordance with EN 12350-6 [27].

The testing programme for the hardened concrete comprised:

- compressive strength at 28 days, determined in accordance with EN 12390-3 [28]; and
- freeze-thaw resistance, assessed according to SRPS U.M1.016 [29].

2.1. Component Materials

The self-compacting concrete (SCC) mixtures were produced using locally available constituent materials.

The binder system consisted of CEM II/B-M (S-LL) 42.5 N cement manufactured by Dalmacijacement (Sv. Juraj, Kaštel Sućurac, Croatia), with a specific gravity of 3140 kg/m³, and a Type I mineral addition in the form of limestone filler supplied by Japra Ltd. (Novi Grad, Bosnia and Herzegovina), having a specific gravity of 2780 kg/m³.

Natural river aggregate (NRA), sourced from the Petroševci deposit and supplied by Niskogradnja Laktaši (Bosnia and Herzegovina), was washed and separated into 0/4 mm, 4/8 mm, and 8/16 mm fractions. The corresponding loose bulk densities were 1606, 1554, and 1582 kg/m³; the particle densities were 2740, 2696, and 2683 kg/m³; while the water absorption values amounted to 0.6, 0.8, and 0.4 %, respectively.

Natural crushed aggregate (NCA), originating from the Dobrnja quarry and supplied by Binis (Banja Luka, Bosnia and Herzegovina), was likewise classified into 0/4 mm, 4/8 mm, and 8/16 mm fractions. The measured loose bulk densities were 1546, 1354, and 1318 kg/m³; the particle densities were 2709, 2746, and 2718 kg/m³; and the water absorption values were 0.6, 1.2, and 0.7 %, respectively.

Two types of recycled concrete aggregate (RCA) were employed.

The first, denoted as RCA-K, was produced by crushing waste concrete of a known origin and controlled composition (strength classes C25/30 and C35/45). This recycled material was separated into 4/8 mm and 8/16 mm fractions, exhibiting loose bulk densities of 1278 and 1231 kg/m³, particle densities of 2350 kg/m³, and water absorption values of 2.4 and 2.2 %, respectively.

The second recycled aggregate, designated as RCA-U, originated from construction and demolition waste collected from a dedicated storage depot, thereby representing a recycled aggregate of unknown origin. Its 4/8 mm and 8/16 mm fractions exhibited loose bulk densities of 1267 and 1221 kg/m³, particle densities of 2330 kg/m³, and water absorption capacities of 3.6 and 3.1 %, respectively.

A polycarboxylate-based high-range water-reducing admixture (HRWRA), Cementol® Zeta Super S (TKK, Srpenica, Slovenia), was utilized to ensure the required rheological properties of the SCC mixtures.

Potable tap water was used for both mixing and curing purposes.

2.2. Mix Proportion

The concrete mixtures were proportioned in accordance with the requirements for SCC belonging to the SF2 consistency class, as defined by *The European Guidelines for Self-Compacting Concrete – Specification, Production and Use* [8]. Consequently, all mixtures were designed to achieve a target slump-flow diameter ranging from 660 to 750 mm.

The composition of individual SCC mixtures, including constituent material contents per cubic metre of concrete, water-cement ratios and calculated fresh concrete densities, is presented in Table 1.

***Table 1** – Mixture compositions, water-cement ratio and calculated density*

Mix identity				SCC_{NCA}	SCC_{NRA}	SCCRCA-K	SCCRCA-U
Cement			[kg/m^3]	448	453	450	450
Limestone filler				153	181	196	193
Aggregate	NCA	0/4 mm		827	–	–	–
		4/8 mm		239	–	–	–
		8/16 mm		539	–	–	–
	NRA	0/4 mm		–	909	832	860
		4/8 mm		–	185	–	–
		8/16 mm		–	460	–	–
	RCA	4/8 mm		–	–	234	262
		8/16 mm		–	–	394	335
HRWRA				6.73	6.74	6.75	6.75
Effective water				188.7	202.4	189.0	189.0
Additional water				–	–	14.3	19.9
Water-cement ratio			[–]	0.42	0.45	0.42	0.42
Density			[kg/m^3]	2401	2397	2316	2316

2.3. Experimental Program

All SCC mixtures were prepared, cast, and cured under identical laboratory conditions to ensure comparability of results. Throughout specimen production and curing, the ambient temperature was maintained at 20 ± 3°C, and the relative humidity at 65 ± 5 %.

Concrete mixing was performed using a laboratory pan mixer (CONTROLS, model TTM 140V). The experimental setups and procedural stages for evaluating the concrete mixtures in fresh and hardened states are illustrated in Figures 2 and 3.

The temperature of the fresh concrete was monitored using digital thermometers manufactured by CONTROLS (model 82-D1226/A). The entrapped air content was measured using a CONTROLS pressure air meter (model 54-C0170/D) featuring a vessel capacity of 8.0 l.

The consistency of the SCC mixtures was assessed by means of the slump-flow test. Testing was conducted using a standard Abrams cone (CONTROLS, model C150/A) and a corresponding base plate (CONTROLS, model 54-C0149/20), with the cone positioned in its normal orientation during the test procedure.

Fresh concrete density was determined as the average value obtained from three cube specimens with an edge length of 150 mm.

Following casting, all specimens remained in their moulds for the first 24 h, protected against moisture loss by plastic sheeting. Subsequently, they were demoulded and stored in water tanks at a temperature of 20 ± 3°C until reaching the testing age of 28 days.



Figure 2 *– Testing of fresh concrete: slump-flow appearance after consistency testing (left) and measurement of entrapped air content (right)*



Figure 3 *– Testing of hardened concrete: failure pattern after compressive strength testing (left) and positioning of specimens inside the freeze-thaw chamber (right)*

Compressive strength was determined as the mean value obtained from three 150 mm cube specimens tested at the age of 28 days.

Freeze-thaw resistance was evaluated using the destructive method prescribed by the relevant national standard. For each concrete mixture, fifteen specimens were prepared and divided into five groups:

- E_0 – reference specimens tested for compressive strength at the onset of the exposure regime;
- E_I – reference specimens not subjected to freezing, tested at an age equivalent to that of specimens exposed to 150 freeze-thaw cycles;

- E_{II} – reference specimens not subjected to freezing, tested at an age equivalent to that of specimens exposed to 200 freeze-thaw cycles;
- M_{150} – specimens exposed to 150 freeze-thaw cycles; and
- M_{200} – specimens exposed to 200 freeze-thaw cycles.

Freeze-thaw cycling was carried out in a programmable climatic chamber (CONTROLS, model 65-D1409) with a capacity of 50 kg. The equipment enabled precise temperature control within the range from −20 to +65°C, with an accuracy of ± 0.1°C, while continuously monitoring and recording the air temperature in the vicinity of the concrete specimens throughout the testing period.

2.4. The Results

Table 2 presents the measured properties of the self-compacting concretes in the fresh state, including the parameters utilized to evaluate their workability and fundamental physical characteristics.

***Table 2** – Test results of fresh concrete*

Mix Identity	Temperature	Entrapped Air Content	Density	Slump-flow
	T	A_c	D	SF
	[°C]	[%]	[kg/m^3]	[mm]
SCC_{NCA}	25	1.8	2400	700
SCC_{NRA}	26	1.1	2396	760
SCC_{RCA-K}	29	4.2	2316	660
SCC_{RCA-U}	29	4.2	2317	710

The compressive strength results determined at the age of 28 days are summarized in Table 3. In addition to the average compressive strength values, the corresponding standard deviations and coefficients of variation are provided to assess the uniformity and reliability of the experimental data.

***Table 3** – Test results of compressive strength at the 28 days of age*

Mix Identity	Compressive Strength	Standard Deviation	Coefficient of Variation
	$f_{c,cube,28}$	S_n	$v(f_{c,cube,28})$
	[MPa]	[MPa]	[%]
SCC_{NCA}	63.1	1.178	1.865
SCC_{NRA}	59.1	4.267	7.225
SCC_{RCA-K}	65.1	2.670	4.099
SCC_{RCA-U}	60.9	2.470	4.053

Table 4 contains the results of the freeze-thaw resistance assessment. The table includes the compressive strengths of the reference specimens determined at the onset of testing, as well as the strengths of the companion reference specimens tested at ages equivalent to those of the specimens subjected to 150 and 200 freeze-thaw cycles. Furthermore, the compressive strengths measured after 150 and 200 cycles of alternating freezing and thawing are presented. To facilitate the durability evaluation, the ratios between the compressive strengths of the freeze-thaw exposed specimens and the corresponding reference specimens of equivalent age are reported for both exposure levels. Additionally, the corresponding standard deviations and coefficients of variation are provided for all determined compressive strength values.

***Table 4** – Test results of freeze-thaw resistance*

Mix Identity		Compressive Strength	Standard Deviation	Coefficient of Variation	Strength Ratio
		$f_{c,cyl}$	S_n	$v(f_{c,cyl})$	$f_{c,cyl,M} / f_{c,cyl,E}$
		[MPa]	[MPa]	[%]	[–]
SCC_{NCA}	E_0	63.0	3.738	5.928	–
	E_I	70.7	7.157	10.118	0.92
	M_{150}	64.8	8.092	12.483	
	E_{II}	74.4	1.035	1.390	0.87
	M_{200}	65.0	1.684	2.589	
SCC_{NRA}	E_0	56.3	2.103	3.736	–
	E_I	62.7	7.636	12.189	0.99
	M_{150}	61.8	11.411	18.467	
	E_{II}	66.1	4.628	7.002	0.87
	M_{200}	57.4	4.726	8.230	
SCC_{RCA-K}	E_0	65.9	2.538	3.850	–
	E_I	66.0	2.169	3.285	1.00
	M_{150}	65.8	3.178	4.830	
	E_{II}	66.1	3.536	5.351	0.92
	M_{200}	60.7	5.319	8.761	
SCC_{RCA-U}	E_0	60.1	3.804	6.330	–
	E_I	60.3	3.077	5.106	0.98
	M_{150}	59.3	1.774	2.993	
	E_{II}	60.3	2.450	4.062	0.79

3. Analysis and Discussion of Results

The incorporation of recycled concrete aggregates (RCA) into self-compacting concrete (SCC) mixtures influenced several fresh and hardened properties. Compared with the reference mixtures produced exclusively with natural aggregates, the utilization of RCA resulted in an average reduction in fresh density of approximately 80 kg/m³. Concurrently, the residual air content in the fresh concrete increased by about 2.75 %. Despite these alterations, the slump-flow diameter was only marginally affected, exhibiting an average reduction of 45 mm. Since the target consistency corresponding to the SF2 class was successfully achieved across all formulations, this reduction cannot be considered significant. The limited effect on workability can be attributed to the additional mixing water introduced to compensate for the higher water absorption capacity of the recycled aggregates. Based on the measured densities, all investigated mixtures are classified as normalweight concretes.

The significance of differences in 28-day compressive strength was evaluated using Student's t-test. Since the mean value for each concrete type was determined from three test specimens, the number of degrees of freedom for each pairwise comparison was four. At a significance level of 0.05, the obtained results indicated that the measured strengths belonged to the same statistical population, confirming that the observed differences were not statistically significant. Although the concretes containing RCA exhibited slightly higher average compressive strengths – approximately 2 MPa above those of the concretes produced with natural aggregates – these variations remained well within the range of experimental variability.

An analysis of compressive strength development under saturated conditions revealed that the concrete produced with NRA and the mixture incorporating natural fine river sand combined with coarse RCA-K exhibited highly comparable strength gains beyond 28 days. In contrast, the SCC containing RCA-U showed a noticeably lower rate of strength development, with compressive strengths approximately 6 MPa lower than those recorded for the SCC containing RCA-K at equivalent ages. This behaviour may be attributed to the presence of impurities and undesirable constituents within the recycled aggregate sourced from construction and demolition waste processing sites. Such materials can adversely affect the bond between the aggregate particles and the cementitious matrix, thereby limiting the continued development of compressive strength at later ages.

The freeze-thaw test results demonstrated that, for all investigated concretes, the ratio between the compressive strength of specimens subjected to repeated freezing and thawing cycles (150 and 200 cycles) and the strength of the corresponding reference specimens of equivalent age remained above 0.75. According to the adopted assessment criterion, all mixtures satisfied the durability requirements after both exposure regimes. A more detailed examination of the results indicated that freeze-thaw resistance was governed by several interrelated factors, including aggregate type, compressive strength, and pore structure characteristics.

Among all investigated mixtures, the SCC containing RCA-U ($SCC_{RCA\text{-}U}$) manifested the most pronounced deterioration. Although this concrete maintained satisfactory performance after 150 freeze-thaw cycles, an additional 50 cycles induced a 21.2 % reduction in the freeze-thaw resistance coefficient. This decrease substantially exceeded the average reduction observed for all other mixtures, which amounted to approximately 11.3 %. Furthermore, after 200 cycles, visible surface scaling and measurable mass loss (under 5 %) were recorded. These findings suggest that, despite satisfying the minimum acceptance criterion, this concrete would likely be unable to meet more demanding durability requirements involving extended freeze-thaw exposure.

A distinctly different response was observed for the SCC produced with RCA-K (SCC_{RCAK}). This mixture maintained a high level of freeze-thaw resistance throughout both testing stages, while the reduction in the relative freeze-thaw resistance coefficient between 150 and 200 cycles was approximately 8 %, closely corresponding to the average value recorded for the remaining concretes. A comparison between SCC_{RCA-K} and the SCC_{NRA} is particularly informative because the original mineral particles within the recycled aggregate were also of river origin. The principal distinction between these materials lies in the presence of adhered old cement paste on the recycled aggregate particles. The superior freeze-thaw performance of SCC_{RCA-K} therefore suggests that the residual cement paste should not necessarily be regarded as a disadvantage from a durability perspective.

On the contrary, the porous structure of the adhered mortar matrix may have contributed positively by providing additional space for water migration and ice expansion during freezing. As a result, hydraulic pressures generated within the newly formed interfacial transition zone (ITZ) could be partially relieved. Similar observations have been reported in previous studies [13, 21], where porous aggregate constituents contributed to enhanced freeze-thaw performance. In addition, SCC_{RCA-K} featured a more porous cementitious matrix, characterized by a larger volume of capillary pores and voids capable of accommodating ice formation. These findings indicate that freeze-thaw resistance in SCC is strongly associated with pore system characteristics and not solely governed by compressive strength.

A comparison between the SCC_{NRA} and the SCC_{NCA} revealed no statistically significant differences in freeze-thaw resistance. After 150 cycles, the concrete containing river aggregate exhibited a slightly higher freeze-thaw resistance coefficient, which can be related to its lower initial compressive strength. However, after 200 cycles, the freeze-thaw resistance coefficients of the two mixtures became practically identical. Nevertheless, the SCC containing crushed limestone aggregate exhibited a somewhat lower rate of deterioration between 150 and 200 cycles, which may be attributed to a more stable and denser interfacial transition zone (ITZ) between the aggregate particles and the cement paste matrix.

4. Conclusion

The experimental investigation conducted on four powder-type self-compacting concrete (SCC) mixtures produced with different aggregate types – crushed limestone (NCA), natural river aggregate (NRA), and combinations of fine river aggregate with coarse recycled concrete aggregate of known (RCA-K) and unknown (RCA-U) origin – demonstrated that all investigated concretes were capable of withstanding 200 freeze-thaw cycles. However, the type and origin of the aggregate significantly influenced the material's freeze-thaw resistance.

The results indicated that the rate of concrete deterioration escalated with the increasing number of freeze-thaw cycles, which is consistent with the behaviour commonly observed in conventionally vibrated concretes. Among all investigated mixtures, SCC incorporating RCA-U exhibited the most pronounced reduction in freeze-thaw resistance after both 150 and 200 cycles. In contrast, concretes produced with NRA, NCA, and RCA-K showed considerably smaller performance losses. This behaviour can be ascribed to the heterogeneous nature of RCA-U derived from construction and demolition waste, where residual impurities and lower-quality constituents may adversely affect durability. Consequently, recycled concrete aggregate of unknown origin cannot be expected to satisfy more stringent durability requirements involving an extended number of freeze-thaw cycles.

No statistically significant differences in freeze-thaw resistance after 200 cycles were recorded among the concretes produced with NRA, NCA, and RCA-K. Furthermore, the

results revealed that improved freeze-thaw resistance was associated with lower compressive strength and higher residual porosity. It should be emphasized that this observation is specific to SCC and cannot be directly generalized to other concrete types.

The SCC mixture containing RCA-K manifested the smallest reduction in freeze-thaw resistance, which may be attributed to the presence of residual pores within the adhered old cement paste surrounding the recycled aggregate particles. These pores likely acted as pressure-relief zones during ice formation, thereby mitigating freeze-thaw damage. In addition, the smallest increase in deterioration between 150 and 200 cycles was observed in the SCC produced with NCA, which can be associated with the stronger bond between the aggregate particles and the cement paste, as well as the formation of a denser interfacial transition zone (ITZ).

From a practical perspective, the findings support the use of recycled concrete aggregate of known and controlled origin as a viable alternative to natural river and crushed aggregates in structures exposed to freeze-thaw action. Conversely, recycled aggregates of uncontrolled composition and insufficiently processed construction waste should not be recommended for concrete structures expected to operate under severe freeze-thaw conditions.

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Illegal Landfills in the Bosnian-Podrinje Canton: Causes, Impacts, and Circular Economy-Based Solutions

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Abstract

The formation of illegal landfills represents one of the significant environmental challenges in the Bosnian-Podrinje Canton, indicating an insufficiently developed and inefficient waste management system. This paper analyzes the causes of illegal waste dumping, including the lack of adequate waste collection and sorting infrastructure, limited public environmental awareness, and weak institutional coordination in waste management.

A special focus is placed on the connection between this issue and the principles of the circular economy. Illegal landfills are viewed as a consequence of the linear "take-make-dispose" model, which still dominates the current waste management system. The paper emphasizes that the implementation of circular economy principles such as waste reduction, reuse, recycling, and resource recovery can significantly contribute to reducing illegal landfills and improving sustainable waste management practices.

Based on the analysis, recommendations are provided, including strengthening separate waste collection systems, developing recycling infrastructure, improving public awareness, and enhancing institutional control and enforcement of environmental regulations. The application of circular economy principles is identified as a key framework for the long-term resolution of illegal waste disposal issues.

Keywords

Illegal landfills, waste management, circular economy, sustainable development, recycling.

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1. Introduction

Waste management is one of the key challenges of modern society, as it directly affects environmental quality, public health, and sustainable development. With population growth, urbanization, and increasing industrial activities, the amount of generated waste continues to rise, placing additional pressure on existing systems for waste collection, treatment, and disposal. In this context, inadequate waste management can lead to serious environmental problems, among which the emergence of illegal or so-called wild landfills is particularly significant.

According to the Waste Management Law in Bosnia and Herzegovina, waste is defined as any substance or object that the owner discards, intends to discard, or is required to discard in accordance with prescribed waste lists and relevant legal regulations. The law also establishes the fundamental principles of waste management, emphasizing the prevention of waste generation, the reduction of its environmental impact, and the rational use of resources through reuse, recycling, and recovery processes.

Despite the existing legal framework, Bosnia and Herzegovina still largely relies on a linear waste management model based on the “take–make–dispose” principle. This approach results in the accumulation of waste in unmanaged locations, leading to the formation of illegal landfills, which represent a significant source of soil, water, and air pollution, as well as a direct threat to human health and biodiversity.

The situation is particularly concerning in the Bosnian-Podrinje Canton, where insufficient waste management infrastructure, limited capacities of municipal utility services, and low environmental awareness among the population contribute to the emergence and expansion of illegal dumping sites. These locations are often outside institutional control, resulting in the uncontrolled disposal of various types of waste, including municipal, construction, electronic, and potentially hazardous waste.

Illegal landfills generate numerous negative environmental impacts, including the emission of landfill gases, the generation of leachate that can contaminate surface and groundwater, and an increased risk of fires and the release of harmful substances. Uncontrolled waste disposal contributes to different forms of environmental pollution. Air pollution occurs due to the release of harmful gases and toxic compounds, including dioxins, furans, carbon monoxide (CO), and hydrogen sulfide (H_2S). Soil pollution is associated with the accumulation of heavy metals and hazardous chemicals, while water pollution may occur as a result of leachate infiltration into surface and groundwater resources. In addition to environmental degradation, illegal waste disposal sites pose significant risks to human health, including the spread of infectious diseases, allergic reactions, and long-term exposure to hazardous substances (Figure 1).

Figure 1 illustrates the main environmental and health consequences associated with illegal waste disposal sites, highlighting their impacts on air quality, water resources, soil contamination, and human health.



Figure 1 *– Environmental and Health Consequences of Illegal Waste Disposal Sites (Source : Authors)*

In addition to environmental consequences, illegal landfills also have significant health and socio-economic impacts, reflected in higher remediation costs, reduced quality of life, and the degradation of public spaces. The presence of unmanaged waste disposal sites can negatively influence local communities, reduce the attractiveness of affected areas, and create additional challenges for sustainable regional development.

In this context, the concept of the circular economy emerges as a modern framework for improving waste management systems. The circular economy is based on the transition from a linear to a circular model, in which waste is treated as a resource that can be reused, recycled, and reintegrated into production cycles. This approach reduces the amount of waste ending up in landfills, extends the lifecycle of materials, and decreases pressure on natural resources.

