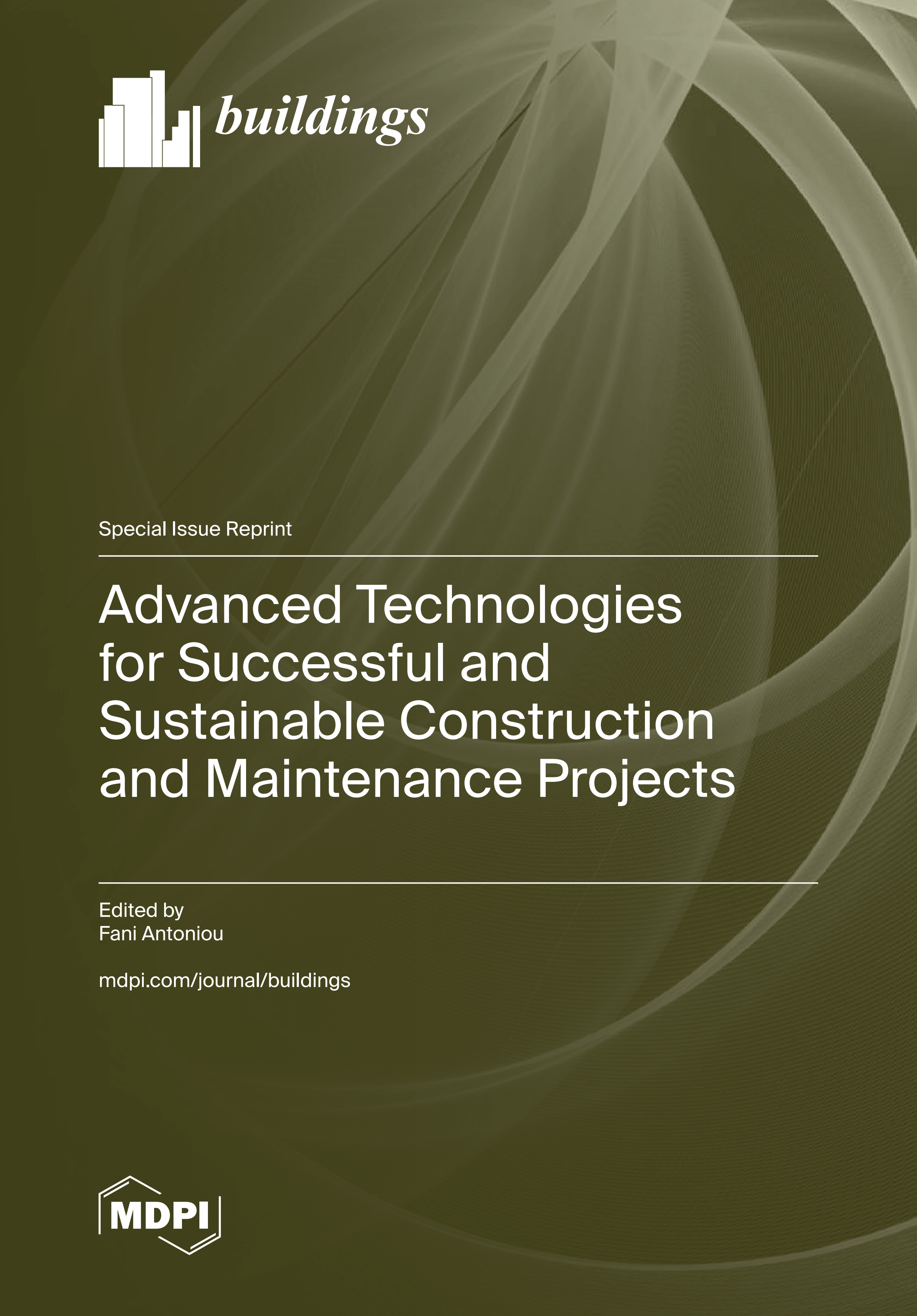

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Special Issue Reprint

Advanced Technologies for Successful and Sustainable Construction and Maintenance Projects

Edited by
Fani Antoniou

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Editor

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About the Editor

Fani Antoniou

Associate Professor Fani Antoniou holds a BEng (1994) in Civil Engineering and an MSc degree (1995) in Concrete Structures from Imperial College of Science Technology and Medicine, London, UK, and a PhD degree (2015) from the Aristotle University of Thessaloniki, Greece. In 2019, she progressed from Assistant Professor and is currently Associate Professor with the Department of Environmental Engineering, International Hellenic University, Thessaloniki, Greece. During her 22-year professional career in project management as a member of staff at Egnatia Odos S.A., she progressed from Project Planner to Project Engineer, to Project Manager, and finally International Projects Director. This experience gave her the opportunity to gain an in-depth knowledge of all phases, i.e., planning, design, land acquisition, environmental planning, tender and construction of major motorway projects for the construction of the 680 km Egnatia Motorway, its vertical axes and other smaller scale projects in the Aegean islands and in the general Balkan Area. Her research interests include construction managment, contract management, claim and risk management, as well as standardization and environmental sustainability in construction; she has published 37 articles in refereed journals and conference proceedings, as well as five chapters in scientific books. She has served as a reviewer for 15 international scientific journals and has served as a Guest Editor for two Special Issues in the MDPI journal *Buildings*.

Prof. Fani Antoniou is a member of the Technical Chamber of Greece, the Civil Engineering Society of Greece, European Federation of National Engineering Associations (FEANI) and IPMA Greece. She was the national representative in the Technical Committee "Performance of Transport Administrations" of the World Road Organization (PIARC) for two consecutive cycles in 2012–2015 and 2016–2019, and is a certified IPMA-Level D: PM Associate.

Preface

What constitutes a successful project? The recent debate surrounding this question refutes the well-known “iron triangle” and includes factors other than cost, time and quality, such as safety, environmental impact, and client and user satisfaction. Similarly, the environmental concerns of recent decades have led us to question what a sustainable project is. It is well known that the factors significantly contributing to climate change and global warming during construction are increased levels of carbon emissions and other atmospheric pollutants, the generation of waste and the consumption of natural resources. Therefore, construction projects that exert minimal detrimental effects on the environment can be considered sustainable. These can be projects that encompass environmentally friendly construction materials and techniques during their initial construction, as well as those that employ ecological retrofitting methods and materials during operation. Environmental protection issues augment the complexity of construction and maintenance projects, thus resulting in a greater need for advanced management and decision-making tools and techniques.