Therefore, analysing the causes contributing to the formation of illegal landfills in the Bosnian-Podrinje Canton, as well as developing recommendations for their reduction, requires the integration of circular economy principles as a key strategic approach. This paper aims to examine the causes of illegal dumping sites, assess their environmental impacts, and propose guidelines for improving the waste management system towards a more sustainable circular waste management model.

1.1. Causes of Illegal (Wild) Landfill formation

Illegal landfills are primarily the result of an insufficiently developed and inefficient waste management system. Their occurrence is closely associated with inadequate waste collection and disposal infrastructure, low levels of environmental awareness among citizens, and weak legal and inspection enforcement mechanisms. Under such conditions, waste is often disposed of at uncontrolled locations, creating significant environmental and public health risks.

In the Bosnian-Podrinje Canton, as well as in other parts of Bosnia and Herzegovina, illegal landfills are a widespread issue. Since these sites are not legally regulated or systematically integrated into waste management planning, there is no long-term or sustainable approach to their prevention, management, and remediation. Furthermore, the high costs associated with landfill cleanup and rehabilitation represent an additional challenge, often leading to delayed or incomplete interventions.

Within the Bosnian-Podrinje Canton (BPC) Goražde, three municipal landfills are officially registered. However, these sites function as open dumping areas that do not meet sanitary landfill standards and therefore require urgent rehabilitation and closure. For instance, the “Šišeta” landfill is located in a valley area and lacks essential environmental protection systems, such as leachate collection and landfill gas control systems, while its operating permit expired in 2012. The “Gavrić” landfill in Foča–Ustikolina is situated near settlements and watercourses, has limited remaining capacity, and is planned for closure and rehabilitation. Similarly, the “Šainovići” landfill, located along the M5 road, has been addressed through technical planning documents aimed at its closure and transformation into a more sustainable waste management facility, including the establishment of a recycling centre.

Following the closure of these municipal landfills, municipal waste is planned to be transported to the regional landfill “Trešnjica” in Goražde, representing an important step toward establishing a more centralized and structured waste management system.

In addition to officially registered disposal sites, approximately 29 illegal landfills have been identified within the canton, with new sites continuing to emerge annually. Although municipal services periodically remove waste from these locations, the problem persists due to its systemic nature, making illegal dumping a recurring environmental challenge.

From the perspective of the circular economy, illegal landfills represent a direct consequence of the prevailing linear “take–make–dispose” model, which continues to dominate waste management practices in the region. Within this model, waste is perceived as a final output rather than as a valuable resource, leading to its accumulation in uncontrolled environments instead of its reintegration into production cycles.

The circular economy provides a fundamentally different approach by prioritizing waste prevention, material reuse, recycling, and resource recovery. When effectively implemented, these principles can significantly reduce the amount of waste disposed of in landfills while simultaneously decreasing the demand for new disposal facilities. In the context of the Bosnian-Podrinje Canton, strengthening recycling systems, improving separate waste collection, investing in appropriate infrastructure, and increasing public awareness are essential steps toward transitioning from a linear to a circular waste management model.

Therefore, the issue of illegal landfills should not be considered an isolated environmental problem, but rather as an indicator of structural deficiencies within the existing linear waste management system. Addressing this challenge requires an integrated approach based on circular economy principles, which can transform waste from an environmental burden into a valuable resource and contribute to sustainable regional development.

2. Materials and Methods

The conducted analysis provided a comprehensive insight into the causes of illegal landfill formation in the Bosnian-Podrinje Canton (BPC), their spatial distribution, and associated environmental impacts. The results indicate that an inadequate waste management system, particularly insufficient infrastructure and low levels of environmental awareness, represent the main contributing factors to this problem. Furthermore, the analysis

demonstrates that most illegal landfills pose significant threats to water and forest ecosystems, representing considerable environmental and public health risks.

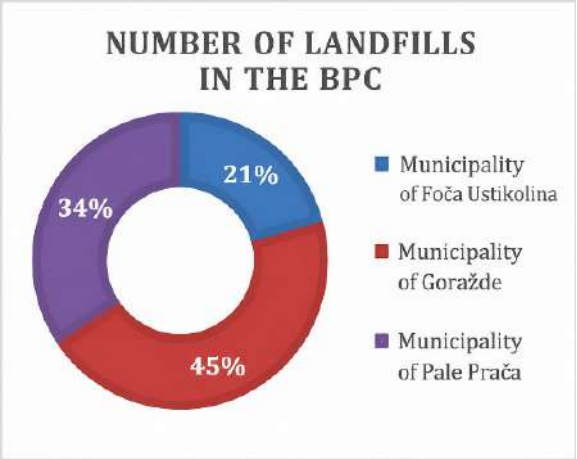
From the perspective of the circular economy (CE), these findings clearly reflect the dominance of the linear “take–make–dispose” model within the current waste management system. In such a system, waste is perceived as a final output rather than as a resource that can be reintegrated into production cycles. Consequently, valuable materials are lost from the economic system and accumulate at uncontrolled disposal sites, contributing to the formation and persistence of illegal landfills.

In the Bosnian-Podrinje Canton, three municipal utility companies operate: JKP "6. Mart", JKP "Ušće", and JKP "Prača", with a waste collection coverage rate of 73.33%. However, the remaining proportion of uncollected waste contributes significantly to the emergence of illegal landfills, where more than 10,000 m³ of mixed waste has been identified, with new sites continuing to appear. The lack of systematic records regarding the rehabilitation of illegal landfills further indicates that waste management practices are predominantly reactive rather than preventive.

Field and spatial analyses identified a total of 32 illegal landfills in the canton (Table 1), including three officially registered municipal landfills that operate as open dumping sites and do not comply with sanitary landfill standards. The highest concentration of illegal landfills was recorded in the Municipality of Goražde (45%), followed by Foča-Ustikolina (34%) and Pale-Prača (21%). Their spatial distribution reveals a clear pattern, as most sites are located near rivers, settlements, forest areas, and inaccessible terrain, increasing environmental vulnerability and complicating remediation efforts.

Table 1 *– Identified Illegal Landfills in the Bosnian-Podrinje Canton (BPC) (Source : Authors)*

Municipality of Goražde	***Municipality of Foča -Ustikolina***	***Municipality of Pale-Prača***
Bačci	Bratovčići	Brdarići
Belvedere	Brđalići 1	Donja Čemernica
Biserna	Gavrić	Datelji-Banjišta
Dučići	Kosovska rijeka	Datelji-Rudo brdo
Glamočki potok	Krivač	Gornja Vinča
Gubavica	Osanica	Gornje Bare
Haldište? drina		**Komrani?**
Krčevine		Lunje
Gradska dep. Šišeta		Podnehaje
Podhranjenski potok		Prešpica 1
Podložje?? - drina		Prešpica 2
Putni pravac Goražde-Prača		
Radići		
Trešnjica		
Ul. Rade Jovanovića		



Approximately 66% of illegal landfills are located in close proximity to the Drina River and its tributaries, significantly increasing the risk of water contamination through uncontrolled leachate infiltration. Furthermore, 60% of the identified sites are located on steep terrain, which limits accessibility for municipal services and increases the costs and complexity of remediation activities. The most significant environmental risk identified is fire occurrence (68%), primarily due to the presence of combustible waste and the proximity of landfill sites to forest ecosystems. This is followed by flood-related impacts (23%), which may result in waste dispersion and further contamination of surrounding areas. Health-related risks account for 9% and are associated with potential exposure to pathogens, air pollution, and deteriorated living conditions in nearby settlements.

The results further indicate that illegal landfills in the BPC have existed for more than two decades, confirming the presence of long-term systemic weaknesses in waste management governance. The absence of adequate recycling systems, limited infrastructure for separate waste collection, and insufficient enforcement of environmental regulations have all contributed to the persistence of this issue.

Within the circular economy framework, such conditions highlight structural deficiencies within the existing linear waste management model. Waste is not recognized as a secondary raw material but rather as a burden requiring disposal. Consequently, opportunities for reuse, recycling, and resource recovery remain largely underutilized. Strengthening circular economy principles, including improving waste separation at source, investing in recycling infrastructure, enhancing institutional coordination, and increasing public awareness, could significantly reduce the occurrence of illegal landfills and improve overall environmental performance.

Therefore, the findings of this study clearly demonstrate that illegal landfill formation is not an isolated environmental issue but rather a systemic consequence of an inefficient linear waste management model. Transitioning towards a circular economy approach is essential for achieving long-term sustainability, reducing environmental risks, and transforming waste from an environmental liability into a valuable resource.

Through photographic documentation obtained during field research, the specific locations of illegal landfills, their dimensions, waste composition, and surrounding environmental conditions have been presented. These images further confirm the identified risks and emphasize the urgent need for remediation measures and the establishment of a more efficient waste management system within the Canton.

Within the territory of the Bosnian-Podrinje Canton, a significant number of illegal waste disposal sites requiring remediation have been identified. Based on waste composition analysis, the most frequently observed materials include construction waste, bulky waste

(such as furniture), electrical and electronic waste (components of technical equipment), packaging and municipal waste, animal waste, used tires, and biodegradable waste.

From the perspective of the circular economy, the presence of diverse waste streams at illegal dumping sites clearly demonstrates the failure to implement effective waste separation, recycling, and resource recovery systems. Instead of being managed as secondary raw materials within a circular system, these materials are discarded in uncontrolled environments, resulting in environmental degradation and the loss of valuable resources.

According to the Waste Management Plan of the Bosnian-Podrinje Canton Goražde for the period 2022–2027, no short-term measures for the removal of illegal landfills have currently been planned. To enable effective remediation of these sites, it is necessary to develop a Remediation Plan that defines priorities, implementation timelines, remediation methods, funding sources, and monitoring mechanisms.

Since these locations represent illegal disposal sites, remediation should involve the complete removal of waste and its appropriate disposal at the planned regional landfill “Trešnjica”, while simultaneously introducing circular economy measures aimed at preventing the recurrence of illegal dumping practices.

The Waste Management Plan of the BPC foresees improvements to the municipal waste management system through several key activities, including the preparation of technical and environmental documentation for landfill rehabilitation, obtaining the necessary permits, and implementing a regional waste management concept. Within the circular economy framework, these measures should be complemented by investments in recycling infrastructure, separate waste collection systems, and resource recovery facilities in order to facilitate the transition from the linear “take–make–dispose” model towards a circular system that minimizes waste generation.

Illegal landfills represent a significant environmental challenge requiring a multi-level approach involving legislation, institutional strengthening, education, and the promotion of responsible waste management practices among citizens. From a circular economy perspective, this requires a systemic transformation in which waste is no longer perceived as a burden but as a resource that can be reintegrated into production cycles. Failure to address this issue comprehensively may result in long-term negative consequences for environmental quality, public health, and economic efficiency.



***Figure 2** – Prešpica landfill (Municipality of Pale–Prača) (Source : Authors)*

Although legal regulations establish requirements for proper waste management, their practical implementation remains insufficient, as local authorities, particularly within this Canton, often lack adequate financial and institutional capacities to address the problem effectively. Therefore, the transition towards a circular economy model, supported by appropriate infrastructure development and increased public awareness, is essential for reducing the number of illegal landfills and improving overall environmental performance.

The Waste Management Plan also foresees the revision of the existing regional landfill development plan, initially proposed within the Federal Waste Management Plan for the period 2012–2017 [22], with the aim of creating conditions for the establishment of new regional or inter-municipal landfill facilities. Within the circular economy approach, these efforts should not focus solely on disposal infrastructure but also on developing systems for waste prevention, reuse, recycling, and resource recovery. Furthermore, it is necessary to improve or upgrade existing municipal landfills that, due to geographical constraints or other limitations, cannot be fully integrated into the regional waste management system.

3. Conclusion

Illegal landfills represent a major environmental challenge in the Bosnian-Podrinje Canton and are primarily caused by inadequate waste management infrastructure, insufficient waste collection coverage, weak enforcement of environmental regulations, and low levels of public awareness. The identified illegal dumping sites pose significant risks to water resources, ecosystems, and public health, while also highlighting the limitations of the current linear “take–make–dispose” waste management model.

The findings emphasize the need for a transition towards a circular economy approach based on waste prevention, reuse, recycling, and resource recovery. Strengthening waste separation systems, investing in recycling infrastructure, improving institutional coordination, and increasing environmental awareness are essential measures for reducing the occurrence of illegal landfills and achieving sustainable waste management practices.

Through the implementation of circular economy principles, waste can be transformed from an environmental burden into a valuable resource, thereby contributing to environmental protection, improved resource efficiency, and long-term sustainable development in the Bosnian-Podrinje Canton.

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Innovative Construction Materials for Reducing Embodied Carbon in Reinforced Concrete Structures

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Abstract

Carbon emissions generated during the extraction, manufacturing, transportation, installation, maintenance, and end-of-life processing of construction elements, the so-called embodied carbon, have to be reduced for a sustainable built environment. The built environment can contribute significantly to climate action, sustainable urban development, responsible resource use, and industrial innovation by selecting sustainable materials, implementing circular resource management, and adopting innovative construction technologies. Embodied carbon represents one of the most important challenges of contemporary design of reinforced concrete structures. Most of the emissions come from the production of cement and reinforcement, and there is a need for their reduction.

This paper presents a brief review of sustainable materials such as low-carbon concrete incorporating supplementary cementitious materials, geopolymer concrete, carbon-cured concrete, recycled aggregates, and recycled steel reinforcement can achieve the reduction of embodied carbon in reinforced concrete structures. These materials contribute to greenhouse gas emissions reduction while maintaining the required structural performance and durability.

Keywords

Emissions, embodied carbon, sustainable built environment, sustainable and innovative construction materials.

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1. Introduction

The reduction of embodied carbon in buildings is directly connected to United Nations Sustainable Development Goals such as: Climate Action; Sustainable Cities and Communities; Responsible Consumption and Production; Industry Innovation and Infrastructure and Affordable and Clean Energy [1]. As part of the European Green Deal [2], the European Union has set the goal of achieving climate neutrality by 2050, which includes not only reducing operational energy consumption in buildings, but also reducing built-in emissions throughout the entire life cycle of building materials. EU regulations and policies increasingly introduce the obligation or recommendation for Life Cycle Assessment and Life Cycle Carbon analyzes in public projects, which directly affects the design of reinforced concrete structures with the aim of reducing the overall carbon footprint. Additionally, initiatives such as the Circular Economy Action Plan [3] and strategies for the Whole Life Carbon assessment of buildings in the construction sector emphasize the need to look at emissions throughout the entire life cycle of a building, including the production of materials such as concrete and steel. In this context, reinforced concrete structures can be optimized by reducing the amount of cement with supplementary cementitious materials, optimizing structural elements, using recycled aggregates etc.

Embodied carbon represents the total amount of carbon dioxide emissions generated during the life cycle of a building material or structure, including the exploitation of raw materials, production, transportation, installation, maintenance, and life end of the building [4], [5]. In reinforced concrete constructions, embodied carbon is particularly important due to the high CO_2 emissions that occur during the production of cement and reinforcing steel [6], and becomes one of the key criteria of sustainable design, especially after the adoption of new European regulations that require the assessment of emissions during the entire life cycle of the building [7].

In reinforced concrete constructions, the largest part of embodied carbon emissions comes from the processes of cement production, reinforcement production, transport of materials, concreting process and execution of works and maintenance and rehabilitation during the exploitation of the building [4], [6].

Design optimization is a very important approach to reducing embodied carbon emissions [4]. Reducing the amount of material is achieved by: rational dimensioning of sections, span optimization, using structures of greater strength, a more efficient reinforcement layout and using prestressed concrete where justified [6]. Modern design approaches increasingly include parallel optimization: strength capacity, durability, economy and the carbon footprint of the construction [7].

Use of recycled materials, as a part of the circular economy, represents one of the key directions of the sustainable construction strategy [3]. Within reinforced concrete structures, the concrete can be made with recycled aggregate from demolished buildings, recycled steel for reinforcement, and secondary cement materials [3], [7]. Recycled steel has a significantly lower carbon footprint than primary steel production, especially when produced in electric arc furnaces powered by renewable energy [6]. The reuse of structural elements further reduces the need for new materials and emissions associated with production [3].

The durability of the construction has a direct impact on the embodied carbon [4]. Structures that have longer service life, less need for repair and lower degree of degradation have lower total emissions during the life cycle of the building [5]. European standards and guidelines increasingly insist on designing according to the principles of durability, protecting reinforcement from corrosion, crack control and correct choice of concrete exposure class [5], [8].

The assessment of embodied carbon emissions is most often carried out using Life Cycle Assessment (LCA) methodology [9], [10], [11], and Environmental Product Declaration

(EPD) [12]. The Standard EN 15978 [5] defines the methodology for assessing the impact of a building during its life cycle, while standard EN 15804 [12] defines the rules for EPD declarations of construction products. EPD declarations allow designers to compare different types of concrete, to analyze the emissions of different cements, and to choose materials with a smaller carbon footprint. In European practice, LCA tools become an integral part of BIM design and the decision-making process during construction design [7].

This paper presents a brief review of sustainable materials that reduce embodied carbon in reinforced concrete structures, such as supplementary cementitious materials, geopolymer concrete, carbon-cured concrete, recycled aggregates, and recycled steel reinforcement.

2. Sustainable and Innovative Construction Materials

The construction sector represents one of the largest emitters of carbon dioxide on a global level, while reinforced concrete structures, as one of the most widely used construction systems in civil engineering, have a particularly significant environmental impact and contribute to total CO_2 emissions due to the large consumption of cement and steel [13]. In recent years, the focus of sustainable construction has increasingly been directed towards the reduction of embodied carbon emissions, i.e. emissions generated during the production of materials, transportation, construction, maintenance and the end of the construction's life cycle [5]. Traditional concrete relies heavily on cement, sand, and aggregates, whose extraction and production contribute significantly to environmental degradation and carbon emissions. To promote sustainability, researchers and engineers have explored the use of various waste materials as partial replacements for conventional concrete ingredients, such as industrial, agricultural, biodegradable, and construction waste materials.

2.1. Sustainable Cementitious Materials

The largest single source of carbon emissions is Portland cement. During cement production, the combustion of fossil fuels in furnaces occurs, as well as the release of a large amount of CO_2 through the limestone calcination process. To reduce embodied carbon, the most effective way is to reduce the content of Portland clinker in cement [6], [8]. Cements with reduced clinker content use granulated blast furnace slag, fly ash and other pozzolanic materials, Fig. 1, calcined clays and limestone additions can significantly reduce the emission of CO_2 per cubic meter of concrete, because the amount of energy-intensive clinker is reduced. In addition to reducing emissions, these cements often have lower heat of hydration, better durability of the structure, resistance to sulfates, resistance to chloride penetration, long-term concrete strength and according to environmental sustainability it can divert industrial waste from landfills. As agricultural wastes, they are residues generated from farming and food-processing activities and are commonly used as a cement replacement: rice husk ash, sugarcane bagasse ash, palm oil fuel ash, corn cob ash. Many contain silica and other compounds that can enhance concrete performance, especially in lightweight and sustainable concrete [6-8], [14-18].



Figure 1 *– Materials: cement, fly ash and pozzolan [17], [18]*

2.2. Recycled and Circular Building Materials

Recycled and circular building materials are becoming increasingly important in the construction industry as efforts to reduce environmental impacts and promote sustainable development. The circular economy concept aims to keep materials and resources in use for as long as possible through reuse, recycling, remanufacturing, and recovery processes. In civil engineering and reinforced concrete construction, recycled and circular materials can significantly reduce environmental impacts, particularly embodied carbon.

2.2.1. Recycled aggregate in concrete

Many recycled materials can be used as aggregate in concrete, either replacing natural sand (fine aggregate) or gravel/crushed stone (coarse aggregate). The choice depends on the desired strength, durability, cost, and environmental goals. The application of recycled aggregate from demolished concrete structures represents an important principle of the circular economy [3], [19], [20]. The use of recycled aggregate reduces the exploitation of natural resources, the amount of construction waste, and the energy required for the production of new materials. The process of converting demolished material into aggregate has different stages: crushing, screening, and sorting to remove contaminants such as reinforcement bars, plastic, and glass. Then passes through a primary crusher in a jaw crusher, which can handle residual reinforcement bars and large pieces of concrete. Then, iron scraps are removed using a magnetic separator, and the remaining material passes through sieves. Thus, particles larger than 20 mm were crushed again in a secondary crusher, such as an impact or rotary crusher. Secondary crushing can be repeated if necessary Fig 2, [21].