This Special Issue, entitled ‘Advanced Technologies for Successful and Sustainable Construction and Maintenance Projects’, is a collection of research articles that showcase recent academic and industrial developments in successful and sustainable project management throughrough the whole life cycle of construction projects. It addresses an extensive range of topics, including green construction retrofitting methods and materials; lean construction techniques; the application of robotics and automation in construction; new approaches to budget estimation using machine learning; multicriteria decision-making in design and construction; sustainable procurement and contract management; successful claim management; and the digital transformation of construction processes and organizations.

Authored by prominent academics and industry experts globally, the individual articles offer international perspectives on the subject matter. The authors leverage their experience and research to present practical insights and solutions to the challenges currently faced by construction and project management professionals.

This Special Issue is a useful resource for architects, engineers, contractors, project managers, and consultants in both the private and public sector, and serves as an excellent reference for students in the fields of architecture, civil engineering, and construction, offering them the latest information on the explored topics.

I extend my heartfelt gratitude to all the authors who contributed to this Special Issue and to the readers for their interest in these important topics.

Fani Antoniou
Editor

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Article

Human–Robot Collaboration and Lean Waste Elimination: Conceptual Analogies and Practical Synergies in Industrialized Construction

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Abstract: The presence of robots in industrial environments is a well-established reality in Industry 4.0 and an absolute necessity in Industry 5.0, with human–robot collaboration (HRC) at the paradigm's core. Concurrently, lean production remains one of the most influential production paradigms, which strives to eliminate Muda (non-value adding activities), Mura (unevenness), and Muri (people overburdening). However, what conceptual analogies and practical synergies are there between the lean production paradigm and HRC, and how do other Industry 4.0 technologies support this interaction? This research aims to answer this question in the context of industrialized construction, an ideal implementation field for both those approaches. The constructive research methodology is used to showcase, through evidence from the literature, that HRC aimed at the improvement of ergonomics, safety and efficiency has a positive contribution towards the elimination of all the lean wastes, while technologies like AR, VR, wearables, sensors, cloud computing, machine-learning techniques and simulation are crucially important for the intuitiveness of the collaboration between the human and the robotic partner. This is, to the author's best knowledge, the first attempt to systematically record the commonalities between Lean and HRC, thus enhancing the very limited construction literature related to HRC.

Keywords: Construction 4.0; constructive research; human–robot collaboration (HRC); Industry 4.0; Industry 5.0; industrialized construction; lean; offsite construction

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1. Introduction

The Fourth Industrial Revolution, also referred to as "Industry 4.0", is a novel concept describing a disruptive innovation era in which organizations and processes are connected based on technology and interconnected devices, with the potential to reshape the value delivery mechanisms for services and products across the whole value chain [1]. The presence of robots in industrial environments is a well-established reality in the Fourth Industrial Revolution. However, traditional robotic systems are not suitable for every task. Depending on the required balance between the cognitive knowledge that only humans can provide and the speed, stamina, and physical strength that robots have to offer, an ideal co-working combination between humans and robots can be achieved. This combination seeks for both contributors to make best use of their own strengths and is called human–robot collaboration (HRC) [2]. According to [3], collaborative robotics is an umbrella term that conveys the general idea that proximity between machines and humans goes beyond the bare delimitation of spaces (or material flows or sequences) and results in some useful task. Examples of the "usefulness" could include cognitive and ergonomic benefits for machinery operators, improved flexibility of the organization of workflows, higher quality, and traceability of operations. HRC is also a prominent concept in the already emerging vision of Industry 5.0 [4], which places the wellbeing of the industry worker at the center of the production process.

Construction has long been adapting and incorporating knowledge, practices, and tools from the manufacturing sector, including the lean production system, value engineering exercises, and the 'Design for' approach [5]. In this context, the disruptive innovation of Industry 4.0 has also introduced the construction sector into an intelligent construction era, widely reported as Construction 4.0. In this context, topics such as robotic construction, artificial intelligence, or virtual reality are starting to penetrate the construction industry, making the limits between different scientific fields increasingly diffuse and transforming construction into an interdisciplinary industry [6].

However, despite the concept's popularity in the manufacturing sector, the implementation of robots in traditional construction is objectively difficult: unlike the manufacturing assembly line, tasks in construction are rarely connected in a consecutive chain, there are no standard construction plans as each product is unique, the resources experience frequent spatial-temporal conflicts, the plans are dynamically changing with a high degree of uncertainty, and the environment is harsh, often typified by noise, dust, mud and increased physical risks [7]. Hence, refs. [8] and [9] report that the great majority of robotic technologies still remain at an experimental stage, which puts them in the category of 'challenging' or (distantly) 'achievable'. Kim [10] also find that the current level of robotic reasoning, perception, and adaptability is not sufficient for complex and dynamic construction environments. In this context, robots are still among the least researched and least used areas of the ongoing technological transformation in the industry, despite the wide-ranging real and perceived benefits [11,12].

Nevertheless, construction also presents a non-traditional dimension which eliminates all the above-described restrictions and is thoroughly appropriate for the use of robotic technologies: offsite or industrialized construction, also known as prefabrication or volumetric or modular construction, which refers to the manufacturing of larger building components in a factory and their transportation to the construction site for assembly. The typical modular manufacturing line consists of a series of between 18 and 24 workstations, while the shape of the line varies (straight, U, L, etc.). Major framed sub-assemblies such as floors and roofs are fed to the early main line locations by off-line feeder workstations. Primary construction activities typically range between 40 and 60 activities, with each activity being performed by an independent team of workers on the line [13]. In this controlled 'factory' environment, the potential uses for robots are much more natural (e.g., [14–16]) and include robotic manufacturing and handling of brickwork, concrete components and panels, wooden panels and steel components, and the robotic assembly and finishing of modular blocks. The reported benefits include reduced project duration, higher quality, and improved health and safety [12,17]. Furthermore, as a result of the massively parallel nature of modular construction activities, multiple activity teams are expected to be working in the same module at the same time, while the same team may also have to concurrently juggle between several modules. Additionally, some activities are constrained to a single location because of equipment availability or facility limitations, while others, particularly those in interior finish, are far more flexible. Moreover, a varying degree of complexity will mean that more complex activities may span multiple workstations [13]. The aforementioned complexities call for optimal layout and worker management in operations and waste avoidance [18].

In the above context, the principles and techniques of lean production are necessary for the full potential of productivity and quality associated to the controlled environment of industrialized construction to be achieved [19]. The lean production paradigm, which originated in car manufacturing and specifically in Toyota to eliminate unnecessary effort and complexity, human errors, and quality defects, has been synonymous with the industry's quest for improvement since the early 1990s [20]. Its counterpart in the field of construction, i.e., lean construction, is an amalgamation of a contextual production model emerging from attempts to solve construction-specific problems by means of generic lean production principles, methods, and tools [21]. Lean construction has been constantly attracting the interest of academics since the 1990s and still has a remarkably strong presence in the literature (e.g., [22–25]), which places it among the most influential paradigms in the construction management research. Despite the aforementioned popularity of the lean paradigm, its interactions with the use of robotic applications have so far received minimal attention in the construction management literature e.g., [26]. Furthermore, while HRC is in the core of the already emerging vision of Industry 5.0, there is no previous study systematically highlighting the analogies and synergies between HRC and lean construction towards waste elimination in the field of construction.

Therefore, this paper aimed to fill this gap and address the following questions:

- What commonalities are there between the lean production paradigm and HRC?
- How do HRC and lean construction interact in industrialized construction practices?
- How do other Industry 4.0 technologies support this interaction?

The remaining of the paper is organized as follows: Section 2 includes the theoretical background of this study, i.e., the basics of lean production and lean construction. Then, Section 3 presents a review of the literature related to the interaction of lean construction and Industry 4.0 technologies with special emphasis on robotics. Section 4 presents the methodology adopted and details the process and related choices step by step. Section 5 presents the literature evidence for demystifying the analogies between lean construction and HRC and shows how HRC interacts with waste generation mechanisms in the field of industrialized construction. Section 6 discusses the findings of this research in the context of the very limited relevant literature and particularly emphasizes the connections between the lean–HRC construct and the Industry 5.0 paradigm. Finally, Section 7 summarizes the conclusions of the research.

2. Theoretical Background

Lean production, also known as the Toyota Production System (TPS), means doing more with less—less time, less space, less human effort, less machinery, less material—while giving customers what they want, when they want it [27]. Lean production originated in the Japanese automotive industry in the 1950s and has been a tremendously influential paradigm conceptualized at various levels (continuous improvement philosophy, guiding principles, underlying practices/tools intended to achieve process improvement etc.). Its core target is to remove Muda (7 + 1 wastes), Muri (overburden), and Mura (unevenness/variability) from the processes. The seven Muda (wastes) were originally defined by Taiichi Ohno as transportation, (excess) inventory, motion, waiting, over-production, over-processing, and defects, and later were expanded to also include ‘skills’, or wasted human talent and ideas. However, eliminating Muda only represents one-third of the equation for making lean successful. The root problem is Mura (unevenness/variability), as variability can induce fluctuating and unexpected conditions, making objectives unstable and obscuring the means to achieve them [28,29]. Furthermore, variability causes people and machines overburdening (Muri), which in turn generates other waste [29]. In this context, lean thinking entails a continuous quest for stable and reliable processes, inextricably linked to standardization and standard work, which is one of the pillars of TPS. Furthermore, standard procedures are the only way for ensuring the processes’ consistency, quality, and continuous improvement. One must standardize, and thus stabilize the process, before being able to improve it [30]. In addition, standard work in lean represents the safest, easiest, and most effective way of doing the job that we currently know; it is inextricably linked with ergonomics and, for example, entails proper posture and hand position visual guidelines in the workstations [27].

Lean first emerged in the construction industry with Koskela’s discussion [31] on the value proposition of what he termed as “the new production philosophy”. In this work, Koskela summarized lean thinking for construction into eleven principles fully aligned to the manufacturing paradigm and introduced the concept of flow in construction. His perspective was that the various flows (i.e., previous work, space, crew, equipment, information, materials, and external conditions such as the weather) have been historically neglected in construction, and as a result, the sector demonstrates complex, uncertain, and confused flow processes with a significant amount of waste (non value-adding activities) [32,33]. This point is, according to [34], probably the most important contribution to the understanding of the construction process made by lean construction.

Around the same time, the report 'Rethinking Construction' by the UK's Construction Task Force, also widely referred to as 'the Egan Report' [35], popularized the "lean" label among construction professionals and positioned lean construction at the core of the industry's improvement initiatives [20]. Furthermore, the concept of 'Lean Thinking', the generic term used to describe application of the lean paradigm beyond manufacturing, was introduced by Womack and Jones in their bestselling book [36], which created conferences and a community around the topic of lean thinking. However, the ideas comprising the theoretical framework of lean thinking were a stark and to some extent imprecise simplification of the underlying theoretical framework of the Toyota Production System [37]. This resulted in the lean construction literature developing an 'interpretative flexibility' ranging from a narrow, operational project-level point of view focused on waste elimination to a holistic perspective of the industry with deep implications for the organizational practice, structure, supply chain management, and human resources [20]. As a result, some lean construction tools were uniquely developed for construction, while other manufacturing-based tools are being used in a different context/purpose compared to the original ones [38]. For instance, the Last Planner System for production control by Ballard [39] is a tool with significant industrial penetration—often considered synonymous with lean construction [20]—and has been exclusively developed in the context of lean construction. The same applies to the integrated project delivery approach by Matthews and Howell [40] as well as the target value delivery by Ballard [41], which are both inextricably linked to lean construction.

In this context, Bertelsen in [34] highlights the risk for lean production to be overextended to construction and further comments that industrialized construction should not be considered part of lean construction as it conceptually belongs to lean production. In [21], Koskela agrees with the previous view, noting that lean production is biased towards manufacturing in stable factory conditions by a permanent organization: a condition which traditional construction clearly does not fulfill. Ballard and Howell [42] also confirm this perspective, supporting the view that the part of construction that actually belongs to contemporary product manufacturing should be claimed from construction, which is a dynamic system, in contrast to prefabrication. Given the above, this research conceptually places itself in the context of lean production and not lean construction.

3. Literature Review

The interaction of Lean and Industry 4.0 paradigms is a very well-researched topic. The scale of the relevant research interest in the recent years is reflected in hundreds of relevant publications in the past few years, indicatively including analyses on conceptual similarities (e.g., [43–46]), systematic reviews of the relevant literature (e.g., [47–50]), studies on implementation barriers and challenges [51,52], and critical success factors [53]. Lean methods are generally considered as enablers for Industry 4.0 implementation, and conversely, Industry 4.0 as a means to realize the extended lean enterprise [54]. Mayr et al. [55] argue that Lean and Industry 4.0 complement each other on a conceptual level with the main points of convergence being the reduction of complexity, the holistic approach and the pivotal role of employees. Bokhorst et al. [56] reinforce the above points by concluding that lean principles constitute a necessary condition for the efficient application of smart technologies in every operational context, while the opposite is not an equally strong requirement.