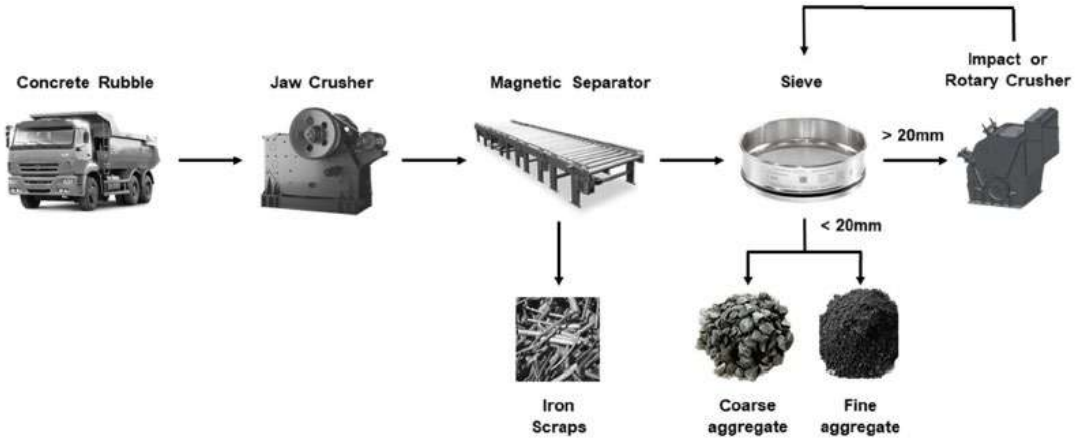


Figure 2 *– Ordinary recycling process [21]*

Properly designed concrete with recycled aggregate can, besides recycled aggregate from demolished concrete structures as widely used, include uses of crushed bricks and masonry waste and ceramic tile waste, satisfactorily achieve mechanical characteristics, durability and resistance to freezing and thawing [22], [23]. Also crushed recycled glass, copper slag, steel slag, foundry sand cab be used as recycled fine aggregate in concrete, but with moderate impact on embodied carbon reduction, and plastic aggregate and rubber from tires, but with low-moderate impact [24], [26].

2.2.2. Recycled steel for reinforcement in reinforced concrete structures

Production of reinforcement bars from recycled steel significantly reduces embodied carbon emissions compared to primary steel production. Steel produced in electric arc furnaces using renewable energy sources has a much lower carbon footprint. European sustainable construction strategies favor increasing the share of recycled steel in the construction industry through circular economy principles [3], [4], [7]. Steel recycling is a widely used technology in the decarbonization process of steel production. Steel can be continuously recycled without any damage to its properties, regardless of the product or form it takes. Steel recycling includes melting steel products at the end of their lifecycle to make new steel. Scrap is a term used to describe steel that has reached the end of its life, and is a valuable raw material used in every steelmaking process. Due to its inherent magnetism, steel is very easy to separate and recycle after demolition, making steel the most recycled material in the world. Melting steel scrap at the end of its life allows the creation of new steels, adjusting the chemistry and shape of the new product. Almost every steel plant uses scrap as part of its raw materials mix, and therefore almost every steel plant is also a recycling plant. Long-term sustainability and recycling in the steelmaking sector primarily depend on scrap quality. The ideal scrap for steelmaking is called black. This scrap is undesirable to contain metallic and organic coverings/coatings, attachments, and tramp elements. The Electric Arc Furnace, Fig.3, is an modern method of steel production by remelting steel scrap into new steel and is called scrap-based steel production. Steel scrap is a secondary-sourced material, i.e., discarded steel that becomes available from manufacturing waste generation and from recovered steel in buildings, infrastructure, equipment, etc. [26].

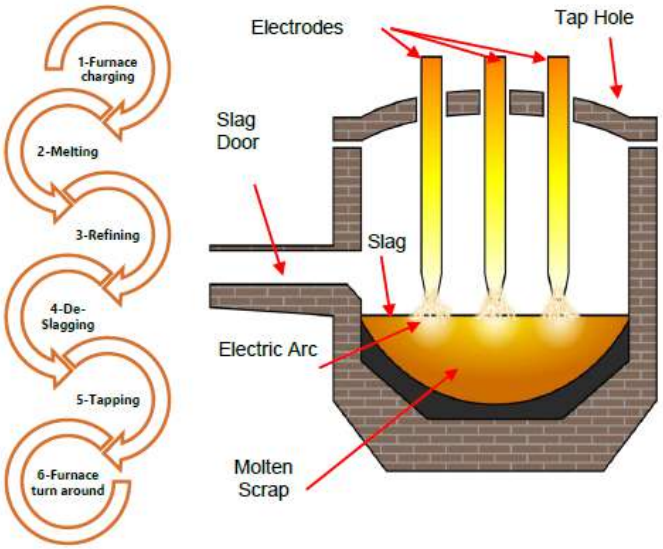


Figure 3 *– The Electric Arc Furnace process: steps and inside view, [26].*

Sustainable steel is made from recycled materials, which significantly reduces the amount of energy required to produce new steel. Steel can be recycled multiple times without losing its properties, making it one of the most sustainable materials in the construction

industry. Sustainable steel is produced using innovative methods that prioritize energy efficiency, the use of recyclable materials, and lower carbon emissions, which is very important for environmental impact. Sustainable steel bars and reinforcing mesh play a vital role in reinforcing concrete structures. They are used to provide tensile strength and improve the load-bearing capacity of concrete, thereby preventing cracking and enhancing its durability. Reinforcing mesh is often made from high-quality steel, making it essential for creating strong, long-lasting buildings, roads, bridges, and other infrastructure [27].

2.3. Innovative concrete

Innovative concrete refers to advanced concrete materials and technologies developed to improve the performance, durability, sustainability, and functionality of traditional concrete. Researchers and engineers continuously search for innovative solutions to fulfill challenges such as high carbon emissions, resource consumption, durability issues, and increasing infrastructure demands, as concrete is the most widely used construction material in the world.

2.3.1. Geopolymer concrete

Geopolymer concrete represents one of the most significant innovations in the field of low-carbon building materials. Unlike classic Portland cement, geopolymer concrete uses fly ash, slag and alkaline activators, as basic binders. The geopolymerization mechanism is shown in Fig.4, [28]. The advantages of geopolymer concrete include very low CO_2 emissions, high chemical resistance, good durability, lower drying shrinkage, better fire resistance than concrete with Portland cement and reduced consumption of natural resources. Research shows that geopolymer concrete can reduce embodied carbon emissions by up to 80% compared to conventional reinforced concrete [11]. However, wider application of geopolymer concrete is still limited due to lack of standardization, limited availability of materials and problems with long-term design guidelines [7].

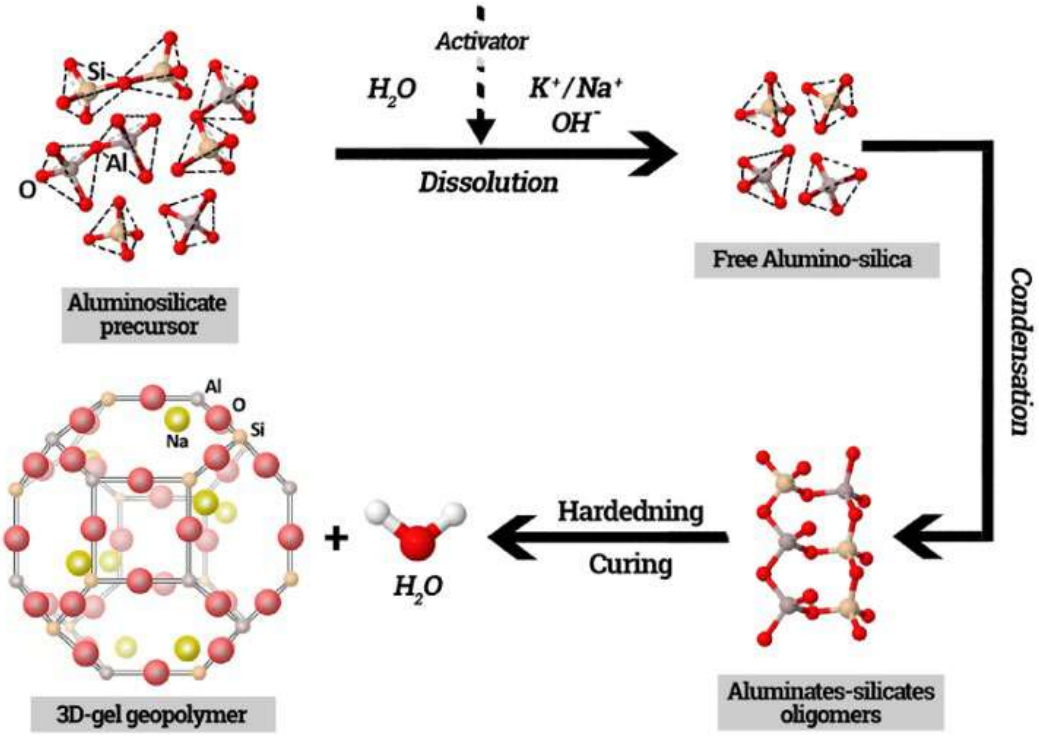


Figure 4 *– General geopolymerization mechanism [28]*

2.3.2. Ultra High Performance and Fiber Concrete

Ultra high performance and fiber concrete, with very high strength and durability, although it contains a higher amount of cement per unit volume, the total embodied carbon of the structure may be lower due to reducing the dimensions of structural elements, a smaller total amount of material, and an extended lifetime of the structure. Because of very high mechanical characteristics, it can be designed with thinner plates, smaller cross-sections of columns, and lighter structural systems. In this way, the total amount of concrete and reinforcement used is reduced, which contributes to reducing the overall carbon footprint of the structure. While ultra high performance concrete exhibits enhanced tensile properties, but it does not reach 1% until the peak load is approached. These characteristics highlight the material's enhanced performance in terms of durability and strength compared to conventional concrete, and its maximum tensile strain capacity is achieved under specific loading conditions [29]. Various fibers have been incorporated into cementitious composites to enhance their performance. These range from synthetic fibers, such as polypropylene and polyester, to natural and steel fibers, each offering distinct advantages and limitations when included in concrete. Fiber orientation plays a pivotal role in dictating the mechanical properties of concrete, such as toughness and tensile strength, which directly correlate to the material's durability. An optimal fiber content is up to 3% by volume. Synthetic fibers are known for their resistance to chemical and biological degradation and can enhance the composite's toughness and ductility. But, they typically have a lower modulus of elasticity compared to steel fibers, which can result in a less significant impact on crack prevention and load-bearing capacity. Environmentally friendly and renewable natural fibers, often face issues with durability and potential degradation within the alkaline cement matrix, which can affect the long-term performance of the composite. The application in the construction sector and comparison with other types of concrete can be seen in Fig.5, [29].

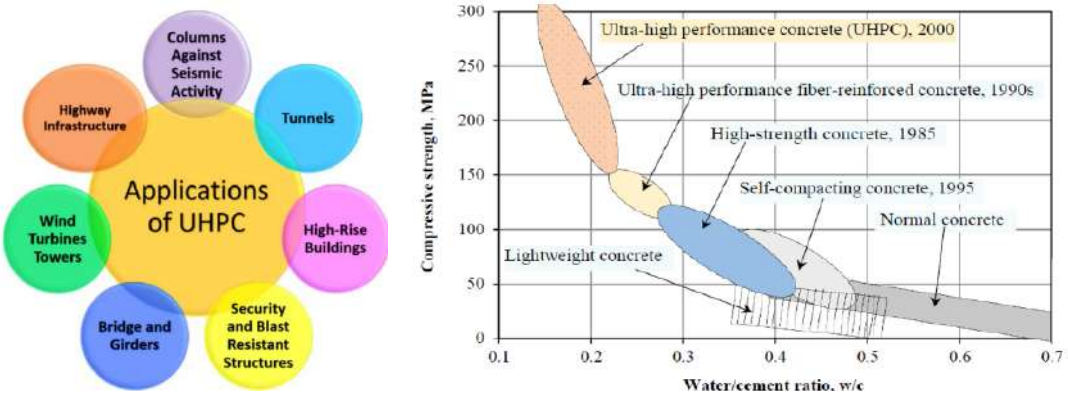


Figure 5 *– Ultra high performance concrete: application in the construction sector and comparison with other types of concrete [29]*

Fiber Reinforced Concrete represents an important direction in the development of sustainable building materials. These concretes are used with steel fibers Fig.6, [30], basalt fibers, glass fibers and synthetic fibers. The application of fibers allows reducing the amount of classical reinforcement, better crack control and increasing the durability of the structure [31]. In addition, the increased durability of the structure contributes to the reduction of carbon emissions during the life cycle of the building.



Figure 6 *– Materials: Hooked steel fibers and Micro steel fibers [30]*

2.3.3. Carbon Cured Concrete

One of the innovations in the field of sustainable building materials is the application of CO_2 during the concrete curing process. During this process, carbon dioxide is bound in the cement matrix through the process of carbonation. This technology enables the reduction of net CO_2 emissions, permanent storage of carbon in concrete and the increase in the early strength of concrete. Such systems have great potential for the future decarbonization of reinforced concrete structures and it is seen as a technique that directly supports the concepts of a circular economy [32]. The early age strength of carbon-cured concretes can be markedly superior to that of concretes generated by traditional curing processes. This presents the possibility of reduced construction project delivery times and provides decreased material requirements. Carbonation curing of concrete means that the concrete is cured in a high-pressure atmosphere of pure CO2, and the unhydrated cement minerals react with CO2 to solidify it in concrete in the form of carbonate. Hence, the hardening process of concrete is accelerated and its mechanical and durability properties are improved. For severe environmental conditions carbon curing can enhance the mechanical properties, durability, microstructure of concrete, and the long-term performance attributes of concrete, including impermeability, freeze-thaw resistance, and chemical resistance. The duration of carbon curing directly influences the mechanical characteristics and microstructural development of concrete. Extended curing durations enable concrete to sequester increased amounts of CO_2 for carbonation processes, leading to enhanced compressive strength and durability [33], [34]. The carbon dioxide injection system can be directly added to the mixer with a retrofitting operation, and all the components of the mix are simultaneously amalgamated to form the carbonated concrete, Fig 7 [35].

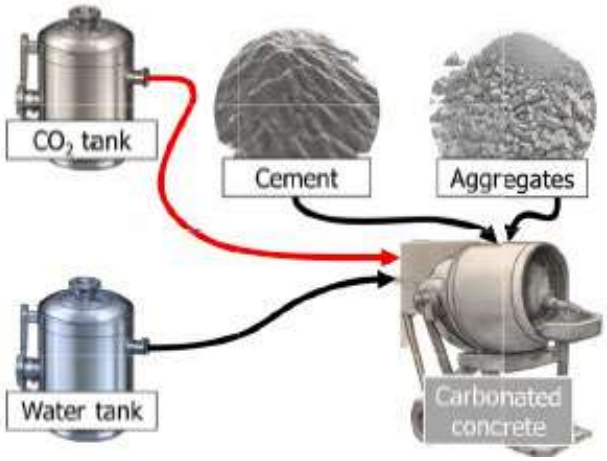


Figure 7 *– Carbonated concrete: direct injection of CO_2 during mixing proces [35]*

3. Conclusion

The construction sector is one of the largest sources of greenhouse gas emissions. Special attention is focused on the so-called embodied carbon - carbon dioxide emissions associated with the production of building materials, transportation, construction, maintenance and end of life cycle of the building. Embodied carbon represents one of the most important challenges of contemporary design of reinforced concrete structures. Most of the emissions come from the production of cement and reinforcement, and there is a need for the reduction of the clinker content, optimizing construction, using recycled materials, increasing the durability of buildings, using LCA methodology, and EPD declarations.

In reinforced concrete structures, besides reducing the amount of cement, modern strategies for the decarbonization of reinforced concrete structures are also focused on the development of alternative cement binders, increasing the use of recycled steel, and the development of innovative concrete such as geopolymer concrete, ultra high performance and fiber concrete and carbon-cured concrete. Modern regulations set embodied carbon as one of the key criteria of sustainable construction, and the limitation of CO_2 emissions is becoming a standard part of the design of reinforced concrete structures. The construction sector will therefore increasingly switch to low-carbon reinforced concrete structures and optimized design approaches. Civil engineering and reinforced concrete structures are essential components of modern urban development, providing the infrastructure necessary for economic growth and social well-being. The adoption of sustainable construction practices and innovative engineering solutions is essential to reduce these impacts and support the development of resilient and environmentally sustainable cities.

Acknowledgement

This research has been supported by the Ministry of Science, Technological Development and Innovation (Contract No. 451-03-34/2026-03/200156) and the Faculty of Technical Sciences, University of Novi Sad through project “Scientific and Artistic Research Work of Researchers in Teaching and Associate Positions at the Faculty of Technical Sciences, University of Novi Sad 2026” (No. 01-3609/1).

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Structural Framework of the Circular Economy: Sustainability, Implementation Challenges, and Regional Perspectives

[Zdenka Perović][1]

Abstract

The circular economy (CE) has emerged as a strategic framework for sustainable development, offering an alternative to the traditional linear economic model based on the "take–make–dispose" principle. This paper examines the structural foundations of the circular economy, highlighting its core principles of waste prevention, resource efficiency, product life extension, and ecosystem regeneration. By promoting closed-loop systems through reuse, repair, remanufacturing, and recycling, the circular economy seeks to decouple economic growth from the consumption of finite natural resources and reduce environmental degradation.

The study analyzes the relationship between the circular economy and sustainable development, emphasizing its contribution to achieving global sustainability objectives and climate targets. Particular attention is given to quantitative indicators of circularity, including the Material Circularity Indicator (MCI), Circular Material Use Rate (CMUR), and material productivity metrics. Furthermore, the paper explores the technological drivers of circular transformation, such as artificial intelligence, the Internet of Things (IoT), blockchain technology, advanced recycling processes, and additive manufacturing, which enable more efficient resource management and transparency across supply chains.

In addition to theoretical and technological perspectives, the paper presents sectoral case studies from the automotive, textile, and construction industries, demonstrating practical applications of circular business models. The analysis also focuses on the Western Balkan region, identifying legislative progress, implementation barriers, and emerging opportunities for industrial symbiosis and resource recovery. The findings suggest that while significant economic, infrastructural, and institutional challenges remain, the circular economy represents a viable pathway toward long-term environmental sustainability, economic resilience, and inclusive regional development.

Keywords

Circular Economy, Sustainable Development, Resource Efficiency, Material Circularity Indicator (MCI), Circular Material Use Rate (CMUR), Industry 4.0, Recycling, Remanufacturing, Industrial Symbiosis, Western Balkans, Environmental Sustainability, Green Transition.

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1. Introduction

In the 21st century, the circular economy (CE) has become a key strategy for sustainable development, replacing the traditional linear "take-make-dispose" model that caused resource depletion, biodiversity loss, and waste accumulation. CE offers an alternative macroeconomic framework based on closed-loop systems. Through recycling, reuse, repair, and remanufacturing, this model eliminates waste and decouples economic growth from finite resource consumption, leading governments and corporations to increasingly integrate it into their policies and supply chains.

The objective of this paper is to critically evaluate the implementation of circular economy frameworks, with a specific focus on high-impact sectors and developing regions. To achieve this, the study addresses three specific objectives: to analyze economic and ecological benefits through key industrial sectors, to identify systemic structural and technological implementation challenges, and to assess the regulatory frameworks and pathways required to support transitioning economies like the Western Balkans.

1.1. Development of the Circular Economy Concept

The concept of a circular economy (CE) is not a sudden revelation but rather an evolution of ideas grappling with the fundamental unsustainability of industrial systems. It emerges from a confluence of ecological economics, industrial ecology, design philosophy, and practical necessity [6].

While early conceptualizations of closed-loop systems date back to Kenneth Boulding's 1966 "Spaceship Earth" thesis [1], the formal introduction of the circular economic model into academic literature is widely attributed to environmental economists David Pearce and R. Kerry Turner in 1989 [8]. They demonstrated how traditional linear economics ignored the physical laws of thermodynamics, specifically regarding how waste returns to the ecosystem as a pollutant [8].

On a policy level, the concept gained massive institutional momentum over the last decade. A major milestone occurred in 2015 when the European Commission launched its first Circular Economy Action Plan [2], which was later updated under the European Green Deal in 2020 [3]. These legislative frameworks shifted the debate from purely ecological activism to a binding economic and regulatory agenda for industrial transition.

According to institutional frameworks established by organizations like the Ellen MacArthur Foundation, the macro-objectives of this transition can be synthesized into five key pillars [5]:

- The absolute minimization of systemic waste generation;
- The optimization and preservation of natural capital through efficient resource management;
- The extension of product lifecycles through structural durability and modular design;
- The integration of high-value cascading recycling loops;
- The reduction of corporate scope 1, 2, and 3 greenhouse gas (GHG) emissions.

1.1.1. Principles of Circular Economy

The operational architecture of the circular economy relies on three fundamental principles established by contemporary ecological engineering [5]:

- **Design Out Waste and Pollution** [2,5]**:** Up to 80% of a product's environmental impact is determined during the initial design phase. Therefore, products must be systematically engineered for disassembly, utilizing non-toxic, easily separable technical and biological nutrients.
- **Keep Products and Materials in Use** [2,5]**:** This principle focuses on maintaining value at the highest possible utility level. It prioritizes inner loops such as sharing platforms, predictive maintenance, remanufacturing, and refurbishment over high energy recycling loops.
- **Regenerate Natural Systems** [2,5]**:** Moving beyond mere "sustainability" (doing less harm), circularity actively enhances ecosystems. This involves transitioning to 100% renewable energy inputs, returning organic materials back to the soil via safe composting, and supporting regenerative agro-ecological practices.

Table 1 *– Structural Comparison between Linear and Circular Economy Models*

Evaluation Criteria	Linear Economic Model	Circular Economic Model	Macro-Ecological Impact
Resource Dynamics	Intensive extraction of virgin raw materials	Regenerative and closed-loop resource management	Drastic reduction in natural resource depletion
Product Design Philosophy	Built-in obsolescence; focus on short lifecycles	Eco-design; modularity, durability, and easy disassembly	Minimal end-of-life waste generation
Value Chain Approach	"Take→make→dispose" transactional model	Value retention via Reuse, Repair, and Remanufacturing	Conservation of embedded energy and labor value
Energy & Carbon Footprint	High energy consumption for primary processing; heavy reliance on fossil fuels	Utilization of embedded energy via material retention; powered by renewable inputs	Significant reduction of structural Scope 1, 2, and 3 GHG emissions

Source: Author's own elaboration based on Ellen MacArthur Foundation frameworks.

2. Circular Economy and Sustainable Development

The paradigm of sustainable development is traditionally anchored in the definition provided by the United Nations World Commission on Environment and Development (WCED) in its seminal 1987 Brundtland Report, *Our Common Future* [11]. The report defines it as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs"[11].

While sustainable development provides the overarching macro-philosophical vision, the circular economy serves as its practical, operational vehicle [2,3]. By balancing the triple bottom line economic growth, environmental protection, and social equity the circular model offers a concrete methodology to operationalize the United Nations Sustainable

Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) [2,3].

2.1. Quantitative Metrics of Circularity: Micro and Macro Level

To transform circular economy principles from qualitative concepts into verifiable corporate and national strategies, robust economic and mathematical indicators must be deployed [4,5]. These metrics allow organizations and governments to monitor material flows, benchmark performance, and evaluate thermodynamic efficiency.

At the micro (corporate and product) level, the premier standard is the Material Circularity Indicator (MCI), developed by the Ellen MacArthur Foundation and Granta Design [5]. The MCI quantifies the extent to which a product's material flows are restorative. The mathematical formulation constructs a linear flow index (LFI) by assessing the amount of virgin feedstock (V) and the amount of unrecoverable waste (W) generated during manufacturing and end-of-life disposal.

The basic linear flow index is expressed as:

$$LFI = \frac{V + W}{2M + (W_F - W_C)}$$

Where M represents the total mass of the product, W_F is the waste generated in the recycling process to produce recycled content for the product, and W_C is the waste generated in the recycling process at the product's end-of-life.

The final Material Circularity Indicator (MCI) adjusts the LFI by a utility factor $F(X)$, which accounts for the product's lifetime and intensity of use relative to the industry average:

$$MCI = 1 - LFI \times F(X)$$

The value of MCI ranges strictly from 0 (purely linear system) to 1 (fully circular, closed-loop system with 100% recycled content and absolute recovery).

At the macro (national and global) level, two primary thermodynamic and economic indicators are monitored by institutional frameworks like Eurostat [3]:

- **Circular Material Use Rate (CMUR):** This indicator measures the share of secondary raw materials in the overall material consumption of an economy. It is calculated as the ratio of circular material use (U) to the overall material use (M), where overall material use is the sum of Domestic Material Consumption (DMC) and the circular material use:

$$CMUR = \frac{U}{DMC + U} \times 100\% [3] $$

- **Socio-Ecological Material Efficiency:** This tracks the coupling between Gross Domestic Product (GDP) and Direct Material Input (DMI). An economy achieves absolute decoupling when GDP exhibits positive growth while DMI continuously decreases:

$$\text{Material Productivity} = \frac{GDP}{DMI} \quad (\text{EUR / kg})[3] $$

3. Systemic and Technological Challenges

Despite the clear benefits of the circular economy, the systemic transition faces profound structural, economic, and institutional barriers [4]. This resistance is largely driven by the "linear lock-in" effect, where existing industrial infrastructures, supply chains, and regulatory systems have been optimized exclusively for linear throughput for over a century [4], making alternative models financially and operationally disruptive.

The primary macroeconomic obstacle is the high initial Capital Expenditure (CAPEX) required to build modern circular infrastructure [4]. Transitioning to zero-waste manufacturing requires substantial investments in advanced chemical and mechanical recycling facilities, reverse logistics networks, and product-redesign R&D. For many small and medium sized enterprises (SMEs), these upfront costs are prohibitively high, especially when traditional financial institutions lack standardized metrics to evaluate the risk and long-term return on investment (ROI) of circular business models.

3.1. Technological Enablers and Fourth Industrial Revolution (Industry 4.0)

The operationalization of a scalable circular economy is deeply dependent on the technologies of the Fourth Industrial Revolution (Industry 4.0) [4]. Without advanced digital and industrial technologies, tracking materials through complex global supply chains and maintaining their purity during recycling loops is technically impossible.

The technological bottlenecks can be systematically addressed through the integration of five key digital enablers [4]:

- **Artificial Intelligence and Machine Learning** [4]**:** Deployed in automated waste sorting facilities to identify, categorize, and separate complex polymer blends and composite materials with a speed and precision unattainable by human labor.
- **Internet of Things (IoT) and Cyber-Physical Systems** [4]**:** Utilizing smart sensors to monitor product health, predict maintenance cycles, and track assets in real time, which is foundational for Product-as-a-Service (PaaS) models.
- **Blockchain Technology and Digital Product Passports (DPP)** [3,4]**:** Providing immutable, decentralized ledgers that record the exact material composition, hazardous substance content, and recycling history of a product across its entire value chain, ensuring transparency.
- **Advanced Chemical Recycling** [4]**:** Moving beyond traditional mechanical shredding which downgrades material quality toward molecular depolymerization, allowing plastics to be recycled infinitely without loss of structural integrity.
- **Smart Additive Manufacturing (3D Printing)** [4]**:** Enabling localized, on demand production of replacement parts, thereby reducing transport emissions and eliminating massive warehouse inventories of obsolete components.

4. Expanded Sectoral Case Studies and Industrial Practices

To understand how these mathematical metrics and digital enablers manifest in the global marketplace, it is essential to look beyond standard administrative practices and examine critical industrial sectors that carry the heaviest ecological footprints.

4.1. The Automotive Industry: Circular Supply Chains and Remanufacturing

The automotive sector is highly resource intensive, consuming substantial percentages of global steel, aluminum, plastics, and critical raw materials like lithium and cobalt [7]. The transition to electric vehicles (EVs) introduces a double dged sword: it eliminates tailpipe emissions but drastically escalates the demand for rare earth minerals [7], rendering linear end-of-life vehicle (ELV) management obsolete.

A prime corporate operationalization of circularity is found in the **Renault Re-Factory** in Flins, France which represents a leading example of circularity in the automotive industry [3]. Renault has transformed a traditional vehicle assembly plant into Europe's first dedicated circular economy factory for mobility. The facility operates on four structured pillars:

- **Re-Trofit:** Extending vehicle operational lifecycles by converting commercial internal combustion engine (ICE) vehicles into 100% electric drivetrains.
- **Re-Energy:** Optimizing the use phase of EV batteries. When a battery's capacity drops below 70-80%, it is no longer suitable for vehicular propulsion, but retains high utility for stationary energy storage (e.g., storing solar energy for smart grids).
- **Re-Cycle:** Implementing closed loop recycling loops for technical nutrients. Demolished automotive parts are dismantled, cataloged, and raw components like aluminum and copper are funneled directly back into the casting of new components.

Through this architecture, the value of the embedded engineering labor is preserved, and the production of a remanufactured engine requires 80% less energy and nearly 90% less water than casting a new unit from virgin materials [3,7]."

4.2. 4.2 The Textile and Fashion Sector: Shifting from Fast to Circular

The modern textile industry operates on an aggressive linear trajectory characterized by fast-fashion business models [6] that rely on cheap polyester fibers derived from fossil fuels. This sector generates over 92 million tons of waste annually [4], with less than 1% of clothing globally being recycled [4] back into new apparel.

To combat this, the circular transition requires a fundamental structural redesign of textile chemistry and ownership models. An empirical benchmark is set by companies like MUD Jeans, a Dutch enterprise that pioneered the "Lease A Jeans" model [5].

***Table 2** – Operational Framework of Circular Fashion vs. Linear Fashion*

Operational Parameter	Linear Fast-Fashion	Circular Textile Framework (e.g., MUD Jeans)
Material Sourcing	Virgin polyester (petrochemicals) & intensive cotton	100% organic cotton blended with post-consumer recycled denim
Ownership Model	Transactional sale; customer assumes disposal	Product-as-a-Service (PaaS); lease model where brand retains ownership
End-of-Life Processing	Landfill incineration or downcycling into industrial rags	Mechanical shredding and spinning into high-value new yarn

By retaining ownership of the raw material, the manufacturer treats the product as a future resource asset. When the consumer returns the worn jeans, the fibers are mechanically unraveled and spun into new denim blends, completely bypassing the landfill matrix.

4.3. The Built Environment and Construction Sector

The construction industry is globally responsible for approximately 40% of solid waste streams and nearly one-third of total greenhouse gas emissions [3,10]. The circular transformation of this sector relies on the concept of Buildings as Material Banks (BAMB) [3,10].

Under this framework, buildings are no longer designed as static, monolithic concrete structures, but as dynamic, modular repositories of raw materials. Utilizing Building Information Modeling (BIM**)** software, every component of a building can be cataloged and reused at the end of its lifecycle [3]. When a building reaches its end-of-life phase, it is not imploded; it is systematically disassembled, and the structural steel beams, concrete aggregates, and timber frameworks are mapped for direct reuse in new local infrastructure projects.

5. Regional Analysis: Circular Economy in the Western Balkan Countries

The transition dynamics toward a circular economy vary significantly outside the highly industrialized core of the European Union [9]. In the Western Balkan region encompassing countries such as Serbia, Bosnia and Herzegovina, Montenegro, North Macedonia, Albania, and Kosovo the adoption of circular paradigms is constrained by historical, financial, and institutional factors, yet it presents a vital pathway for European integration.

5.1. Legislative Frameworks and EU Alignment

The main driver for circular economic reform in the Western Balkans is the accession process to the European Union, specifically the alignment with Chapter 27 (Environment and Climate Change) and the endorsement of the Green Agenda for the Western Balkans, signed at the Sofia Summit in 2020 [9]. This regional framework aligns with the European Green Deal and legally commits Western Balkan nations to the EU's climate neutrality targets for 2050 [3,9].

- **Serbia:** Launched its *Roadmap for Circular Economy in Serbia* and updated its national Waste Management Strategy [9]. However, its infrastructure remains largely linear, with the circular material use rate (CMUR) hovering significantly below the EU average of approximately 11.5% [3].
- **Montenegro:** Formally declared as an ecological state by its constitution, Montenegro adopted a national *Circular Economy Strategy until 2030* [9]. The primary challenge lies in translating this high-level policy into municipal level infrastructure, particularly across the tourism and waste management sectors.
- **Bosnia and Herzegovina:** Operates on a highly decentralized administrative structure, which complicates unified environmental enforcement. Circular initiatives are largely supported by international development programs and donor-funded projects [9] rather than state-led market-making mechanisms.

5.2. Structural Barriers Specific to the Western Balkans

The region faces a unique set of structural bottlenecks that prevent circular models from achieving economic scale:

- **Underdeveloped Waste Separation Infrastructure** [9]**:** The baseline infrastructure for primary waste separation at the household level is deficient. Most municipal solid waste is co-mingled and disposed of in non sanitary landfills or illegal dumpsites, which contaminates potential secondary raw materials and renders mechanical recycling economically non-viable.
- **Artificially Low Landfill Tariffs** [9]**:** The economic cost of dumping waste in landfills across the Western Balkans is extremely low compared to the European Union, where high landfill taxes act as an economic disincentive. As long as landfilling remains cheap, private enterprises have no financial pressure to invest in reverse logistics or eco-design.
- **The SME Linear Lock-In:** Small and medium sized enterprises (SMEs) constitute over 95% of the regional economy [9]. These businesses face severe liquidity constraints and high borrowing costs, making the upfront capital expenditures (CAPEX) required for circular technology transition prohibitively high [4,9].

6. Conclusion

The circular economy represents a profound paradigm shift and a viable, structurally sound alternative to the ecologically destructive " take→make→dispose" linear economic model [2,3,8]. By systematically redesigning industrial systems to prioritize resource efficiency, material value retention through quantitative metrics like the Material Circularity Indicator, and natural ecosystem regeneration, this economic framework offers a definitive blueprint for achieving long-term macroeconomic stability and environmental resilience [5].

As demonstrated throughout this analysis, the successful transition to a fully functional circular economy provides deep environmental, economic, and social dividends. The expansion of these systems into critical sectors with a high environmental impact proves that financial profit and environmental recovery are not mutually exclusive. However, this transformation cannot be realized through isolated microeconomic efforts. It demands a highly coordinated, systemic approach characterized by intensive technological innovation, aggressive government regulatory support, and targeted assistance for developing regions like the Western Balkans to overcome infrastructure and capital lock ins [3,4,9]. As global environmental challenges, resource vulnerabilities, and climate impacts continue to intensify, the circular economy will become increasingly important for achieving sustainable, resilient, and inclusive global prosperity.

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The Circular Economy–SDGs Nexus: Pathways to Sustainable Development in the Western Balkans

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Abstract

This paper examines the importance of introducing circular economy courses into higher education and lifelong learning programmes in response to the growing emphasis on sustainable development and the green transition. As global economic and social conditions continue to evolve, there is an increasing need to raise awareness of practices that support sustainable growth and responsible resource management. Education plays a crucial role in this process by equipping students and professionals with the knowledge and competences required for emerging green-sector jobs and for supporting the twin green and digital transition.

The circular economy represents one of the key building blocks of the European Green Deal and has the potential to contribute to the achievement of the United Nations Sustainable Development Goals (SDGs), particularly those related to responsible consumption and production, climate action, sustainable cities and communities, quality education, and decent work and economic growth. The study employs desk research and descriptive analysis, combining a qualitative mapping of the potential contribution of the circular economy across the SDGs with secondary data from the Balkan Barometer 2025 to assess awareness of circular economy principles in the Western Balkans.

By promoting resource efficiency, waste reduction, recycling, reuse, and sustainable production and consumption patterns, the circular economy has significant potential to transform current economic systems. However, this potential remains insufficiently recognized in many countries, particularly within educational frameworks. The aim of this paper is therefore to emphasize the importance of the circular economy through the analysis of its contribution to the achievement of sustainable development goals and to highlight the urgency of integrating circular economy courses into higher education curricula and lifelong learning programmes. The paper argues that strengthening education in this field is essential for developing a more resilient, environmentally responsible, and sustainable Western Balkan society.

Keywords

Circular economy, Sustainable Development Goals (SDGs), twin transition, lifelong learning, green skills, Western Balkans, European Green Deal, sustainability education

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1. Introduction

The transition towards sustainable development requires a fundamental shift from the traditional linear economic model of extraction, production, consumption, and disposal towards more resource-efficient and regenerative systems. The circular economy (CE) has emerged as one of the central building blocks for addressing resource scarcity, climate change, biodiversity loss, and waste generation by extending product life cycles, promoting reuse and recycling, and improving resource efficiency. The CE and the SDGs are closely interrelated, and a holistic understanding of these linkages is essential for aligning environmental objectives with broader socio-economic progress. CE practices support climate action, sustainable cities, biodiversity conservation, decent work, innovation, and resource security, creating synergies across multiple SDGs [1].

Higher education institutions and lifelong learning programmes therefore play a strategic role in enabling the circular transition. Universities contribute by developing the technical, managerial, and interdisciplinary competences required for circular business models, sustainable production systems, and green innovation, while lifelong learning supports the reskilling and upskilling of the existing workforce. Progress towards quality education (SDG 4) thus represents an important enabling condition for achieving broader environmental, economic, and social sustainability objectives. This challenge is particularly relevant for the Western Balkans, where the green transition is advancing within the framework of the Green Agenda for the Western Balkans, yet awareness of CE principles and their integration into higher education remain limited. Against this background, this paper examines the relationship between the CE and the SDGs with particular emphasis on the role of higher education and lifelong learning in supporting the green transition in the Western Balkans. It argues that strengthening CE education is essential for developing the knowledge, skills, and institutional capacity required to accelerate the region's sustainable development. This paper employs desk research and descriptive analysis based on academic literature, policy documents, and secondary data from the Balkan Barometer 2025. The mapping of the CE to the SDGs was conducted through a qualitative analysis of the contribution of CE principles to individual SDGs, which were subsequently organised into four analytical dimensions: environmental, social, economic, and governance.

2. Sustainable Development Dimensions and the Role of the Circular Economy

Although the SDGs are inherently interconnected, they can be analysed through four dimensions, as illustrated in Figure 1.

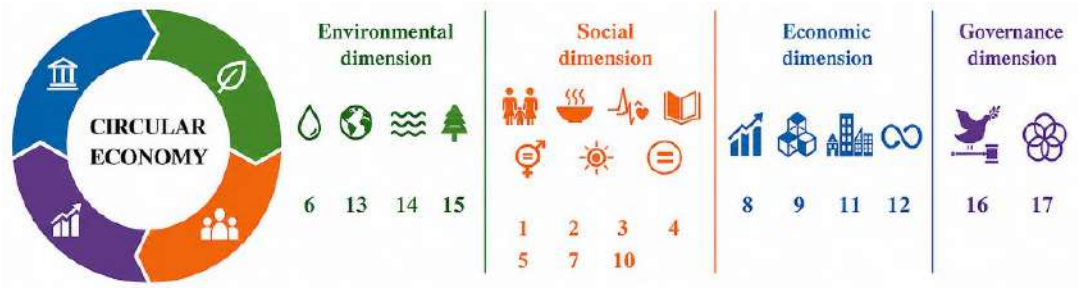


Figure 1 *– The circular economy as a cross-cutting contributor to the SDGs*

The adapted "wedding cake" model [2] extends the traditional environmental, social, and economic layers by introducing governance as an enabling dimension comprising SDGs

related to institutions, justice, and partnerships. This framework provides the basis for analysing the contribution of the circular economy to sustainable development.

2.1. Environmental Foundations of Sustainable Development

The importance of water is reflected in SDG 6 ("clean water and sanitation" for all). Water is at the epicentre of socio-economic development and ultimately underpins the success or failure of each and every SDG. Sustainable use of water can only be achieved through circular approaches. Transition to a CE can avoid water misuse, valorise water as a resource, and promote water reuse as an alternative water supply, on par with the use of freshwater resources [3]. In terms of "climate action" (SDG 13), the contribution of the CE is among the most clearly quantified. A significant share of global greenhouse gas (GHG) emissions is associated with the production and use of materials and food, and estimates suggest that circular interventions could reduce global GHG emissions by 39% and virgin resource use by 28% [4,5].

The CE also has a role to play for "life below water" (SDG 14), especially in preventing marine litter. Circular approaches such as product redesign, reuse, and closed-loop recycling address marine pollution at its source by reducing the generation of waste and limiting the use of single-use materials that may enter aquatic ecosystems [6]. The CE makes a direct contribution to "life on land" (SDG 15). The CE reduces the pressure to source virgin biomass, minerals and metals, which contribute to habitat destruction, land degradation, and biodiversity loss. By keeping materials in use, the CE reduces demand for these resources. The strength of the link between the CE and SDG 15 therefore lies in addressing the upstream driver of terrestrial ecosystem loss – the scale of primary resource use – rather than only its symptoms [7,8].

2.2. Social Well-Being Through Circular Economy

The CE has a strong, direct impact on job creation and decent employment, but its impact on gender equality, reducing inequalities and quality education depends on a workforce and a broader population equipped with green and circular skills. The contribution of the CE to "reduced inequalities" (SDG 10) is less obvious and depends on how the transition is structured. Circular models can mitigate inequality by integrating informal workers into more regulated value chains, creating jobs in locations and communities outside traditional centres of linear economic activity, and boosting access to goods at an affordable level through reuse, repair, and refurbishment. Interaction between "gender equality" (SDG 5) and the CE is also subject to similar conditionality and significant risk. The jobs linked to the green and circular transition are in sectors such as waste management, manufacturing, renewable energy and construction, which are currently male-dominated. Thus, unless there are concerted efforts to reduce occupational segregation, the transition could actually reduce rather than increase the share of women in the labour force [7,9,10].

The CE contributes to "quality education" (SDG 4) in a distinct way, by generating demand for new knowledge and competences. The transition requires skills in areas such as eco-design, material recovery, sustainable production and systems thinking, together with the broader capacity for education for sustainable development set out in SDG target 4.7 [11]. The CE also supports "affordable and clean energy" (SDG 7) by reducing energy demand through resource efficiency and by recovering critical materials for renewable technologies [4].

CE practices can significantly contribute to achieving "zero hunger" (SDG 2) by promoting more sustainable agricultural production and improving resource efficiency. It emphasizes the importance of reducing food waste, recycling nutrients, and reusing

agricultural biomass to support long-term food security. Integrating CE principles into agriculture and food systems is an important strategy for advancing SDG 2 and building more resilient food systems [12]. CE has the potential to support the goals of "no poverty" (SDG 1). Poverty is a complex social and economic phenomenon that goes beyond a lack of income and includes various forms of deprivation that affect the quality of life of individuals and households. In addition to financial hardship, it encompasses limited access to education, healthcare, adequate housing, safe drinking water, sanitation, and other essential services. CE strategies contribute to sustainable development by improving resource efficiency and reducing environmental pollution, which has a direct positive impact on public health within the framework of SDG 3 ("good health and well-being") [13,14].