In this context, terms like Lean 4.0, lean automation, smart lean manufacturing, and Lean Industry 4.0 have also emerged, and a vast part of the literature contemplates how the combined use of specific Industry 4.0 and lean tools can improve operational efficiency in the context of manufacturing. Nevertheless, as certain Industry 4.0 technologies will support lean better than others, a clear understanding of how technology can support lean efforts is needed, or else it may become a type of waste in its own right [57]. To address this, ref. [58] provided an extensive analysis of the interactions between 9 Industry 4.0 technologies and 14 lean manufacturing practices, and in this context, they identified 24 pairs with high synergistic relationships where cyber–physical systems (CPS) and Internet of Things (IoT) have the highest contribution. Other research in the same field includes, for example, the work by [59], who demonstrated how e-Kanbans supported by CPS-based real time data enable automatic orders and inventory level control. Furthermore, ref. [60] presented a production system which, assisted by the radio frequency identification (RFID) technology, can collect information about inventory, location, networking, and man–machine interfaces and enable digitized information sharing between shop floors and business departments. In addition, a similar mechanism based on sensors was proposed by [61] to recognize failures and automatically trigger fault-repair actions on other CPS. In the field of IoT and Cloud, ref. [62] proposed an IoT/IIoT based logistics model with Lean Six Sigma elements that enables the flow of real-time data to optimize processes, reduce costs, and resource consumption. Additionally, ref. [55] highlighted how cloud computing and machine-learning-based condition monitoring enhance product quality and total productive maintenance (TPM). Furthermore, ref. [63] discussed value-stream mapping (VSM) 4.0 as a new data-centered approach for achieving maximum waste reduction and appreciation of how information flows within the logistic processes. Similarly, ref. [64] supported the potential use of data analytics, simulation, and an RFID-supported user interface for improving the VSM with real-time result visualization.

In the field of industrialized construction, the adoption of automated processes has been associated with quality and productivity benefits resulting from reductions in time, cost, and human error in line with what the lean principles—inherent to offsite construction—seek to achieve [26,34]. In this context, industrialized construction provides the ideal environment, a factory, to fully apply lean principles and automation, with manufacturing robotic systems being particularly appropriate for use [26]. The relevance between lean and robotics is further confirmed by Pan and Pan [12], who investigated the determinants of adoption of robotics in offsite construction based on four case studies. Their findings reveal that a fair share of the factors emerging as critical for the adoption of robotics are closely relevant/directly affected by the implementation of lean principles. Specifically, they found that the adoption of robotics is mostly triggered by the perceived cost reduction and improvement in productivity, quality, accuracy, and safety, all of which are also among the targets of lean. Furthermore, they found that when the top management supports the vision of continuous improvement, which is synonymous to lean, then the adoption of robotics is easier. Similarly, the short delivery time requirement, which is part of any lean system's mission, was also placed in the list of factors driving robotics adoption. In addition, the complicated architectural and structural requirements of products were found to be potential barriers, meaning that simplification of the design, inherent to lean, is a critical factor for the successful use of robots in offsite construction. Finally, increased standardization, also inherent to lean, was listed among the factors positively influencing the adoption of robots in offsite construction. Therefore, it can be concluded that the use of robotics is far more likely to be successfully adopted in the context of a lean factory. Moreover, ref. [65] confirmed through an experimental process the beneficial impact of lean awareness in the efficient integration of a collaborative robot (also known as a "cobot") in the workstation, while [57] specifically showed how the use of Industry 4.0 technologies in manufacturing practice contributes to waste elimination, conceptualizing lean on the basis of the eight lean wastes. Furthermore, the interactions between lean principles and automation technologies in offsite construction, including robotic systems, were specifically investigated by [26] based on evidence in the literature. They found that robots can contribute to the reduction of variability and cycle times, can increase flexibility and standardization, and can also contribute to the system's flow and value. Therefore, it can be concluded that the adoption of robots also enhances and supports the successful implementation of the lean production paradigm.

4. Research Methodology

Methodologically, this study is constructive research, i.e., an applied study for defining and solving problems or improving existing systems or their performance, with the overall goal of adding to the existing body of knowledge [66]. The paper proposes a conceptual view of the interactions between two transformative paradigms, HRC and lean production, while the analogies and synergies evidenced by the experimental and practical literature are intended to guide and stimulate further research. The same approach has been previously implemented by Sacks et al. [67,68], who developed a framework for assessing the interconnections of lean and BIM. Da Rocha et al. [69] noted that the constructive research approach is commonly applied in the context of lean, since it can be used to develop solutions that aim to solve practical problems while also providing a theoretical contribution. AlSehaimi et al. [70] advocate the value of the constructive research approach to construction management as a non-traditional way to develop different models or tools that do not describe an existing reality, but on the contrary, help to create a new reality. They highlight the superiority of this underused research approach for bridging the gap between theory and practice compared to typical research methods such as surveys and questionnaires. The same need for constructive research to support construction project management has also been highlighted by [66], who demonstrated how practical and innovative solutions, grounded by valid research instruments, can be developed and applied in practice through the approach.

According to Kasanen et al. [71] constructive research is composed of six steps: (1) identification of the problem with theoretical and practical relevance, (2) understanding of the issue to be researched, usually through literature review and empirical studies, (3) construction of the solution in the form of a physical device or model, (4) implementation and test of the proposed solution, (5) connections between the solution and theoretical developments, and (6) analysis of the scope of applicability of the solution.

- Steps 1 and 2: finding a practical, relevant problem that has research potential and obtaining a general, comprehensive understanding of the topic.

According to [66], in the constructive approach, specifying the research problem entails making initial theoretical connections to the literature in the form of an analysis of the state of the art, as described in the previous sections.

Given that the lean production paradigm and the use of robots have a mutually beneficial influence on each other [12,26,57], this research puts into perspective the exact mechanisms of interactions between HRC and lean in the field of industrialized construction. For this purpose, lean was conceptualized on the basis of the three kinds of waste (Muda, Mura, Muri) that it strives to eliminate, while HRC is represented by its goals of efficiency, ergonomics, and safety [72]. This approach is in line with the original, remains the most succinct way to conceptualize lean [29], and expands the approach adopted by [57], who only considered Muda. Furthermore, compared to the lean framework adopted by [26], the approach of the current research has the additional advantage of revealing with greater clarity the conceptual analogies between lean's and HRC's main missions. As far as the 7 + 1 Muda wastes are concerned, this research focuses on the wastes of motion, waiting, over-processing, and underused human skills, which are most affected by the use of collaborative robots in the assembly line. The wastes of overproduction, inventory, and transportation have not been included, as they relate to organizational aspects that are not directly affected by the arrangement of the assembly line.

- Step 3: Designing a new construct

The constructive approach requires that the design of a construct should be based on an in-depth interpretation and synthesis of the contextual literature review and the practicalities of the problems [66]. Therefore, a comprehensive literature review/research synthesis was conducted. This is a data collection approach that involves activities such as identifying, recording, understanding, meaning-making, and transmitting information [73]. As asserted by [74], conducting a literature review is equivalent to conducting a research study, with the information that the literature reviewer collects representing the data. When the goal of the literature review is to inform primary research, as is the case in this study, the literature review represents an embedded study [73].

The strategies employed for the review of the literature were chosen to suit to the characteristics of the different themes involved. Specifically, for lean production, three books contemplating the Toyota Production System were selected to provide the conceptual basis used for this research, i.e., [27,29,30]. Books were preferred over journal publications, as journal papers from the field of construction tend to be flexibly interpreting the lean paradigm with a varying degree of adherence to its original manufacturing features, as previously explained.

As far as HRC and lean in offsite construction are concerned, relevant searches were conducted in Scopus with the use of suitable combinations of keywords such as Robotics, Human-Robot Collaboration, Lean, Lean 4.0, Industry 4.0, Construction 4.0, Ergonomics, Efficiency, Waste, Offsite Construction, Modular, Prefabrication, Precast, Industrialized construction. Various combinations of the above keywords were searched among titles, abstracts, and keywords of published papers, which returned thousands of relevant articles. To reduce the number of the articles, papers from out-of-scope fields/sources were excluded, while relevant sources from the construction research field were prioritized (e.g., Automation in Construction, ASCE Journal of Construction Engineering and Management, proceedings from conferences specifically devoted to automation and robotics in construction). Furthermore, the most recently published (after 2019) and most cited articles were reviewed with priority. This was a strategy to ensure that both the latest advancements and the most widely acknowledged studies were represented. Additionally, some research papers emerged from the literature reviews of other publications (backward snowball search) and from automatic suggestions made by the publishers' websites based on past citation trends. The review of the literature presented herein is by no means exhaustive, but it is sufficient to fulfill the purpose of this study, which was to shed light on the nature and practical side of the interactions accompanying the conceptual analogies between HRC and lean, as these emerge from the theoretical framework.

- Step 4: Demonstrating that the new construct works

According to [66], testing, justification, and validation can be empirical or theoretical, quantitative or qualitative, or both. This study further notes that the most appropriate method to test and improve a construct is via a pilot case study, but in most cases in the construction industry, this approach is not realistic because of the risks and costs involved. Hence, he suggests that an alternative triangulation-based approach be implemented, such as data source triangulation, in which the data are expected to remain the same in different contexts, investigator triangulation, in which the same phenomenon is examined by several investigators, and methodological triangulation, in which several approaches are utilized in order to increase confidence in the interpreted and synthesized concept. Kasanen et al. [71] postulate that the adequacy of the research is not affected by the practical aspect of validation, as the latter is difficult to achieve without the actual implementation of the construct. In this regard, ref. [57] confirmed that the maturity of the actual implementation of digital technologies—let alone HRC, which is mainly experimental—in lean organizations is not high enough for reliable quantitative research to be conducted. This is further confirmed by the quantitative data presented by [58], which makes clear that conceptual research is much more frequent than empirical research in the field of Industry 4.0 applications, while particularly in the field of robotics, empirical research is minimal. In this context, the current research draws on literature-based investigator and methodological triangulation to confirm that the pivotal goals of HRC (efficiency, ergonomics, and safety) have close analogies to the target of lean to eliminate Muda, Mura, and Muri, as presented in the following section. These analogies make it easier to trace the mechanisms of support between lean and HRC and track them with greater transparency by specifically linking HRC effects with the elimination of given wastes.

- Steps 5–6: Showing the connections between the solution and theoretical developments/examining the scope of applicability

Constructive research demands that the construct should add to the body of knowledge and that the theoretical contributions should be posited: its novelty and scope of application should be clearly stated [66]. The findings of this research contribute a theoretical view towards understanding the impact of HRC on lean waste generation mechanisms, which are are further discussed in connection to the Industry 4.0 paradigm and the emerging vision for Industry 5.0 and its goal to create human-centric, efficient, and sustainable industries. This is, to the author's best knowledge, the first study that specifically addresses the analogies and synergies between the lean paradigm and HRC in this context, and it also adds to the very limited literature addressing the interactions between automation and the lean paradigm in the field of construction.

5. Results and Analysis

This section presents the combined output of Steps 3 and 4 and describes the process of demystifying the interactions between lean and HRC in offsite construction.

5.1. Elimination of Muri: Enhancement of Ergonomics/Safety

Although industrialization relocates many field operations to a more controlled factory environment, the construction techniques involved in offsite construction share many similarities with those employed in traditional sites [75]. Most of the time, workers are compelled to repetitively perform the same activities; due to this, they may experience fatigue or repetitive strain injuries [76]. Forceful exertion and awkward body posture are also listed as common causes of work-related musculoskeletal disorders in industrialized construction, as process standardization intensifies muscular tension [77]. Gautam et al. [78] describe how the screwing of gypsum board panels is a repetitive and strenuous task, where the installer frequently experiences shoulder injuries resulting from holding the tools overhead and exerting force on screws. Another such example of a strenuous, repetitive task is that of drilling on concrete surfaces [79]. These examples show that ergonomic improvements are necessary in the field of industrial construction; both HRC and lean can respond to this need as described below.

The use of collaborative robotics for ergonomic purposes is a major solution for the prevention of injuries associated with repetitive and dangerous tasks and workplace redesign [72]. Gualtieri et al. [80] present an extensive review of the relevant literature. Furthermore, ref. [81] propose the use of virtual reality (VR) technology for the ergonomic comfort of collaborative workplace design solutions to be studied and optimized before their implementation in real workplaces. The use of VR is also relevant to cases where HRC needs a more intuitive approach, possibly involving frequent human intervention. One such case is when a robot is manipulating a large object (e.g., a building panel), as the moving object's trajectory needs to be assessed in terms of operator safety [82].