2.3. Economic Prosperity in the Circular Transition

The CE can strongly support "decent work and economic growth" (SDG 8). In line with SDG target 8.4 on improving global resource efficiency, circular activities such as recycling, repair, remanufacturing, and reuse are often labour-intensive and locally based and can decouple economic activity from raw material extraction by keeping goods and materials in use. The CE enables sustainable industrial development by improving resource efficiency and reducing material waste in production systems, thereby supporting the objectives of SDG 9 ("industry, innovation and infrastructure"). The transition to CE models promotes innovation in industrial processes and infrastructure systems, contributing to more resilient and sustainable industrial sector [15].

Circularity involves rethinking and redesigning current production and consumption patterns to do more with fewer resources while transforming waste into valuable inputs for new production cycles. CE has its strongest and most direct relationship with "responsible consumption and production (SDG 12) as its core principles directly promote resource efficiency, waste prevention, sustainable production, and mindful consumption. The CE contributes to "sustainable cities and communities" (SDG 11) by promoting the design of buildings and infrastructure using renewable, secondary, and low-carbon materials, while ensuring they are adaptable, reusable, and easily deconstructed at the end of their life cycle [16,17].

2.4. Governance as a Sustainable Development Accelerator

Governance can be perceived as a fourth pillar or layer of sustainability, as delivering on the SDGs presents a governance challenge for all countries. This requires that public authorities synchronize efforts, engage in cross-sectoral collaboration, and foster partnerships with private entities and civic stakeholders to a degree previously unseen. Closing supply loops requires global cooperation between governments and the private sector. The CE contributes to "partnerships for the goals" (SDG 17) by fostering inclusive public-private collaboration across value chains to identify and remove barriers, co-develop effective policies, and strengthen capacity for systemic change. It promotes the integration of CE principles into national and international policy frameworks while enhancing coordination across government departments and aligning policies across borders [18,19]. The European Union encourages partnerships through funding programmes such as Horizon Europe and Erasmus+, which support the implementation of CE projects by fostering collaboration among higher education institutions, research organisations, SMEs, industry, public authorities, and civil society organisations. Digital Product Passports (DPPs), foreseen in the second CE Action Plan, provide a practical mechanism for strengthening partnerships, policy alignment, and data exchange that underpin CE. DPPs require collaboration among manufacturers, suppliers, recyclers, regulators, digital service providers, and consumers.

Implementation of DPPs contributes primarily to SDG 17 by fostering collaboration among public authorities, businesses, and value-chain actors. DPPs also support SDG 16 by enhancing transparency, traceability, regulatory compliance, and accountability, thereby strengthening governance and enabling more effective implementation of CE policies [8,20].

3. Circular Economy in Higher Education in the Western Balkans

Higher education institutions are identified as key actors in this transformation, since educating people is one of the most successful first steps in the transition from a linear to a circular model. As a result, education for the CE has become a specific field of education that attempts to integrate circular ideas into different disciplines and curricula [21-24]. By 2025, only 17.6% of workers from 84 countries reported possessing at least one green skill. Employment of green talent has been growing by about 8% a year, nearly twice as fast as the workforce is acquiring those skills. Higher education institutions and lifelong learning programmes are well positioned to provide green skills and sustainability competences [10] and help close the gap by educating future professionals, advancing research, and driving innovation for the CE. Since much of the workforce that will implement the CE has already completed formal education, integrating CE into higher education should be complemented by lifelong learning initiatives. This integration helps translate the potential contributions of the CE into realized benefits while strengthening the reinforcing interactions across the four goals of the framework [25-27].

The Green Agenda for the Western Balkans recognizes the CE as one of its five main pillars, and the region's commitment to carbon neutrality by 2050, with human capital and skills as key enablers [28]. The achievement of these goals depends on a skilled workforce and the adoption of circular principles, thus placing higher education and lifelong learning at the heart of the region's green transition. However, this foundation remains fragile. The Public Opinion Balkan Barometer 2025 indicates that awareness of the CE among Western Balkan populations is low, ranging from approximately 11% to 27% across the six countries, as shown in Figure 2 [28,29].

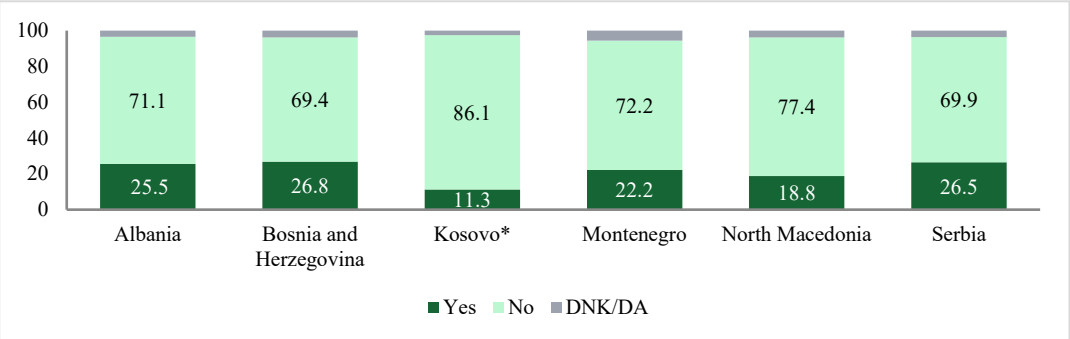


***Figure 2** – Familiarity with the circular economy and its principles by country, 2025*

As shown in Figure 3, awareness increases with educational level in a stepwise fashion from less than 6% among those with only primary education to more than 44% among those with a master's or doctoral degree. This gradient indicates that formal schooling is a very significant correlate of circular literacy. The fact that less than half of the most educated respondents report familiarity suggests that circular economy concepts are not well integrated into current curricula, even at advanced levels.

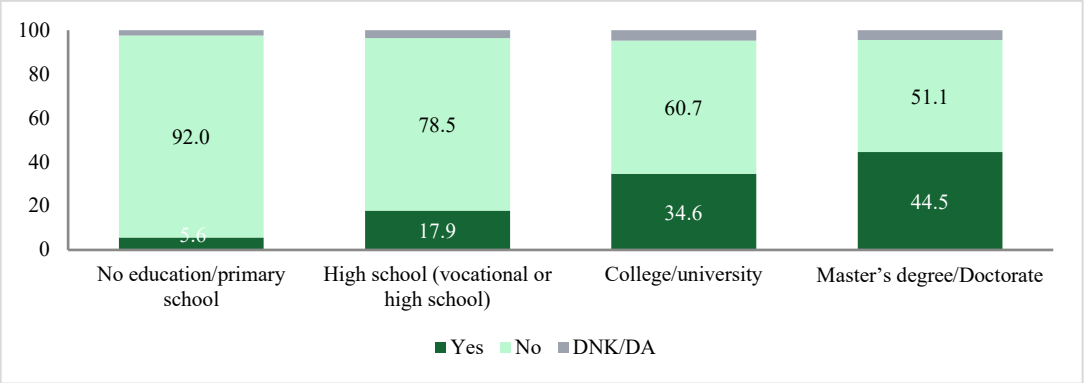


***Figure 3** – Familiarity with the circular economy and its principles by education level, 2025*

The age distribution supports the case for lifelong education. Figure 4 shows that familiarity is highest among mid-career groups and declines sharply among older people. It is consistently lower among those working in the private sector compared to those working for government and public agencies (Figure 5). Because a large part of the knowledge gap concerns people already in the workforce, curriculum improvements alone will not suffice. Reskilling and lifelong learning are key to upskilling the present workforce and strengthening their circular competences.

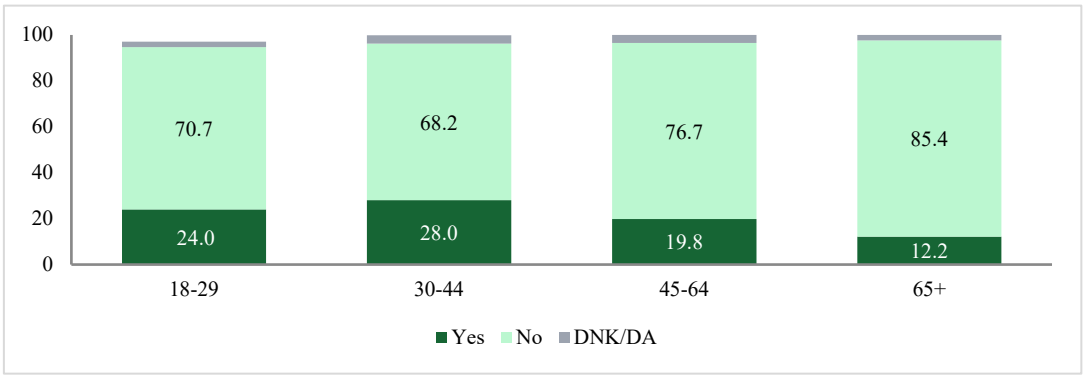


***Figure 4** – Familiarity with the circular economy and its principles by age group, 2025*

Awareness is also uneven across sectors (Figure 5) and different industries (Figure 6). Awareness is highest in information technology, education, and health services.

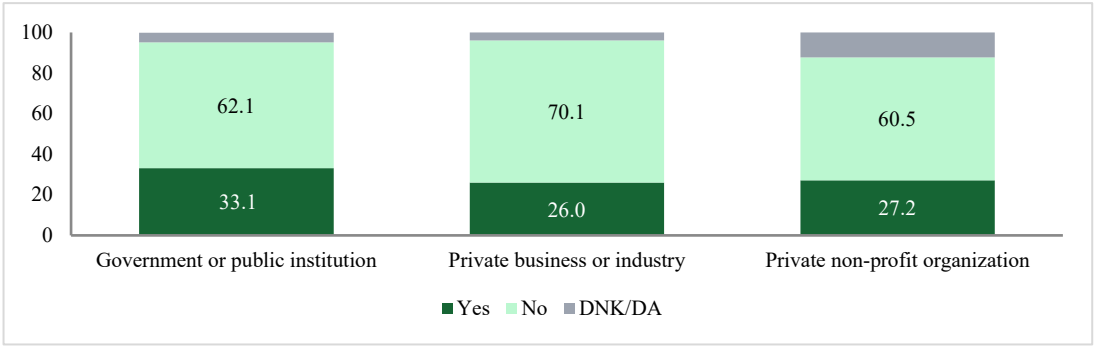


***Figure 5** – Familiarity with the circular economy and its principles by sector, 2025*

Figure 6 shows that familiarity is least common in manufacturing and agriculture, where circular processes are particularly important. According to the Balkan Barometer Survey, women report less awareness than men.

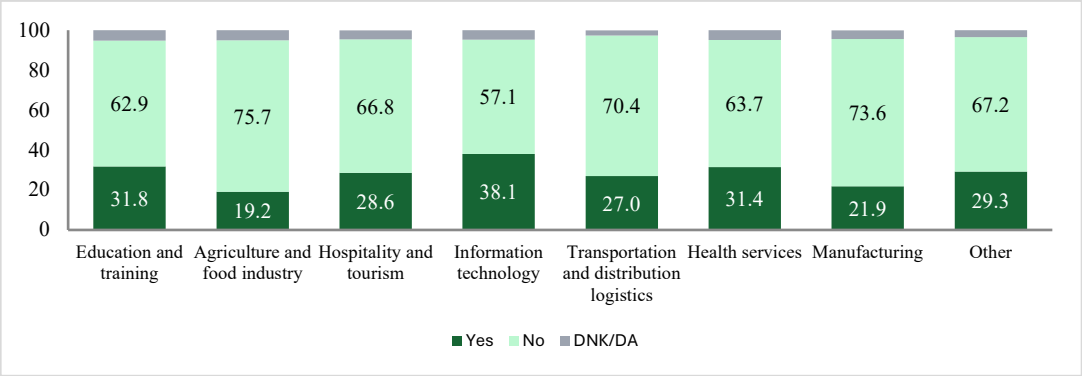


***Figure 6** – Familiarity with the circular economy and its principles by industry, 2025*

Research shows that CE is mainly taught in sustainability-related programs, while EU-funded initiatives remain poorly integrated into curricula [21].

4. Conclusion

The transition towards a CE represents one of the key prerequisites for achieving the SDGs and ensuring long-term environmental, economic, and social sustainability. As demonstrated throughout this paper, the adoption of CE principles has the potential to support progress towards the SDGs by promoting more efficient resource use, reducing waste, supporting climate action, fostering sustainable production and consumption, and creating new opportunities for innovation and green employment. However, the successful implementation of these principles depends not only on policy frameworks and technological progress but also on the availability of knowledge and skills needed to support this transition. This challenge is particularly significant in the Western Balkans, where awareness of CE concepts remains relatively low despite the region's commitment to the Green Agenda and the European Green Deal. Integrating CE into higher education curricula and lifelong learning programmes should therefore become a strategic priority for universities and policymakers. By strengthening CE education and promoting cooperation between academia, industry, and public institutions, the Western Balkans can accelerate its transition towards a more resilient, competitive, and sustainable future while contributing more effectively to the achievement of the SDGs.

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Regional Cooperation & EU Policy Alignment (EU Green Deal, Digital Education Action Plan)

Corporate governance as a catalyst for green, digital and AI-Enabled competence development

[Domagoj Hruška][1], [Ana Andabaka][2], [Elena Perić][3]

Abstract

The transition toward resilient and sustainable economies requires firms to develop new combinations of green, digital and artificial-intelligence-related competencies, yet the strategic conditions that enable such development remain insufficiently understood. This paper argues that corporate leadership and the composition of executive and supervisory boards play a decisive role in advancing these competencies, and it extends the existing debate by integrating artificial intelligence as a distinct strategic and governance challenge. Boards shape competence development through strategic priorities, investment decisions, performance metrics, organizational culture, risk oversight and stakeholder accountability. We propose that board composition matters because expertise in sustainability, digital transformation, environmental management, artificial intelligence, data governance and organizational learning shapes a firm's strategic orientation, while diversity in age, gender, professional background, international experience and technological literacy strengthens innovation, continuous learning and responsible transformation. Artificial intelligence is framed not merely as a technological tool but as a general-purpose technology that reshapes managerial work, decision-making, competence requirements and organizational design. Emphasizing a human-centered approach and complementarity rather than substitution, we contend that firms increasingly require hybrid competencies that combine sustainability literacy, digital and AI literacy, ethical judgment, data-informed decision-making, creativity, change leadership and problem formulation, alongside enduring human capabilities such as empathy, presence, judgment and hope. Boards bear responsibility for preventing automation bias, accountability diffusion and judgment atrophy, while supervisory boards ensure transparency, responsible AI governance, ESG accountability, and alignment between technology adoption and long-term value creation. The paper contributes an integrative conceptual framework linking corporate governance, green skills, digital skills and AI governance, with practical implications for board education, executive development and organizational capability building, particularly relevant to firms across the Western Balkans and the wider European context.

Keywords

Corporate governance, green and digital skills, artificial intelligence, supervisory boards, sustainable transformation, Western Balkans.

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1. Introduction

The simultaneous green and digital transitions have become defining features of contemporary economic policy in Europe, reshaping the competitive environment within which firms operate. The European Green Deal and the digital agenda of the European Union have established ambitious decarbonization and digitalization objectives, and the realization of these objectives depends to a considerable extent on the capacity of firms to renew their knowledge base and acquire new competencies. For economies of the Western Balkans, which are pursuing accession to the European Union while modernizing their productive structures, the development of green and digital skills is not a peripheral concern but a precondition for resilience, competitiveness and sustainable convergence with the European single market [1]. Skills, in this respect, function as the connective tissue between macro-level transition policies and micro-level organizational performance.

Artificial intelligence introduces a further layer of complexity into the digital transition. No longer confined to specialized technical functions, artificial intelligence increasingly permeates managerial work, analytical processes and decision-making across organizational levels. It is best understood not as a discrete tool but as a general-purpose technology whose diffusion alters production functions, redefines the boundaries of human and machine work, and reshapes the competencies firms require [2]. Consequently, the competence agenda can no longer be framed solely in terms of green and digital skills; it must accommodate a third, intersecting category of artificial-intelligence-related competencies that combine technical fluency with ethical judgment and contextual understanding.

While much of the literature on competence development emphasizes human-resource practices, training systems and individual learning, comparatively less attention has been devoted to the governance conditions that enable or constrain such development. This paper locates the explanation at the level of corporate governance. Executive and supervisory boards set strategic priorities, allocate resources, design incentive structures and exercise oversight; through these mechanisms they shape whether a firm treats green, digital and artificial-intelligence-related competencies as strategic assets or as discretionary expenditures. Board composition, in turn, conditions the cognitive and experiential repertoire available for these decisions [3, 4].

The aim of this paper is to develop an integrative conceptual framework that connects corporate governance and board composition to the development of green, digital and artificial-intelligence-related competencies, and to responsible governance of artificial intelligence. The paper is conceptual rather than empirical; its contribution lies in synthesizing previously separate strands of scholarship—corporate governance and board diversity, sustainability and ESG, digital transformation, dynamic capabilities, and the emerging field of responsible artificial-intelligence governance—into a single, coherent argument. The remainder of the paper defines the relevant competencies, examines the governance mechanisms through which boards influence competence development, articulates a human-centered approach to artificial-intelligence governance, presents the integrative framework, and discusses implications for firms, universities and policy makers in the Western Balkans.

2. Green, digital and AI-Enabled competencies in the context of sustainable transformation

Green skills are conventionally understood as the knowledge, abilities and values required to support an environmentally sustainable economy, encompassing technical competencies such as energy and resource efficiency, life-cycle thinking and environmental

management, as well as transversal competencies such as systems thinking and the capacity to integrate sustainability considerations into ordinary decision-making [5]. Digital skills span a comparable spectrum, from basic digital literacy to advanced data analysis, cybersecurity awareness and the ability to redesign processes around digital technologies. Artificial-intelligence-related competencies extend this digital category, but are not reducible to it: they include an understanding of what algorithmic systems can and cannot reliably do, the ability to interpret model outputs critically, and the judgment required to decide when human deliberation should prevail over automated recommendation.

A central proposition of this paper is that these three competence domains increasingly converge into hybrid profiles rather than remaining the preserve of separate specialists. Sustainable transformation under conditions of digitalization requires individuals and teams who combine sustainability literacy, digital literacy and a working understanding of artificial intelligence with ethical judgment, data-informed decision-making, change leadership, creativity and the capacity for problem formulation—the ability to frame the right questions before analytical tools are applied. Such hybridity reflects the reality that environmental, digital and algorithmic challenges rarely present themselves in isolation; designing a low-carbon, data-enabled operating model, for instance, simultaneously engages all three domains.

Treating artificial intelligence as a general-purpose technology has direct implications for how competencies are conceived. General-purpose technologies generate value not through adoption alone but through the complementary organizational and human investments that surround them [2]. The competitive returns to artificial intelligence therefore depend less on the sophistication of the technology than on a firm's ability to reconfigure roles, processes and skills around it. This understanding aligns the competence question with the dynamic-capabilities tradition, which locates competitive advantage in a firm's capacity to sense opportunities, seize them through resource commitment, and continuously reconfigure its asset and competence base in response to change [6]. Green, digital and artificial-intelligence-related competencies, in this light, are constituent elements of dynamic capability, and their development is itself an organizational capability that must be deliberately cultivated rather than assumed.

3. Corporate governance and board composition as strategic drivers of competence development

Corporate governance establishes the structures and processes through which firms are directed and controlled, and through which the interests of shareholders, managers and wider stakeholders are reconciled [7]. Within this architecture, executive and supervisory boards occupy a decisive position. The executive board formulates and implements strategy, while the supervisory board—in the two-tier systems prevalent across much of continental Europe and the Western Balkans—appoints, monitors and advises the executive, exercising strategic oversight without engaging in day-to-day management. Both bodies shape competence development, though through different mechanisms.

Boards influence competence development first through strategic priorities and orientation. When a board frames sustainability and digital transformation as integral to long-term value creation rather than as compliance obligations, it signals that the associated competencies are strategic assets warranting sustained investment. This orientation translates into resource allocation: decisions to fund training programs, to invest in digital and data infrastructure, and to recruit or retain specialized talent are governance decisions before they are operational ones. Boards further shape competence development through performance metrics and incentives. By incorporating sustainability and capability-building

indicators into executive evaluation and remuneration, boards align managerial behavior with the longer time horizons that competence development requires, counteracting the short-termism that purely financial metrics can encourage [8]. External partnerships, with universities, technology providers and industry networks, represent a complementary mechanism through which boards can extend the firm's access to knowledge and accelerate learning.

Board composition conditions the quality of these decisions. A board whose members collectively possess expertise in sustainability and environmental management, digital transformation, data governance and artificial intelligence is better equipped to interpret emerging challenges, to evaluate proposals on their merits, and to exercise informed oversight of technically complex initiatives. Where such expertise is absent, boards may either neglect these domains or defer uncritically to management, weakening the oversight function. Beyond functional expertise, the diversity of the board matters. Diversity of gender, age, professional background and international experience broadens the range of perspectives brought to strategic deliberation and has been associated, in the governance literature, with more thorough information processing and a greater openness to innovation and responsible transformation [3, 4]. Technological literacy across the board, rather than its concentration in a single member, supports a shared understanding that sustains continuous learning at the apex of the organization. The argument is not that diversity mechanically produces superior outcomes, but that a cognitively varied and technologically literate board enlarges the firm's capacity to recognize and act upon the competence requirements of the green and digital transitions.