Similarly, the lean paradigm has inextricable links to ergonomics, as the latter is inherent to safety, quality, and standard work, which are all among lean's fundamental elements (Table 1). Poor safety is an unambiguous form of waste, as injuries are costly not only in terms of human suffering, but also in terms of compensation costs, lost time, and productivity [75]. Furthermore, previous studies have confirmed the positive contribution of lean to occupational accident reduction (e.g., [75,83]). In this context, there is no doubt that at the conceptual level, there is substantial overlap between the lean objective to eliminate Muri (overburdening people) and HRC's goal of ergonomic improvement (Table 1).

Table 1. Comparison of scope between lean's goal for Muri elimination and HRC's goal for improved ergonomics/safety.

Lean Objective: Elimination of Muri (Overburdening People) [27,30]	**HRC Objective: Improvement of Ergonomics/Safety [14,72]**
Muri is pushing a machine or person beyond natural limits and results in safety and quality problems.	Cobots are increasingly adopted in tasks involving repetitive motions to minimize MSDs, injuries provoked by poor ergonomics, reduce the operator's fatigue, and increment the overall level of comfort.
Muri means "hard to do" and can be caused by poor job design or ergonomics, poor part fit, inadequate tools or jigs, unclear specifications, etc.	Construction robots offer improved working conditions by removing workers from dangerous environments.
Clearly define the best way to perform each job action and the proper sequence. Poor ergonomic design negatively affects productivity and quality as well as safety.	

On the practical side, the contribution of HRC to construction ergonomics and overburdening avoidance has also been confirmed in the construction literature. Ikuma et al. [84] report substantial fatigue reduction following the involvement of a collaborative robot in the execution of overhead gypsum board screwing. Brosque et al. [79] reported a 98% reduction of strenuous work after the involvement of a mobile robot in the process of drilling on concrete surfaces. Furthermore, ref. [85] found that a glazing robot assisted by a human worker on a high-rise building achieved similar productivity to the workers, with a reduction in potential safety incidents.

This evidence leads to the conclusion that the involvement of collaborative robots in construction, potentially supported by technologies such as VR, can have a direct positive impact on the lean goal of Muri elimination. Similarly, repetitive/strenuous construction processes like screw driving, nut driving, part fitting, grinding, milling, and drilling, fall within HRC areas for future development [72], which demonstrates that there is ample space for the joint application of lean and HRC to benefit construction employee wellbeing.

5.2. Elimination of Mura: Enhancement of Efficiency

The goal of lean is to deliver the highest possible quality to the customer, at the lowest possible cost, with the shortest possible lead time. This is achieved through stable and repeatable yet flexible processes that represent the current standard, ensure product quality, and embed a culture of continuous improvement (Table 2). However, the concept of stability in physically demanding processes, such as construction, is challenging; human workers do not perform identical work cycles and can also get tired. On the other hand, a robot can always work with the same programmed efficiency [86]. For instance, ref. [79] compared robotic and manual drilling on the same site and confirmed the certainty of production rates with robot task reports. Furthermore, structured environments, such as off-site factories, present more favorable conditions for robot operation because the task trajectories are known and repeated and lack obstacles or human interference [14].

Table 2. Comparison of scope between lean's goal for Mura elimination and HRC's goal for improved efficiency.

Lean Objective: Elimination of Mura (Unevenness) [27,29,30]	HRC Objective: Enhancement of Efficiency [72]
Use stable, repeatable methods but try to build as much flexibility into the system as possible.	Efficiency results from simultaneously obtaining the shortest production time, high quality of products, accuracy, and optimal flexibility in the industrial process
Flexibility is needed for operators to easily adjust work cycles in response to demand changes.	
Standard work aims to create processes and procedures that are repeatable, reliable, and capable.	
Standardized work is key to building with quality and without defects and establishes the foundation for continuous improvement.	
The more that the production is leveled, the shorter the lead time and the less strain experienced by operators.	

Aside from stability, HRC can also enhance the flexibility of the system, in line with what the lean organizational paradigm postulates. Specifically, mobile robots can provide the opportunity to increase or decrease the number of workplaces and thus facilitate the creation by companies of configurations that change dynamically based on the current demand. The same mobile robots can also be used to transport all the components that the human workers need for each task [87]. Moreover, a mobile robot can be equipped with a cobot to create a collaborative mobile robot that can pick and transport components and then execute assembly tasks based on the same components [81]. Given that the goal of lean is to embed both stability and flexibility in production processes, the expedience of collaborative practices towards this is evident from the above. Furthermore, the fact that efficiency in the context of HRC is defined in relation to quality, short lead time, accuracy, and flexibility (Table 2) makes the conceptual analogy between the goals of Mura elimination (lean) and efficiency (HRC) even more evident.

Furthermore, lean tools like 5S (Sort, Straighten (orderliness), Shine (cleanliness), Standardize (create rules), Sustain (self-discipline)) and Total Productive Maintenance (TPM) can further support HRC's efficiency and success. Implementing 5S ensures that the work stand only has what is needed to carry out a pre-defined work task, everything has a specific place, and the work area is clean and inspected [86]. This is particularly important for HRC, because a robot performs a programmed sequence of movements and the tools and/or assembly parts need to be located in specific places for the robot to detect them. Similarly, human workers cannot do their work if they cannot find the components that they need [81,86]. Furthermore, the cleaning process (Shine) often acts as a form of inspection that exposes abnormal and pre-failure conditions that could hurt quality or cause machine failure [30]. Additionally, TPM including both proactive and preventive maintenance is extremely important in HRC, as it ensures that a robot is continuously ready for work [86]. Along the same lines, ref. [81] highlighted the importance of timely, regular, and thorough maintenance to ensure the continuity of operations, as well as the reliability and availability of the technologies, including mobile robots, cobots, AR, and VR devices. This reveals that there is extensive interaction and significant synergy potential between HRC and lean for achieving efficiency through the elimination of Mura.

5.3. Elimination of Muda (Motion, Waiting, Overprocessing): Enhancement of Efficiency

The wastes of Motion, Waiting, and Overprocessing represent time, effort, and resources spent with no value added, bad design of task sequences, and/or inefficient standard operating procedures [88]. However, HRC can improve, shorten, and simplify processes and optimize the sequence of tasks, which means that there is an evident opportunity for waste, as perceived by the lean paradigm, to be eliminated through the involvement of robots (Table 3). This is also confirmed in the construction literature, e.g., by [79], who in their comparison between manual and robotic drilling, report a 10% time reduction and elimination of a 12 h period for cleaning that was no longer required. Additionally, ref. [89] also reported a 20% time savings for brick construction when a robotic partner was involved. Furthermore, ref. [90] notes that robotic tools have the potential to eliminate waste from construction assembly processes that lead to low efficiency, such as surveying and calibration.