4. Responsible AI governance and the human-centered approach

The integration of artificial intelligence into managerial and organizational processes raises governance questions that extend beyond efficiency. A human-centered approach holds that artificial intelligence should be designed and deployed to complement and augment human capabilities rather than to substitute for them indiscriminately. The distinction is consequential: an excessive orientation toward automation, even where technically feasible, can erode the human contributions on which long-term value and legitimacy depend, whereas augmentation preserves human agency and tends to generate new forms of value [9]. Complementarity implies a deliberate division of labor in which analytical and pattern-recognition tasks are supported by algorithmic systems while judgment, contextual interpretation, ethical reasoning and relational work remain human responsibilities. Certain human capabilities—among them empathy, presence, judgment, creativity and a sense of hope or purpose—are not readily replicated by statistical systems and remain central to leadership in organizations that rely heavily on artificial intelligence.

A human-centered orientation also requires explicit attention to the risks that accompany artificial-intelligence adoption. Automation bias—the tendency to over-trust algorithmic outputs and to discount disconfirming evidence—can degrade the quality of decisions even as it appears to improve their speed. Accountability diffusion arises when responsibility for outcomes becomes blurred between human decision-makers and automated systems, weakening the lines of answerability on which governance depends. Prolonged reliance on automated recommendation may contribute to judgment atrophy, as the human capacities that systems are meant to support fall into disuse. To these cognitive and organizational risks must be added algorithmic opacity, the difficulty of explaining how certain systems reach their conclusions; data-security and cyber risks; and the risks attending the unguided use of generative artificial intelligence, including the propagation of inaccurate or fabricated content.

The supervisory board has a distinctive role in addressing these risks. As the body charged with oversight rather than execution, it is well positioned to require transparency in how artificial-intelligence systems are developed, procured and used; to ensure that lines of accountability remain clear; and to integrate artificial-intelligence governance into the firm's broader risk-management and internal-control frameworks. Supervisory oversight can also align technology adoption with environmental, social and governance commitments, ensuring that efficiency gains do not come at the expense of stakeholder trust or sustainability objectives. Emerging regulatory frameworks, including the European Union's risk-based approach to the regulation of artificial intelligence, reinforce the expectation that boards exercise informed oversight of these systems [10]. In this sense, responsible artificial-intelligence governance is not an adjunct to corporate governance but an extension of its core monitoring and value-protection functions, oriented toward long-term sustainable value creation.

5. An integrative conceptual framework

The preceding arguments can be drawn together into an integrative framework comprising three connected layers. The first layer concerns governance capabilities, understood as the expertise and diversity embedded in board composition. The second layer comprises the strategic governance mechanisms through which boards act—priorities, investments, oversight, metrics, incentives and stakeholder accountability. The third layer consists of organizational outcomes, including the development of green, digital and artificial-intelligence-related competencies and, beyond them, innovation capacity, resilience, sustainability performance and competitiveness.

The causal logic of the framework runs primarily from the first layer through the second to the third, with feedback effects completing the cycle. Governance capabilities shape the quality of strategic governance mechanisms: a board endowed with relevant expertise and cognitive diversity is more likely to set coherent priorities, to allocate resources toward capability building, and to exercise informed oversight of sustainability and artificial-intelligence initiatives. These mechanisms, in turn, generate organizational outcomes; sustained investment, aligned incentives and credible oversight foster the hybrid competencies and dynamic capabilities through which firms adapt to the green and digital transitions. The relationship is not deterministic. Its strength is moderated by organizational culture, by the institutional environment, and by the genuineness of the board's commitment, since governance mechanisms adopted symbolically rather than substantively are unlikely to produce real capability. A feedback loop closes the framework: the competencies and capabilities developed at the third layer enhance the firm's capacity for future learning and may, over time, inform the renewal of board composition itself, as firms come to value the expertise their transformation requires. The framework thus positions corporate governance as a catalyst that links strategy, skills and sustainability, and it is summarized in Table 1.

Table 1 *– The three layers of the integrative framework*

Layer 1: Governance capabilities (board composition)	**Layer 2: Strategic governance mechanisms**	**Layer 3: Organizational outcomes**
Sustainability and environmental-management expertise; digital-transformation and data-governance expertise; AI literacy; organizational-learning orientation; diversity of age, gender, professional background and international experience.	Strategic priorities and orientation; resource allocation and investment in training and technology; performance metrics and incentives; risk oversight and internal control; stakeholder accountability and external partnerships.	Green skills; digital skills; AI-enabled competencies; innovation capacity; organizational resilience; sustainability and ESG performance; long-term competitiveness.

Read in this way, the framework reframes competence development as an outcome of governance rather than solely of human-resource management. It also clarifies why investments in green and digital skills sometimes fail to yield expected returns: where governance capabilities are weak or where strategic mechanisms are deployed symbolically, the connection between investment and capability is severed.

6. Implications for firms in the Western Balkans

The framework carries several implications for firms, universities and policy makers in the Western Balkans, a region in which the green and digital transitions intersect with the broader process of European integration. For firms, the central implication is that the development of green, digital and artificial-intelligence-related competencies should be treated as a matter of strategic governance rather than as an operational or compliance task delegated to lower levels of the organization. Boards that internalize this view are better placed to avoid the trap of symbolic initiatives, sustainability reporting unconnected to operational change, or digital pilots that never scale into capability. Building real organizational capability requires sustained investment, aligned incentives and the patient reconfiguration of roles and processes around new technologies.

A specific implication concerns board education. If board composition conditions the quality of governance decisions, then strengthening the sustainability, digital and artificial-intelligence literacy of board members is a high-leverage intervention. Programs of continuing board education, covering ESG accountability, digital transformation and responsible artificial-intelligence governance, can raise the collective competence of governing bodies and improve the oversight of technically complex initiatives. Universities and business schools in the region have a complementary role, both in delivering such education and in producing graduates with the hybrid competencies that firms increasingly require; closer collaboration between firms and universities can align curricula with the evolving competence agenda. For policy makers, the implication is that frameworks supporting the green and digital transitions are more likely to succeed where they engage the governance level of firms, encouraging board accountability for capability building rather than focusing exclusively on technology subsidies or individual training schemes.

These implications connect directly to competitiveness and resilience. Firms in the Western Balkans operate in an environment of rising ESG expectations from European partners and investors, intensifying competition, and accelerating technological change. The capacity to develop and continually renew green, digital and artificial-intelligence-related competencies is a source of adaptive resilience and a condition for sustained competitiveness within the European single market. Corporate governance, by linking strategic oversight to capability building, is therefore not a peripheral administrative function but a determinant of how effectively firms in the region navigate the twin transitions and the path toward European integration.

7. Conclusion

This paper has argued that corporate governance and board composition play a decisive role in the development of green, digital and artificial-intelligence-related competencies, and it has extended the existing debate by treating artificial intelligence as a general-purpose technology that reshapes managerial work, competence requirements and the governance agenda itself. Through strategic priorities, resource allocation, performance metrics, incentives, risk oversight and stakeholder accountability, executive and supervisory

boards condition whether firms build the hybrid competencies and dynamic capabilities that the green and digital transitions demand. A human-centered approach to artificial intelligence, grounded in complementarity rather than substitution and attentive to risks such as automation bias, accountability diffusion and judgment atrophy, defines the boundaries of responsible adoption and assigns the supervisory board a central role in ensuring transparency, ESG alignment and long-term value creation.

The principal contribution of the paper is the integration of corporate governance, green skills, digital skills and responsible artificial-intelligence governance into a single conceptual framework of three connected layers, governance capabilities, strategic governance mechanisms and organizational outcomes, linked by a causal logic that positions governance as a catalyst connecting strategy, skills and sustainability. The framework offers firms, universities and policy makers in the Western Balkans and the wider European context a structured way of thinking about how governance enables sustainable transformation.

As a conceptual contribution, the paper is subject to limitations. The proposed relationships are argued rather than tested, and their strength is likely to vary across institutional and sectoral contexts. The framework abstracts from the considerable heterogeneity of firms and governance systems, and it does not capture the full complexity of organizational culture and power that mediates the translation of governance decisions into capability. These limitations point toward an agenda for future empirical research. Studies might examine how specific dimensions of board composition relate to measurable competence development, how the artificial-intelligence literacy of boards influences the responsible adoption of these technologies, and how governance mechanisms interact with organizational culture in shaping green and digital capability. Comparative research within the Western Balkans and between the region and established European Union members would be particularly valuable in establishing the boundary conditions of the framework advanced here.

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Digital Transformation and Green Compliance in Albania: Skills Gaps Across Businesses and Public Sector

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Abstract

The digital and green transition has become a strategic priority for organizations seeking to improve competitiveness, sustainability, and resilience. In Albania, both public institutions and businesses are increasingly expected to strengthen their digital capabilities while responding to environmental and regulatory challenges associated with the country's European integration process. However, limited evidence is available on the specific skills gaps that may hinder this transition. This study examines the digital transformation and green compliance skills needs of Albanian public institutions and small and medium-sized enterprises (SMEs). The analysis is based on data collected within the Erasmus+ SKILL2SUSTAIN – Boosting Digital and Green Skills for a Resilient and Sustainable Western Balkan Society project through structured questionnaires administered to representatives of 20 public institutions and 85 SMEs. Descriptive statistical analysis was used to identify organizational readiness, training priorities, and demand for digital and green competencies. The findings indicate a strong willingness among both stakeholder groups to engage in the twin transition, while also revealing important differences in their capacity-building priorities. Public institutions place greater emphasis on data management, e-governance, resource optimization, and energy efficiency, whereas SMEs prioritize process automation, artificial intelligence, market-oriented digital solutions, and practical sustainability measures. Both groups expressed considerable interest in training related to renewable energy, energy efficiency, and digital innovation, highlighting the need for targeted and sector-specific capacity-building initiatives. The study provides empirical evidence that can support policymakers, higher education institutions, and other stakeholders in designing education and training programmes that strengthen digital and green competencies and contribute to Albania's sustainable and inclusive transition.

Keywords

Digital transformation, Green transition, Skills gaps, SMEs, Public institutions, Sustainability, Albania.

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1. Introduction

Digital transformation and sustainability have become two of the main drivers of organizational change, reshaping how businesses and public institutions operate, deliver services, and respond to economic and environmental challenges. Advances in digital technologies, together with increasing environmental concerns and evolving regulatory requirements, are encouraging organizations to invest in new capabilities and rethink traditional practices. Rather than being separate priorities, digital innovation and sustainability are increasingly viewed as complementary processes that support long-term competitiveness, resilience, and sustainable development.

For countries aspiring to closer integration with the European Union, including Albania, this dual transition has become particularly important. Ongoing efforts to align with European policies and standards require both businesses and public institutions to strengthen their digital capacities while adopting more sustainable practices. Although progress has been made in recent years, many organizations continue to face challenges in developing the skills and competencies needed to successfully manage this transition. Identifying existing skills gaps and training priorities is therefore essential for supporting organizational development and future policy initiatives.

Despite growing interest in digital transformation and the green transition, studies examining these two dimensions together remain limited, particularly in Albania and the Western Balkans. Most research addresses digitalization or sustainability separately, even though both transitions rely on the availability of appropriately skilled human resources. Understanding current competencies and identifying priority areas for capacity building can therefore provide valuable evidence for designing targeted education, training, and institutional support measures.

This paper examines digital transformation and green compliance skills gaps among businesses and public institutions in Albania. The analysis is based on data collected within the Erasmus+ SKILL2SUSTAIN – Boosting Digital and Green Skills for a Resilient and Sustainable Western Balkan Society project through structured questionnaires administered to representatives of public institutions and small and medium-sized enterprises (SMEs). The findings aim to support the design of future training programmes and contribute to strengthening digital and green capacities across both sectors.

2. Literature review

Digital transformation has become a strategic priority for both businesses and public institutions, reshaping how organizations operate, deliver services, and create value. Beyond the adoption of new technologies, it represents an organizational process that requires changes in business models, leadership, and workforce capabilities [1,2]. Recent studies highlight that technologies such as artificial intelligence (AI), big data analytics, cloud computing, and process automation can significantly improve organizational performance, provided that organizations possess the necessary digital skills and capabilities [3,4,5].

At the same time, sustainability has become an integral part of organizational strategy. The European Green Deal and related initiatives have encouraged businesses and public institutions to adopt more sustainable practices in areas such as energy efficiency, resource management, circular economy, and environmental reporting. Research suggests that this transition depends not only on technological innovation but also on the development of green skills and continuous capacity building [6,7,8].

More recently, these two processes have converged under the concept of the twin transition, recognizing that digital technologies can accelerate sustainability while environmental objectives stimulate digital innovation. This perspective highlights the need for organizations to develop integrated digital and green competencies. However, evidence from the Western Balkans, particularly Albania, remains limited, making it important to identify existing skills gaps and training priorities that can support organizational resilience and sustainable development [4,5,7].

3. Methodology

This study is based on data collected within the Erasmus+ SKILL2SUSTAIN – Boosting Digital and Green Skills for a Resilient and Sustainable Western Balkan Society project under Work Package 2, which focuses on identifying stakeholders' digital and green skills needs across the Western Balkans. In Albania, the survey was coordinated by the University of Tirana in collaboration with the Polytechnic University of Tirana and ETMI. The analysis presented in this paper focuses exclusively on two stakeholder groups: public institutions and small and medium-sized enterprises (SMEs).

Data were collected between October and November 2025 through two structured questionnaires originally developed in English and translated into Albanian. The questionnaires consisted of closed-ended, single-choice, and multiple-choice questions covering digital transformation, sustainability, artificial intelligence, training needs, and capacity-building priorities. A total of 20 valid responses were obtained from public institutions and 85 valid responses from SMEs, with one representative participating on behalf of each organization. The collected data were analysed using descriptive statistics, primarily frequencies and percentages, to identify key skills gaps, training priorities, and organizational readiness for the digital and green transition. The findings provide an overview of the current needs of Albanian businesses and public institutions and support the development of future capacity-building initiatives.

4. Findings

4.1. Public institutions

This section presents the findings from the survey conducted among representatives of Albanian public institutions. The analysis explores their perceptions of digital transformation, green compliance, and organizational skills needs, with particular attention to training priorities and the adoption of digital and sustainability-oriented solutions. The findings provide an overview of the current level of readiness and the key areas where additional capacity building is required.

4.1.1. Digital Transformation and Sustainability Skills

Public institutions demonstrate a high level of readiness for digital transformation, with 75% of respondents reporting that their institution is very open to digital initiatives, while only 5% expressed limited openness. Similarly, most respondents considered green skills to be

either very important or somewhat important for their daily work, highlighting growing awareness of sustainability within the public sector.

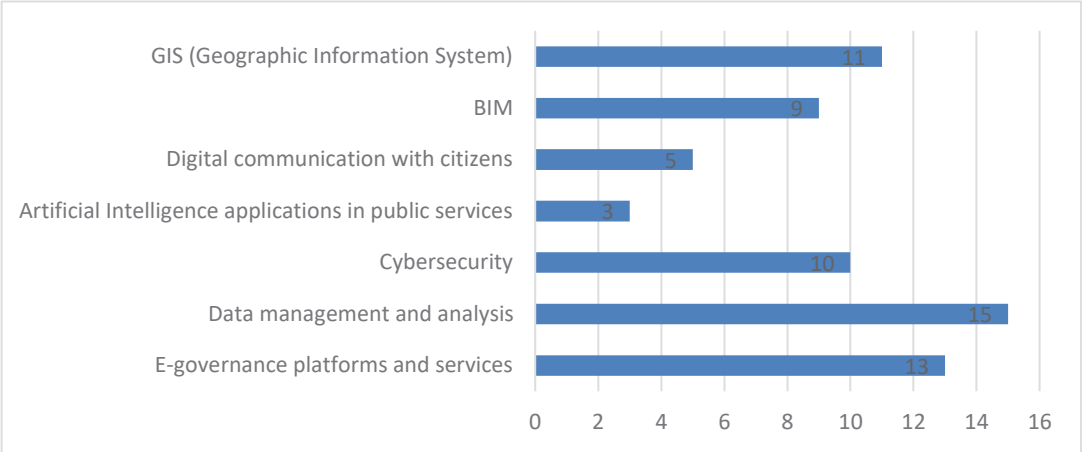


***Figure 1** – Areas of digital capacity-building most relevant for the staff*

As shown in Figure 1, Data Management and Analysis (75%) emerged as the highest training priority, followed by E-Governance Platforms (65%), GIS (55%), and Cybersecurity (50%). Lower interest was reported for BIM (45%), AI applications in public services (30%), and Digital Communication with Citizens (25%), suggesting that institutions currently prioritize digital solutions that strengthen service delivery and operational efficiency.

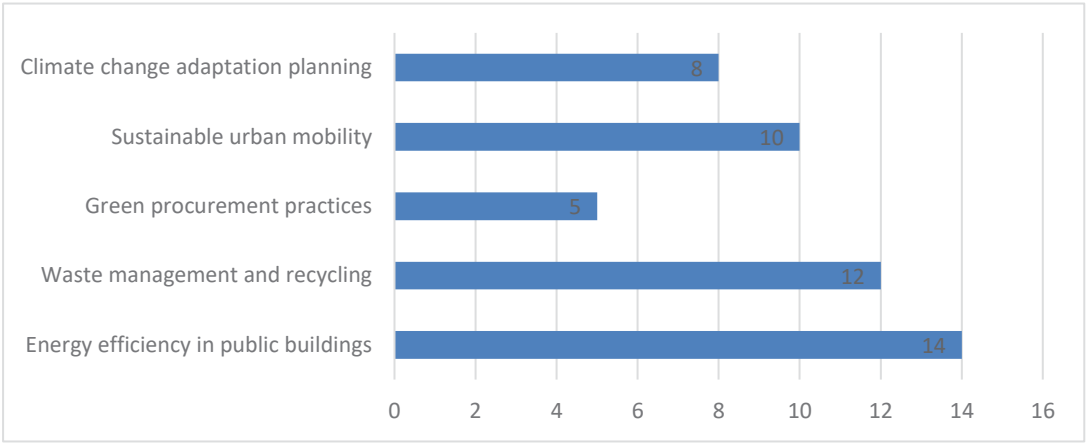


***Figure 2** – Sustainability areas the institutions like more support*

Regarding sustainability, Energy Efficiency in Public Buildings (70%) and Waste Management and Recycling (60%) were identified as the main training priorities, followed by Sustainable Urban Mobility (50%) and Climate Change Adaptation Planning (40%) (Figure 2). Green Procurement Practices received comparatively lower interest (25%). In addition, 75% of respondents expressed strong interest in training on renewable energy and energy efficiency, indicating substantial demand for capacity-building initiatives in these areas.

4.1.2. Potential Products and Services

Public institutions expressed a strong interest in AI-based solutions that can improve operational efficiency and support more effective public service delivery. As shown in Figure 3, Resource Optimization (Energy, Water, Transport) was identified as the most useful AI application (80%), followed by Predictive Analytics for Policy-Making (50%) and Smart City Applications (45%). In contrast, Chatbots for Citizen Interaction received limited interest

(10%), suggesting that institutions currently prioritize AI applications that enhance resource management and decision-making rather than citizen interaction.

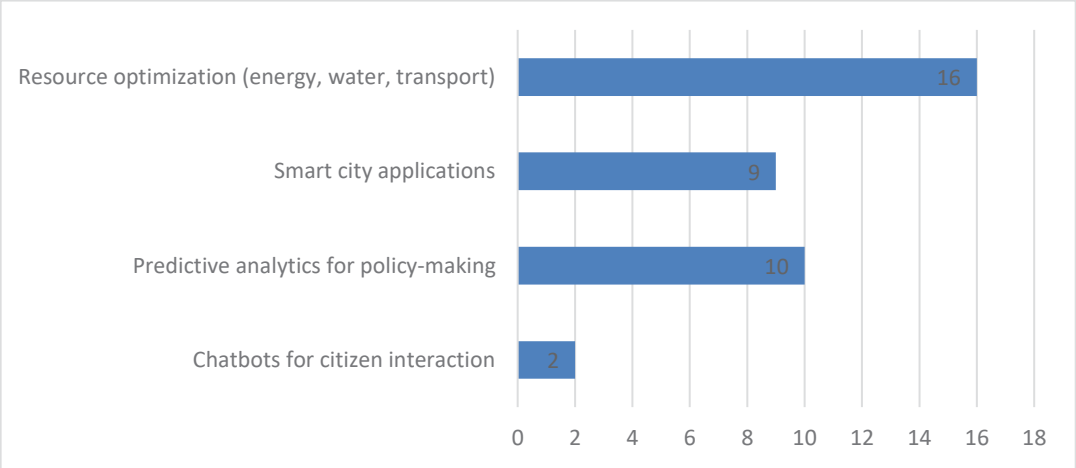


***Figure 3** – AI-based tools would most useful for the institution*

Respondents also showed interest in digital solutions supporting carbon footprint measurement and sustainability reporting.