Table 3. Comparison of scope between lean's goal to eliminate overprocessing, waiting, and unnecessary motion and HRC's goal of improved efficiency.

Lean Objective: Elimination of Muda [30]		**HRC Objective: Enhancement of Efficiency [14,72]**
Unnecessary motion	Any non-value-adding motions such as looking for, reaching for, or stacking parts, tools, etc., and walking, are forms of waste.	Efficiency refers to the improvement of the entire industrial process or simplification of the operator's actions to complete a task by scheduling activities or via optimal planning of worker and robot actions Cobots are increasingly adopted to augment productivity by shortening a task time. Construction robots offer enhanced productivity compared to conventional labor.
Waiting	Waiting for a machine or the next processing step, tool, supply, part, etc., or lack of work because of stockouts, delays, equipment downtime etc., are forms of waste.	
Overprocessing	Overprocessing, i.e., undertaking unnecessary activities during a work process, is waste.	

Specifically, collaborative robots work on optimized trajectories that are designed to minimize the cycle time of a task and/or improve the quality and comfort of collaborative tasks. To this end, control systems like sensors are put in place to create new path configurations and allow for both the coordinated movement and operation of the cobot and the execution of a specific sequence of tasks timely and safely [81,91]. Furthermore, scheduling algorithms can be implemented to optimize HRC productivity and eliminate waiting times. A systematic overview of the relevant motion planning/scheduling and line balancing techniques, usually based on machine-learnfing applications such as optimization algorithms and the artificial neural networks, was conducted in [72]. As [2] notes, the learning mechanism is based on trial-and-error cycles that direct the embedded cost function towards decisions that return the lowest possible cost.

As far as the role of other Industry 4.0 technologies is concerned, the use of augmented reality (AR), VR, wearables, and sensors can significantly contribute to an optimally designed collaborative workplace and efficient assignment of tasks, taking advantage of the data collected from time-and-motion and ergonomic analyses. In addition, even in cases of limited information, simulation based on the assembly line's digital twin gives the opportunity to decision-makers to evaluate and compare the benefits of the technologies under investigation on a potentially infinite number of scenarios before the actual implementation [81].

5.4. Elimination of Muda (Defects): Enhancement of Efficiency

Defects have no place in the lean production paradigm; their elimination is jointly addressed by all lean tools, whose purpose is to deliver exactly what the customer wants at the time that they want it. These include standardized work, 5S, TPM, and creative devices that make it nearly impossible for an operator to make an error (error-proofing devices/poka-yoke) (Table 4). As [30] notes, the role of standardized work is pivotal in defect elimination: whenever a defect is discovered, the first question asked is “Was standardized work followed?” If the worker is following the standardized work protocol and the defects still occur, then the standards need to be modified.

Table 4. Comparison of scope between lean’s goal of defect elimination and HRC’s goal of improved efficiency.

Lean Objective: Elimination of Defects [27,30]	HRC Objective: Enhancement of Efficiency [16,72,86]
Production of defective parts mean wasteful handling, time, and effort.	Construction robots offer improved quality via precise control of functions and operations and by allowing real-time monitoring (and recording) of the operation. Cobots offer higher speed, quality, and pinpoint accuracy. HRC may additionally involve defects due to program or communication errors between the human and the robot.
5S is a series of activities for eliminating wastes that contribute to errors, defects, and injuries.	
Standardized work is key to building with quality and without defects and establishes the foundation for continuous improvement.	
When a poka-yoke detects an error, it should either shut down the machine or deliver a warning	
Poka-yokes reduce a worker’s physical and mental burden by eliminating the need to constantly check for the common errors that lead to defects.	

Furthermore, in both manufacturing and industrialized construction, there is no doubt that automation invariably has a substantial positive effect on efficiency and quality. Bruckmann et al. [92] confirmed that one of the most attractive aspects of automated production is the opportunity to reduce costs while at the same time achieving a constantly high production quality. Nevertheless, when HRC is added in the picture, there is an additional risk for defects due to miscommunication between the human and the robot related to perception, decision-making, execution of motions, predictability of actions, and clarity of intentions [88] (Table 4). This shows that in order for HRC to efficiently serve lean’s objective of defect elimination, the interaction intuitiveness between the human and the robotic partner must be optimized. This has also been highlighted by [93] as a condition for achieving efficiency in HRC.

To achieve this intuitiveness, ref. [94] claim that the presence and deployment of self-aware and self-healing sensors, machines, and workstations in assembly lines can prevent most problems and defects, while [72] presents four different state-of-the art modes (audio-based, touch-based, vision-based, and distance-based) that are often combined with VR/AR to reduce complexity and make interfaces more intuitive and readable by non-expert users. Stadnicka and Antonelli [86] see an analogy between poka-yoke solutions and sensors capable of detecting human movement and stopping the robot to avoid collisions. Dolgui et al. [81] note that the collection of information on these errors allows for the creation of databases for future reference and avoidance of similar situations, while [86] highlight the role of simulations towards this. Further, ref. [81] highlights the crucial importance of cloud computing for the efficient distribution of correct information and sharing across all the devices without physical connections. Sensorless solutions, often based on machine-learning techniques, have also been presented to overcome limitations induced by the presence of sensors (e.g., [95,96]).

This evidence shows that lean is the driving force in defect prevention, as the paradigm’s overarching aim is to eliminate waste from the customer’s perspective and its tools can support the efficient integration of the human and the robotic partner towards an efficient HRC. The human–robot interface that results from HRC is a source of potential risk for defects, but the technological advancements of Industry 4.0 can efficiently mitigate it. Evidently, the more that the autonomy of the robotic partner increases and approaches full autonomy, the more that the risk of defects resulting from the human–robot interface will diminish.

5.5. Elimination of Muda (Unused Employee Creativity): Enhancement of Efficiency

The success of the lean paradigm is deeply founded on the engagement of all team members, especially those on the front lines. Suggestion programs are a main involvement activity for directly channelling problem-solving ideas to management. Furthermore, the involvement of operators for non-value-adding activities that do not need their input is considered disrespectful to the human mind [27]. In this sense, the replacement of human operators with robots for the execution of mundane tasks is an obvious enhancement of the lean objective for employee engagement with and utilization for worthwhile tasks (Table 5).

Table 5. Comparison of scope between lean's goal of elimination of underused skills and HRC's goal of improved efficiency.