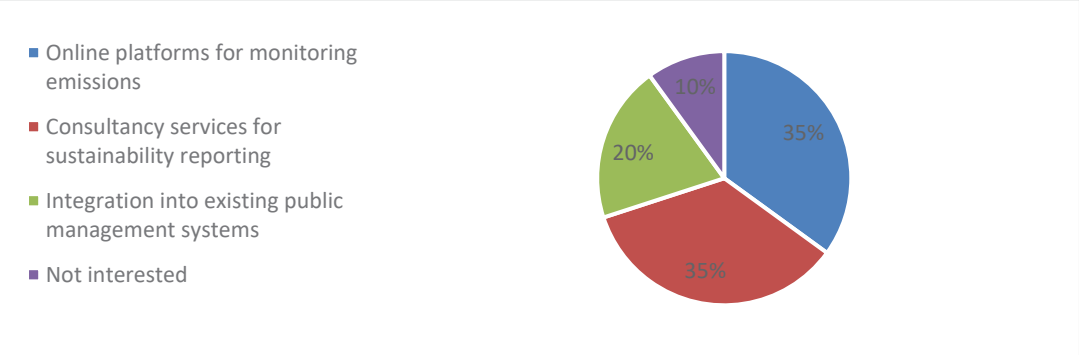


***Figure 4** – Carbon footprint measurement and reporting solutions*

As illustrated in Figure 4, Online Platforms for Monitoring Emissions and Consultancy Services for Sustainability Reporting were equally preferred (35% each), followed by Integration into Existing Public Management Systems (20%). Only 10% of respondents reported no interest in such solutions, indicating broad recognition of the value of carbon monitoring and reporting tools. In addition, respondents emphasized the importance of technical assistance for environmental certifications, while awareness and use of digital partnership platforms remained limited, highlighting opportunities to strengthen collaboration and networking within the public sector.

4.2. Small and medium enterprises

This section presents the findings from the survey conducted among Albanian small and medium-sized enterprises (SMEs). The results highlight businesses' priorities regarding digital transformation, sustainability, and workforce development, while also identifying the main areas where additional skills and practical support are needed to facilitate the digital and green transition.

4.2.1. Training and Skills

Most SMEs expressed a positive attitude toward digital transformation, with 55% reporting that they are very open and 30% somewhat open to digital training. Similarly, 79% showed interest in integrating sustainable practices into their operations, indicating strong recognition of the importance of both digital and green competencies.

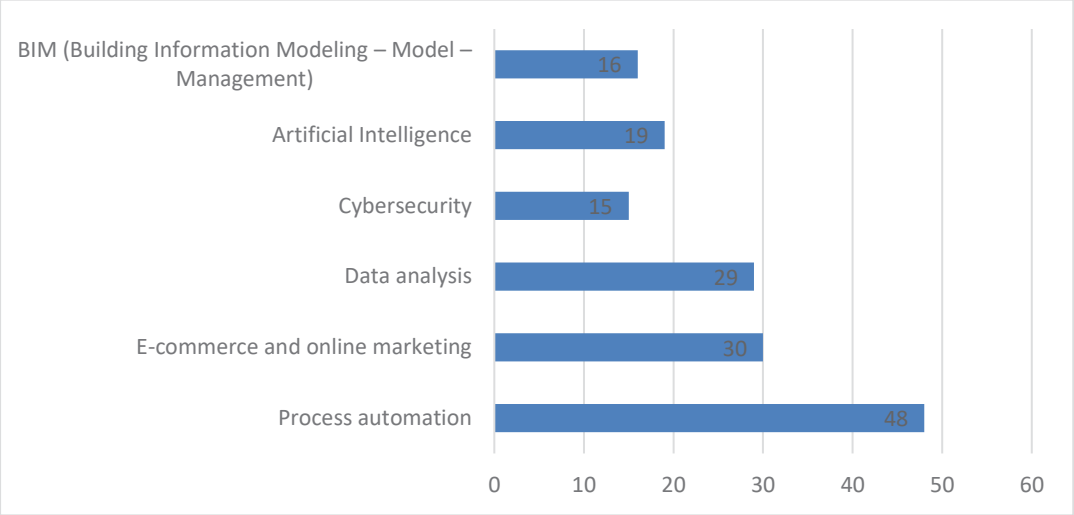


***Figure 5** – Areas of digital training*

As shown in Figure 5, Process Automation (56%) emerged as the highest digital training priority, followed by E-commerce and Online Marketing (35%), Data Analysis (34%), and Artificial Intelligence (22%). Lower demand was reported for Cybersecurity and BIM, suggesting that SMEs currently prioritize digital skills that directly improve operational efficiency, market access, and data-driven decision-making.

Green skills were also considered highly relevant, with 50% of respondents rating them as very important and 33% as somewhat important. SMEs identified Energy Management (65%) as the leading sustainability priority, followed by Sustainable Transport (28%), Waste Reduction (26%), and Circular Economy (25%), reflecting a strong focus on practical resource efficiency and environmental performance. Interest in renewable energy and energy efficiency training was high, with 79% of respondents expressing either high or moderate interest. In addition, most SMEs indicated a willingness to participate in training on sustainability reporting and EU green standards, although 43% stated that their participation would depend on the cost, highlighting the importance of affordable and accessible capacity-building initiatives.

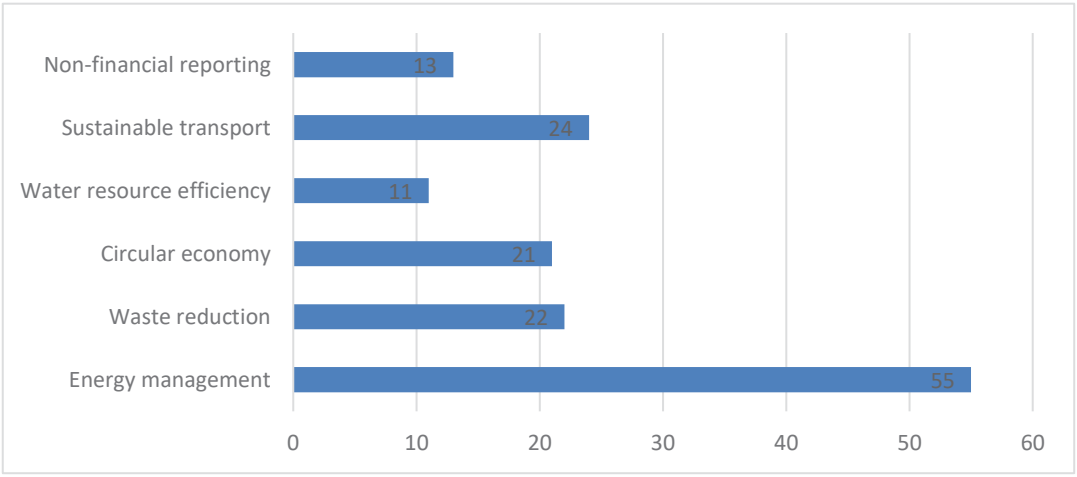


***Figure 6** – Areas of sustainability*

4.2.2. Potential Products and Services

SMEs expressed strong interest in AI-based solutions that can improve customer engagement, market analysis, and business decision-making. As shown in Figure 7, Market and Consumer Analysis (56%) and Customer Assistance (Chatbots) (53%) were the most preferred AI applications, followed by Supply Chain Optimization (26%) and Sales Forecasting (24%). These findings suggest that SMEs primarily view AI as a practical tool for improving customer interaction and operational efficiency.

Respondents also showed interest in digital tools supporting carbon footprint measurement and sustainability reporting.

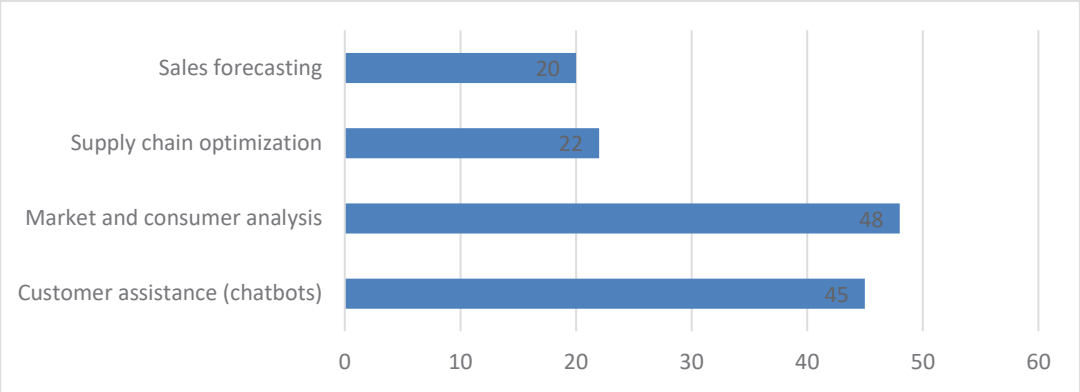


***Figure 7** – AI-based products/services*

An Online Self-assessment Platform (32%) was the preferred solution, followed by Integration into Existing Management Systems (24%) and External Consultancy Services (20%), while 25% of respondents reported no current interest in such tools. In addition, technical assistance for environmental certifications was considered important by most SMEs, particularly in relation to standards such as ISO 14001. Although many respondents expressed willingness to use digital partnership platforms, awareness and actual use of such platforms remain limited, indicating opportunities to strengthen collaboration and knowledge sharing among businesses.

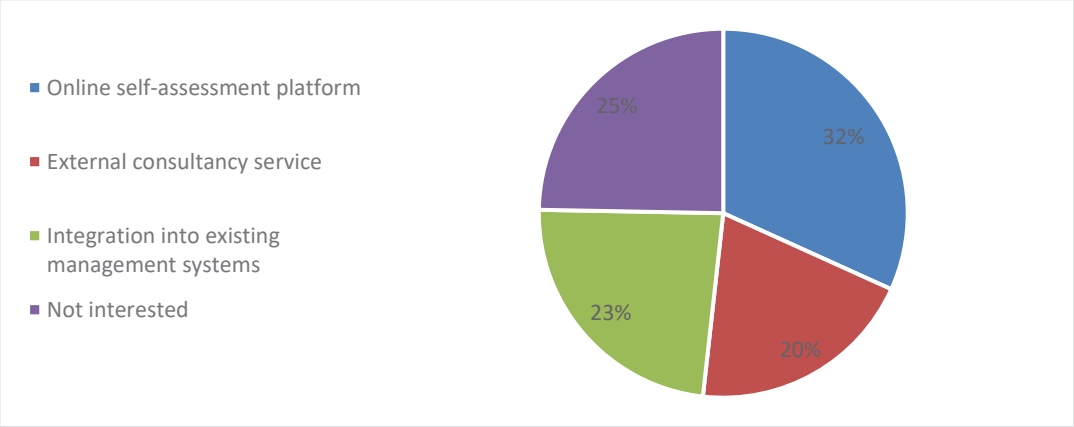


***Figure 8** – Carbon footprint measurement tools*

5. Conclusions

This study examined the digital transformation and green compliance skills gaps among public institutions and SMEs in Albania using data collected within the SKILL2SUSTAIN project. The findings indicate that both stakeholder groups recognize the

importance of digitalization and sustainability and demonstrate a strong willingness to engage in the twin transition. However, the results also reveal important skills gaps that may limit the effective adoption of digital technologies and sustainable practices if not addressed through targeted capacity-building initiatives.

Although both stakeholder groups share similar objectives, their priorities differ. Public institutions place greater emphasis on data management, e-governance, resource optimization, and energy efficiency, reflecting their focus on improving public service delivery and institutional performance. In contrast, SMEs prioritize process automation, market-oriented digital tools, artificial intelligence, and practical sustainability solutions that enhance operational efficiency and competitiveness. These differences highlight the need for training programmes tailored to the specific needs of each sector.

Overall, the findings underline the importance of strengthening collaboration among higher education institutions, businesses, and public organizations to support the development of integrated digital and green competencies. By identifying current skills gaps and priority training areas, this study provides useful evidence for designing future educational programmes and capacity-building initiatives that can contribute to Albania's digital and green transition.

The findings presented in this paper can support policymakers, higher education institutions, public institutions, businesses, and other stakeholders in designing targeted interventions that strengthen digital and green skills and contribute to a more resilient and sustainable Albanian economy. As Albania continues its alignment with European digital and sustainability priorities, investing in human capital and skills development will be essential for ensuring a successful and inclusive twin transition.

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EU Policy alignment assessment of Montenegrin pressure equipment regulations: The case of gas cylinders for breathing apparatus

[Marko Krstajić] [1]

Abstract

The paper analyses the alignment of Montenegrin regulations governing the field of pressure equipment with relevant EU policies, using gas cylinders for breathing apparatus as a model for assessment of the regulatory system. Although at first glance this appears to be a technically simple issue, determining the applicable requirements for periodic inspection and testing reveals significant regulatory inconsistencies.

The research examines the interaction between national legislation, EU directives (PED and TPED), and ADR international agreement. It demonstrates that gas cylinders for breathing apparatus are not clearly covered by a single regulatory framework in Montenegro, resulting in overlaps or gaps in regulations. In particular, the absence of a dedicated national regulation governing periodic inspection and testing of pressure equipment in service results in reliance on rules of profession.

By comparing the Montenegrin framework with regulatory solutions in neighbouring EU and candidate countries, such as Croatia and Serbia, the paper identifies gaps in legal clarity and coherence. The findings highlight the necessity of introducing a comprehensive regulation that would define inspection intervals and requirements for pressure equipment in use, thereby ensuring full alignment with EU policy principles and improving safety and legal certainty.

Keywords

Pressure equipment, periodic inspection and testing, breathing apparatus, EU policy alignment, PED directive, TPED directive, Montenegro regulations, rules of profession.

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1. Introduction

Sometimes it is possible to reach the essence by asking a seemingly simple question that can expose all the weaknesses of a given concept. One such question that can be used to test the quality of the regulatory environment in Montenegro governing pressure equipment is: “What is the periodic inspection and pressure tests interval for breathing apparatus cylinders used for occupational and rescue purposes?”

In other words, these are self-contained breathing apparatus used, for example, by fire and rescue services. It sounds like a question that could be answered clearly and unambiguously within a few minutes, but reality is far more complex.

To arrive at an answer, it is necessary to consider the complex regulatory environment for pressure equipment in Montenegro from the perspective of different regulations.

2. ADR perspective on gas cylinders for breathing apparatus

At first glance, gas cylinders as part of breathing apparatus seem to represent transportable pressure equipment. Let us take this as an initial working hypothesis. In that case, they should be treated as compressed gas cylinders, whose inspection periodicity is prescribed by ADR - Agreement concerning the International Carriage of Dangerous Goods by Road [1].

The Law on the Carriage of Dangerous Goods [2] states in Article 1 that the transport of dangerous goods is carried out in accordance with the law and ratified international agreements, one of which is ADR.

Compressed air, which is used in breathing apparatus, is designated under section 3.2.1 ADR as “UN 1002 COMPRESSED AIR.” According to ADR section 4.1.4.1 and packing instruction P200, the periodic inspection interval for cylinders containing UN 1002 air is 10 years. At first glance, this seems like a trivial conclusion.

However, a closer look reveals that special provision 655 (section 3.3.1 ADR) applies:

“Cylinders designed, constructed, approved and marked in accordance with Directive 97/23/EC [3] or Directive 2014/68 EU [4] and used for breathing apparatus may be carried without conforming to Chapter 6.2, provided that they are subject to inspections and tests specified in 6.2.1.6.1 and the interval between tests specified in packing instruction P200 in 4.1.4.1 is not exceeded. The pressure used for the hydraulic pressure test is the pressure marked on the cylinder in accordance with Directive 97/23/EC or Directive 2014/68 EU. “

However, Directives 97/23/EC and 2014/68/EU do not relate to transportable pressure equipment, but to pressure equipment. This means that ADR-prescribed intervals do not apply to breathing apparatus cylinders.

3. Applicable rulebooks in Montenegro and the TPED directive

If the fields of LPG and simple pressure vessels—being outside the scope of this paper—are set aside, three rulebooks are applicable in Montenegro with respect to transportable pressure equipment and pressure equipment:

1) Rulebook on Transportable Pressure Equipment [5] (2016), with the following considerations:

- The footnote to this Rulebook explicitly states: “This Rulebook transposes Directive 2010/35/EC of the European Parliament and of the Council of 16 June 2010 [6] on transportable pressure equipment.” (the Transportable Pressure Equipment Directive – TPED)
- Pursuant to Article 2(1)(b) of Directive 2010/35/EC, transportable pressure equipment excludes cylinders used in breathing apparatus;
- The Rulebook does not contain provisions governing the repeal of Rulebook [7];
- Article 4 stipulates that the Rulebook does not apply to transportable pressure equipment placed on the market prior to its entry into force.

2) Rulebook on Technical Norms for Mobile and Closed Receptacles for Compressed, Liquefied and Pressure-Dissolved Gases [7] (1980). It should be noted that gas cylinders for breathing apparatus are not excluded from the scope of this Rulebook.

3) Rulebook on Technical Requirements for Pressure Equipment [8] (2017) with the following remarks:
   - The footnote to this Rulebook states: “This Rulebook transposes Directive 2014/68/EU of the European Parliament and of the Council of 15 May 2014.”
   - The Rulebook does not contain provisions governing periodic inspections and testing, including those relating to cylinders used in breathing apparatus.

Based on the foregoing, the following findings may be summarised regarding cylinders used in breathing apparatus:

a) For those placed on the market prior to the entry into force of Rulebook [5], the provisions of Rulebook [7] apply. In particular, Article 26 thereof prescribes that periodic inspections of compressed air vessels shall be carried out at intervals of five years;

b) For those placed on the market after the entry into force of Rulebook [5], that Rulebook does not prescribe periodic inspection intervals.

4. The PED directive and regulatory gap

In order to determine what to do in case (b), it is extremely important to emphasize that Directive 2014/68/EU (the Pressure Equipment Directive – PED) harmonizes the requirements related to the design, manufacture and conformity assessment of pressure equipment and assemblies, but does not regulate issues related to periodic inspections and testing of equipment in service. These matters are left to the national legislation of the Member States, in accordance with the principles of the EU “New Approach” legislation.

A regulatory gap exists in Montenegro, as there is no rulebook governing the periodic inspection and testing of pressure equipment covered by the PED Directive. Positive examples in the region are Croatia and Serbia, which have their respective rulebooks [9] and [10]. Nevertheless, the Serbian rulebook does not explicitly address breathing apparatus, whereas the Croatian rulebook prescribes a periodic inspection interval of five years.

5. "Rules of profession" and MEST standards

In addressing this issue, one may rely on the concept of the "rules of profession", the application of which is elaborated in detail in Article 7 of the Code of Ethics of the Engineering Chamber of Montenegro [11], which states:

"In matters not explicitly regulated by applicable legislation, a member shall act in accordance with the rules of profession, applying the following hierarchy of sources:

1. Montenegrin (MEST) standards,
2. European (EN) standards,
3. International (ISO, IEC) standards,
4. standards, technical requirements, quality norms and related documents of professional European associations,
5. standards, technical requirements, quality norms and related documents of professional international associations,
6. standards, technical requirements, quality norms and related documents of professional institutes and associations of other countries and professional associations of Montenegro other than the Institute for Standardization of Montenegro,
7. elements of technical regulations of other countries exclusively in the technical part, where not regulated by Montenegrin legislation,
8. scientific and professional literature,
9. regulations and standards of former states which included the territory of today's Montenegro, provided that they remain technically relevant and safe for application,
10. unwritten rules of profession established through established engineering practice.

If there are several sources of rules of profession at the same hierarchical level, the member has the right to choose which rule to apply, provided that consistency is maintained in its application to a given object."

Accordingly, reference may be made to the Montenegrin standard MEST EN ISO 18119:2020 Gas cylinders - Seamless steel and seamless aluminium-alloy gas cylinders and tubes - Periodic inspection and testing [12]. In footnote (c) of Table A.1 of this standard, it is stated that in the case of gases used for breathing apparatus:

"c) Local regulations specify the interval of periodic inspection and testing. In the absence of any regulations, an annual internal inspection should be carried out with a periodic inspection carried out every five years. However, if a risk assessment and the specific use of a cylinder indicate that there is a low risk of internal degradation, then the interval for carrying out an internal examination may be increased to a maximum of 2.5 years."

A clear distinction must be made between internal inspection and periodic inspection and testing, as the latter includes pressure testing, whereas the former does not.

This raises the central question: which criterion should be applied in practice?

6. Conclusion

Based on the above analysis, the applicable inspection requirements may be summarised as follows:

- If the breathing apparatus was manufactured on or before 13 January 2016, i.e. prior to the entry into force of Rulebook [5], the inspection interval prescribed by that rulebook shall apply.
- If the breathing apparatus was manufactured after 13 January 2016, the relevant MEST standard shall be applied in accordance with the hierarchy of the rules of profession set out in the Code of Ethics of the Engineering Chamber of Montenegro.
- Even in the absence of an applicable standard, the criteria prescribed by the Croatian rulebook may be applied, also in accordance with the hierarchy of the rules of profession.

Although these approaches differ, they converge on a pressure testing interval of five years, which - strictly speaking - does not necessarily have to coincide in all cases.

Ultimately, this analysis highlights the need for Montenegro to adopt a comprehensive rulebook governing the periodic inspection and testing of pressure equipment in service. Such regulation should address all categories of equipment not covered by ADR provisions for transportable pressure equipment and ensure full alignment of national legislation with the requirements of EU directives.

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Risk culture and digital transformation in Albanian public institutions: Empirical evidence from a national institution

[Perseta Grabova][1], [Armela Alinani][2]

Abstract

In an era of accelerating digital transformation, public institutions face growing organizational and technological risks that demand robust risk management frameworks and adaptive institutional cultures. Albanian public administration, undergoing significant reform in the context of EU accession, represents a particularly relevant yet understudied context for examining these dynamics. This study investigates the impact of risk culture and digital transformation risks on the performance of Albanian public institutions, with a central Albanian public institution in the field of cultural heritage administration serving as the empirical case. The research aims to understand how organizational risk culture and the challenges of digitalization shape institutional effectiveness, contributing empirical evidence to a context where such studies remain scarce. A quantitative research design was adopted. Primary data were collected through a structured questionnaire administered to employees of the institution, covering the core constructs of risk culture, digital transformation risks, and institutional performance. Data analysis followed a sequential approach, moving from reliability assessment to correlation and regression analysis, to examine the relationships among study variables. The findings reveal that risk culture is the only statistically significant predictor of institutional performance, with a strong positive effect, while the perceived risks of digital transformation did not demonstrate a statistically significant direct influence on performance. Descriptive analysis identified a moderate overall level of risk culture, with staff training emerging as the weakest organizational dimension and the most frequently cited challenge. The study concludes that digital transformation should not be viewed solely as a technological initiative but as an organizational and managerial process requiring parallel investment in human capital and institutional risk management frameworks. These findings carry direct practical implications for Albanian institutional reform, the implementation of the Public Financial Management Strategy 2023–2030, and the broader Western Balkans digitalization agenda.

Keywords

Risk culture, digital transformation, institutional performance, public sector, Albania.

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1. Introduction

Digital transformation is fundamentally reshaping the way public institutions operate, deliver services, and manage public resources. This process is not merely technological, it involves organizational, cultural, and institutional change that requires strategic adaptation, human capacity development, and effective risk management. In the public sector, where accountability and public value occupy a central position, risk management cannot be treated as a nonessential function; it must be integrated into the organizational culture and strategic decision-making of every institution.

Albania presents a particularly relevant context for examining these dynamics. The government platform e-Albania has significantly transformed citizen-state interaction by centralizing public services, while the Public Financial Management Strategy 2023–2030 [1] and Ministerial Order No. 4/2024 on Financial Management and Control [2] have established the legal basis for integrating risk management into public institutions. Nevertheless, a significant gap persists between technological investment and the institutional capacities required to manage the risks it generates. The cyberattack of June 2022 against Albanian government infrastructure, one of the most severe cybersecurity incidents in the region, exposed real deficiencies in the organizational risk culture of the public administration.

Despite the growing international literature on risk culture and organizational performance, empirical studies in the Albanian and broader Western Balkans public sector context remain scarce. This study addresses this gap by providing primary quantitative evidence from a central Albanian public institution in the field of cultural heritage administration, one of the most digitally advanced institutions in the Albanian public administration. The study pursues two objectives: to assess the current level of risk culture as perceived by employees, and to test the relationships between risk culture, digital transformation risks, and institutional performance.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature on risk culture, digital transformation, and institutional performance in the public sector, concluding with the research gap and hypotheses. Section 3 describes the methodology, section 4 presents the empirical results, section 5 discusses the findings in light of the literature, and section 6 concludes with implications, limitations, and directions for future research.

2. Literature review

Risk culture is broadly defined as the set of shared norms, attitudes, and behaviors that determine how an organization identifies, discusses, and manages risk [3]. The COSO (2017) Enterprise Risk Management framework [4] positions risk culture at the core of organizational governance, emphasizing the critical role of leadership commitment, the 'tone at the top' and employee engagement in achieving strategic objectives. To make the concept empirically measurable, Sheedy, Zhang, and Liao (2017) [5] operationalized risk culture into four dimensions: leadership, open reporting, individual accountability, and organizational incentive structures. More recently, Bockius and Gatzert (2024) [6], in a systematic literature review, identified four key improvement levers of organizational risk culture, leadership exemplarity, communication and reporting systems, training and awareness mechanisms, and incentive structures, arguing that organizations with strong risk cultures integrate risk awareness into strategic objectives, enabling balanced risk-taking while avoiding both excessive caution and recklessness.

Risk culture becomes particularly consequential in the context of digital transformation, which reshapes both the operations and the risk landscape of public institutions. Mergel, Edelmann, and Haug (2019) [7] distinguish three progressive levels of technological change in the public sector: digitization (the technical conversion of analogue information into digital format), digitalization (the adoption of technology to change and optimize existing work processes), and digital transformation (a holistic organizational and cultural change). Crucially, the success of this progression appears to depend less on technology itself than on the organizational environment surrounding it. Haug, Dan, and Mergel (2023) [8], based on a systematic review of 164 studies, find that a large share of digital initiatives in the public sector fail to meet their objectives not for technical reasons, but due to cultural and organizational factors, internal resistance to change, insufficient digital competencies, and non-proactive leadership. KPMG (2024) [9] similarly ranks internally resistant organizational culture among the main barriers to public sector digitalization, alongside cybersecurity threats and data governance gaps.

Whether risk culture and digital transformation translate into institutional outcomes ultimately depends on how performance itself is conceived and measured in the public sector, a task that presents distinct challenges, as private sector frameworks cannot be applied directly. Moore (1995) [10] formulated the Public Value Creation framework, according to which the performance of a public institution is assessed not by accounting outcomes alone, but by its capacity to increase public trust, guarantee transparency, and protect strategic non-monetary assets. This framework justifies the methodological choice of measuring performance through employee perceptions rather than exclusively through objective financial indicators. Yet the integration of risk management into performance systems remains problematic in practice: Bracci, Bruno, D'Amore, and Ievoli (2024) [11] provide empirical evidence that this integration remains fragmented in public organizations precisely because risk management and performance measurement are treated as separate functions.

Taken together, the literature confirms a positive relationship between risk culture and organizational performance [12, 13], yet three gaps persist. First, empirical studies concentrate on the banking and private sectors of advanced economies. Second, quantitative evidence from the Albanian and Western Balkans public sector is absent. Third, the combined effect of risk culture and digital transformation risks on institutional performance has not been tested empirically in institutions with a historical-cultural mission. Based on this review, two hypotheses are formulated:

H1: Risk culture has a positive and statistically significant effect on institutional performance.

H2: Digital transformation risks have a statistically significant effect on institutional performance.

H2 is formulated as non-directional, as the literature offers competing predictions on whether perceived digital risks impair performance through disruption or enhance it by stimulating proactive protective behavior.

3. Methodology

The study adopts a quantitative, cross-sectional research design grounded in a post-positivist paradigm, following a deductive approach in which hypotheses derived from established theoretical frameworks primarily COSO (2017) [4] and FSB (2014) [3] are tested against empirical data.

The empirical case is a central Albanian public institution in the field of cultural heritage administration, selected for three reasons: it is among the most digitally advanced institutions in the Albanian public administration, digitizing large volumes of documentary material

monthly; its mission preserving irreplaceable national cultural heritage makes risk management existential rather than merely procedural; and the 2022 cyberattack directly affected its institutional context, making the sample particularly informed on the study topic.

Data were collected through a structured questionnaire administered to employees of the institution during a four-week period, with prior institutional approval. Of the 175 total employees, 71 completed the questionnaire, yielding a response rate of 40.6%. The sample includes employees across all hierarchical levels, with 81.7% holding a master's degree and 60.5% having more than ten years of professional experience a profile that supports the evaluative capacity of respondents. Participation was voluntary and anonymous.

The questionnaire comprised five sections: demographics; risk culture (six items, adapted from COSO, 2017 [4] and Sheedy et al., 2017 [5]); digital transformation risks (eight items, based on Haug et al., 2023 [8] and KPMG, 2024 [9]); institutional performance (ten items, informed by Moore, 1995 [10] and Horvey & Odei-Mensah, 2023 [12]); and open-ended questions. All items were measured on a five-point Likert scale (1 = strongly disagree; 5 = strongly agree). A pilot phase with five employees preceded final distribution.

Analysis followed a sequential approach: descriptive statistics, reliability assessment (Cronbach's Alpha, threshold $\alpha \geq 0.70$), Pearson correlation, and multiple linear regression with institutional performance as the dependent variable. Regression assumptions were verified through diagnostic tests: VIF for multicollinearity, Shapiro-Wilk for normality of residuals, Breusch-Pagan for homoscedasticity, and Durbin-Watson for independence of residuals.

The hypothesized relationships were tested through the following multiple linear regression model:

$$PERF_i = \beta_0 + \beta_1 RC_i + \beta_2 DTR_i + \varepsilon_i \quad (1)$$

where $PERF_i$ denotes the perceived institutional performance of respondent i, RC_i represents risk culture, DTR_i represents digital transformation risks, β_0 is the intercept, β_1 and β_2 are the coefficients to be estimated, and ε_i is the error term. Based on H1 and H2, β_1 is expected to be positive and statistically significant.

4. Results

4.1. Sample profile, descriptive statistics and reliability

The demographic profile of the sample reflects the organizational structure of the institution. Specialists constitute the majority of respondents (60.6%), followed by heads of sector (23.9%) and directors (9.9%), a distribution that captures primarily the operational perspective of those who implement processes daily, complemented by the strategic perspective of the leadership level. In terms of professional experience, 60.5% of respondents have worked in the institution for more than ten years, with 36.6% exceeding fifteen years of service, indicating a workforce with deep accumulated institutional knowledge. The educational profile is notably high, with 81.7% of respondents holding a master's degree.

***Table 1** – Descriptive statistics and reliability of constructs (n = 71)*

Construct	Items	M	SD	α
Risk Culture (X1)	6	3.30	0.56	0.808
Digital Transformation Risks (X2)	8	3.51	0.64	0.861
Institutional Performance (Y)	10	3.47	0.57	0.847

Source: Author's calculations.

Table 1 presents the descriptive statistics and reliability coefficients for the three constructs. All constructs demonstrated good internal consistency, with Cronbach's Alpha values ranging from 0.808 to 0.861, exceeding the recommended threshold of 0.70 [14]. Item-total correlation analysis confirmed that no item removal would meaningfully improve reliability, justifying the retention of all indicators.

A closer examination of individual items reveals a distinctly asymmetric profile of the institution's risk culture, summarized in Table 2. The strongest dimension is openness in communication: employees report a high degree of freedom to report errors without fear of penalty (M = 3.94, 60.6% agreement) and solid interdepartmental cooperation in risk management (M = 3.62, 56.3% agreement). These findings indicate a psychologically safe reporting environment — a foundational element of what the FSB (2014) [3] terms 'just culture'. In sharp contrast, the weakest dimensions are the organization of formal training (M = 2.65), with only 14.1% of respondents providing a positive assessment, and the frequency of risk discussion in regular meetings (M = 3.07, 28.2% agreement). Similarly, the embedding of risk management as part of organizational culture remains limited, with only 16.9% agreement (M = 3.20).

***Table 2** – Selected item-level results for risk culture (n = 71)*

Item	M	SD	% Agree (4–5)
Freedom to report errors without fear of penalty	3.94	0.89	60.6%
Effectiveness of interdepartmental cooperation on risks	3.62	0.76	56.3%
Importance senior leadership attaches to risk management	3.34	0.65	29.6%
Risk management as part of organizational culture	3.20	0.62	16.9%
Frequency of risk discussion in work meetings	3.07	0.92	28.2%
Organization of risk management training	2.65	0.78	14.1%

Source: Author's calculations.

Within the digital transformation risks construct, cybersecurity threats received the highest concern rating (M = 3.90, over 70% of respondents rating it 4 or 5), followed closely by the risk of data loss (M = 3.85). These elevated perceptions are consistent with the institutional context following the 2022 cyberattack on Albanian government infrastructure. Notably, resistance to change was rated lowest among digital risks (M = 2.90), suggesting that staff do not perceive themselves as an obstacle to transformation, the barriers are perceived as structural rather than attitudinal.

Within the performance construct, the highest-rated statement in the entire questionnaire concerned the positive impact of effective risk management on institutional

performance (M = 4.54, 91.4% agreement), indicating an exceptionally strong awareness of the value of risk management. The contrast between this near-universal belief and the weak formal training infrastructure constitutes the central organizational paradox identified by the study. In the multiple-choice section, staff training was identified as the primary factor for developing risk culture by 84.5% of respondents, nearly double the second-ranked factor (internal control, 56.3%), followed by internal communication (47.9%) and leadership support (45.1%). Furthermore, 85.5% of respondents expressed the need for a clearer institutional risk management strategy to support digitalization, with an additional 13% responding 'partially', a combined consensus of 98.5%.

4.2. Correlation analysis

Pearson correlation analysis (Table 3) revealed a moderate-to-strong positive and statistically significant relationship between risk culture and institutional performance ($r = 0.536$, $p < 0.001$), providing initial support for H1. In contrast, digital transformation risks showed no significant correlation with performance ($r = -0.049$, $p = 0.685$). The weak negative correlation between the two independent variables ($r = -0.189$, $p = 0.115$) indicates that institutions perceiving stronger risk culture tend to perceive digital risks as slightly lower, an association consistent with a confidence effect, whereby employees in stronger risk cultures feel more capable of managing digital threats. Importantly, this low inter-predictor correlation also rules out multicollinearity concerns in the subsequent regression model.

Table 3 *– Pearson correlation matrix*

	X1	**X2**	**Y**
X1 Risk Culture	1		
X2 Digital Risks	−0.189	1	
Y Performance	0.536**	−0.049	1

*** p < 0.001. Source: Author's calculations.*

4.3. Regression analysis and hypothesis testing

Multiple linear regression was conducted with institutional performance as the dependent variable and risk culture and digital transformation risks as predictors. The overall model was statistically significant ($F(2, 68) = 13.88$, $p < 0.001$), explaining 29% of the variance in institutional performance ($R^2 = 0.290$; adjusted $R^2 = 0.269$). For organizational phenomena, where numerous external factors such as budget constraints, legislation, and political dynamics influence performance and cannot be controlled, this level of explained variance is considered substantively meaningful. Table 4 presents the regression coefficients.

Table 4 *– Multiple linear regression results (DV: Institutional Performance)*

Variable	**B**	**β**	**t**	**p**
Risk Culture (X1)	0.556	0.546	5.247	< 0.001
Digital Risks (X2)	0.048	0.054	0.514	0.609
$R^2 = 0.290$; Adjusted $R^2 = 0.269$; $F(2, 68) = 13.88$, $p < 0.001$				

Source: Author's calculations.

Risk culture emerged as the only statistically significant predictor of institutional performance ($\beta = 0.546$, $p < 0.001$): a one-unit increase in risk culture is associated with an average increase of 0.56 units in perceived performance, holding digital risks constant. Digital transformation risks showed no significant direct effect ($\beta = 0.054$, $p = 0.609$). Hypothesis H1 is therefore supported, while H2 is not supported.

Table 5 *– Regression diagnostic tests*

Assumption	Test	Result	Conclusion
Multicollinearity	VIF	1.04	Satisfied
Normality of residuals	Shapiro-Wilk	W = 0.988, p = 0.785	Satisfied
Homoscedasticity	Breusch-Pagan	p = 0.223	Satisfied
Independence of residuals	Durbin-Watson	DW = 1.73	Satisfied

Source: Author's calculations.

The validity of the regression model was confirmed through a complete set of diagnostic tests, presented in Table 5. All fundamental assumptions of the linear regression model — absence of multicollinearity, normality of residuals, homoscedasticity, and independence of residuals — are satisfied, lending robustness to the estimated coefficients.

5. Discussion

The central finding, risk culture as the sole significant predictor of institutional performance. is theoretically consistent with the COSO (2017) [4] framework, which positions risk culture as the foundational element determining whether formal risk management procedures are genuinely implemented or remain compliance documents. The result aligns with the systematic review of Horvey and Odei-Mensah (2023) [12] and is comparable in magnitude to the findings of Akhtar et al. (2025) [13] suggesting that the risk culture–performance relationship is robust across emerging economies with different institutional traditions. The mechanism appears to operate primarily through open communication: the relatively high rating of fear-free risk reporting reflects the 'just culture' principle advanced by the FSB (2014) [3], whereby psychological safety in reporting errors constitutes the precondition of proactive risk management, particularly critical in an institution managing irreplaceable national heritage.

The descriptive findings reveal an organizational paradox with significant practical implications. Employees overwhelmingly believe that risk management improves performance (M = 4.54, 91.4% agreement), yet formal training, the mechanism that converts belief into capability, is rated lowest in the entire instrument (M = 2.65). This contrast between high declared awareness and weak institutional practice exemplifies the 'knowing-doing gap' documented by Pfeffer and Sutton (2000) [15] and observed by Bracci et al. (2024) [11] in Italian and German public institutions. The explanation is structural: risk culture as an individual attitude forms more readily than risk culture as an institutionalized practice. Employees have absorbed the value of the concept, through international standards, audits, and legal reforms, but the institution has not yet built the formal mechanisms that convert this value into systematic daily behavior. Closing this gap constitutes the primary institutional challenge.

The absence of a significant direct effect of digital transformation risks on performance should not be misread as evidence that digital risks are unimportant. Two considerations explain the result. First, the instrument measures the perceived exposure to digital risks, not

the maturity of digitalization or the quality of its management; heightened risk awareness, particularly following the 2022 cyberattack, may itself reflect a functioning risk culture rather than a performance deficit. Second, the literature suggests that digital risks affect performance indirectly, filtered through the organizational culture that surrounds them [16]. Haug et al. (2023) [8] demonstrate that most digital initiatives fail for cultural rather than technical reasons, an argument consistent with the present finding that culture, not perceived technological risk, is the decisive variable. Testing this mediation model formally represents a natural direction for future research.

6. Conclusions

This study provides the first quantitative empirical evidence on the relationship between risk culture, digital transformation risks, and institutional performance in the Albanian public sector. The findings demonstrate that risk culture is the decisive determinant of perceived institutional performance, while digital risks exert no significant direct effect, indicating that digital transformation should be conceived as an organizational and managerial process rather than a purely technological initiative. The identified training gap, coupled with near-universal staff consensus on the need for a clearer risk management strategy, points to concrete policy priorities: mandatory and systematic risk management training, the institutionalization of risk reporting protocols, and the operationalization of Ministerial Order No. 4/2024 through specific implementation mechanisms.

The study contributes a validated measurement instrument and a replicable methodology for assessing risk culture in transition-economy public institutions. Its main limitations, the single-institution focus, cross-sectional design, and reliance on perceptual measures, define the agenda for future research: cross-institutional replication, longitudinal designs, and structural equation modeling to test the mediating role of risk culture between digital transformation and performance.

Disclaimer: The views expressed are solely those of the authors and do not represent any institutional position. Data were collected anonymously with prior institutional approval, exclusively for academic purposes, and are reported only in aggregate form.

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About the Project

Introduction

Economic and social development is crucial for better living standards in Europe. The challenge of climate change, with its' disastrous consequences for society, needs to be overcome, which is highly dependent on achieving the Millennium Goals, as well as the goals of Green and Digital transition. The use of digital technologies is crucial for achievement of the European Green Deal objectives and for reaching climate neutrality by 2050.

The innovative contribution of the project rests in European dimension in new and modernized academic study programmes and cerified LLL programmes devoted to twin green and digital transition, with introduction of innovative teaching methodologies.

Aim of the Project

The project aims to mainstream a holistic approach towards digitalization and green transition action, by creating effective, contemporary and sustainable education ecosystem.

The project builds up on the needs and the ambition to lead twin green and digital transition in HEIs in the Balkan Region. Within the project, HEIs will serve as the gear that connects different stakeholders for building sustainable and resilient communities in third countries not associated to the Programme in the Balkan Region. Fulfillment of this ambition has been carefully planned through the activities of the project.

Project Goals

The wider aim of the project is to improve regional capacities in implementing Green Deal and Digitalization Agenda goals within HE system, initiating an action towards circular economy, energy efficiency, renovation wave, fire safety, climate change adaptation, sustainability and disaster resilience and boosting digital skills in Building Information Modeling (BIM) and Geography Information System (GIS).

Specific project objectives

SO1: Establish Research and Education Centres (RECs) for green and digital transition within each WBC HEIs.

SO2: Raise awareness of staff and student community on the needs for green and digital skills within HEIs.

SO3: Promote green transition and digitalization culture within WBC HEIs.

SO4: Increase Synergies between academia and stakeholders for implementing joint initiatives for green transition and digitalization.

SO5: Reinforce networking and collaboration between staff and student communities of WBC and EU about digitalization and green transition actions.

The Project CV

Project title:
Boosting digital and green skills for a resilient and sustainable Western Balkan society

Acronym:
SKILL2SUSTAIN

Project number:
101178204-ERASMUS-EDU-2024-CBHE-STRAND-2

EU overarching priorities:
101178204-ERASMUS-EDU-2024-CBHE-STRAND-2

Regional priority areas:
Region 1 – Western Balkans

Geographical targets:
Multi-country project

Number of partners:
14

Number of countries:
7

Project duration:
01/04/2025 - 31/03/2028

Website:
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Project Partners

Co-funded by
the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.