Lean Objective: Elimination of Underused Employee Skills [30]	HRC Objective: Enhancement of Efficiency [9,72]
Losing time, ideas, skills, improvements, and learning opportunities by not engaging or listening to employees are forms of waste. Maintain and improve the skills that enable the production of added value The true value of continuous improvement is in creating an atmosphere of continuous learning. Train exceptional individuals and teams to work within the corporate philosophy to achieve exceptional results	Cobots are designed to focus on repetitive activities so that the operator can focus on problem-solving tasks. Using imitation learning methods, skilled human workers continually train construction robots and work with them to supervise their performance during the task execution.

Furthermore, the role of training is fundamental to the lean paradigm. Training must be the backbone of the management approach: from the moment they are hired into a company, employees go through a similar training regimen of learning-by-doing [30]. One can aptly observe that this is the exact same training paradigm highlighted in [9] as the future of robot use in construction (Table 5). Specifically, imitation learning or learning from demonstration enables human workers to transition their work profiles to those of demonstrators/supervisors and continue to serve essential roles in the performance of construction work. The advantage of such human–robot collaboration is the transfer of knowledge, whereby the robots uses mechanisms such as neural networks to acquire experience in human behavior, learn, and finally apply this knowledge to the task. Finally, the Industry 4.0 era is inextricably linked to training, as the introduction of the new technologies may require new frameworks or guides to enable an understanding of their use [81].

The above show that HRC supports lean's aspiration to develop operator skills and learning and to support their engagement in problem-solving and knowledge transfer processes. Additionally, HRC further enhances a culture of continuous improvement, as the operation of the robotic partners largely depends on machine-learning techniques which are based on continuous training.

6. Discussion

The pivotal goals of HRC for efficiency, ergonomics, and safety have close analogies to the target of lean to eliminate Muda, Mura and Muri, as shown. Robotics, in general, have previously been reviewed in the context of lean construction by Brissi et al. [26] and were associated with the reduction of variability, shorter cycle times, reduced inventories, reduced changeover times, improved control of production through leveling and standardization, and enhanced production flow due to simplification, reliable technology, and guaranteed capability. These findings are largely congruent with this paper's description of the beneficial impact of HRC on the elimination of Mura (unevenness) and Muda (waste) of motion, waiting, over-processing, and defects. The main difference is the absence of the human factor found in the analysis in [26], meaning that there is no basis for confirming the findings related to Muri and human skill underuse. Similar research in the wider context of Industry 4.0 by Cifone et al. [57] also found that robots are among the most promising technologies for process improvement. They concluded that robotic applications contribute to the elimination of all Muda waste, with a greater effect on the prevention of defects, elimination of waiting times, optimization of motion, and avoidance of over-processing. As previously mentioned, this study also has a limited conceptual basis for lean that is restricted to Muda, with Muri and Mura being ignored. Similarly, from the ergonomic perspective alone, ref. [97] confirmed the positive impact of the collaborative workstation in terms of work performance and physical ergonomics in a manufacturing setting. They also highlighted the urgency of these work transformations for companies.

It should be noted though that lean production is a multi-layered paradigm that, along with its operational dimension, has an equally well-defined core of values where continuous improvement and respect for people stand out. In Toyota’s philosophy, the worker is the most valuable resource; their safety, continuous training, and morale are top priorities [30]. Bicheno and Holweg [29] also add courage, creativity, consensus, responsibility, understanding, trust, and teamwork as integral parts of the Toyota value system. Dennis [27] highlights the fact that employee engagement, especially of those on the front lines where the real work gets done, is the key to continuous improvement. As previously explained, this aspect of lean, mainly reflected in Muri waste (people overburdening) as well as in the human skill underuse (Muda waste), has been underrepresented in the literature contemplating the interactions between lean and Industry 4.0. This is a major omission, especially in the light of the emerging vision of Industry 5.0, whose goal is to create a human-centric, efficient, and sustainable industry, able to provide a safe and inclusive working environment while striving for continuous worker up-skilling. A core feature in the Industry 5.0 vision is a collaborative work paradigm with human and robots sharing the same workspace and working together towards a common goal [4,98,99]. In other words, the fundamental difference between Industry 4.0 and Industry 5.0 is the emergence of HRC. Muller [100] notes that Industry 5.0 constitutes a paradigm shift where the use of technologies is primarily focused on supporting worker abilities instead of replacing them and leading to safer, more inclusive, and more satisfying working environments. Furthermore, the European Commission recently supported the Industry 5.0 vision as a forward-looking exercise that complements and extends the existing Industry 4.0 paradigm and addresses its weaknesses in the field of social sustainability [101].

In this context, the conceptual basis chosen to describe the multifaceted paradigm of lean (Muda–Mura–Muri) has proven to be very appropriate, as is the selection of HRC among all the concepts associated with Industry 4.0, given that both of these features of the current study allow for the effective positioning of lean not only in the Industry 4.0 context, but also in the Industry 5.0 vision. Furthermore, it clearly emerges that any future attempt by the construction industry to shift to a theoretical Construction 5.0 paradigm will require the sector to effectively incorporate not only robots, but also HRC. This, however, seems to be a very distant prospect, as despite the growing interest in robotic technologies in construction [10], robots are still among the least researched and least used of the ongoing technological transformations in the construction industry [11,12].

7. Conclusions

In the era of Industry 4.0, collaborative robots offering a safe, ergonomic, and efficient work environment is an established reality for the industrial production process. In construction, however, and despite robotic applications representing a growing research trend, robots are still among the least researched and least used of the ongoing technological transformations in the industry. Given that traditional construction is fundamentally different from manufacturing, the use of robots is much more relevant to industrialized construction, where building components are individually designed, produced, and assembled in a controlled environment that is typically associated with quality and productivity gains. Furthermore, due to the complexity and high product standardization of offsite construction, the lean production paradigm is very well-placed to enhance operational efficiency while also creating beneficial synergies with Industry 4.0 technologies.

In this context, this study explored the interactions between HRC and lean in offsite construction and analyzed the conceptual analogies between lean's goal to eliminate people overburdening (Muri), unevenness (Mura), and waste (Muda) and HRC's goal to enhance ergonomics, safety, and efficiency. Furthermore, the following interactions were identified, using the constructive research approach, through evidence provided by the literature in both construction and manufacturing: First, HRC was found to provide a direct positive contribution to lean's objective of eliminating Muri (people overburdening) through the replacement of human operators with robots for strenuous, dangerous tasks. Second, a significant synergy potential between HRC and lean was established for the elimination of Mura (unevenness/variation) on the basis of the stability and flexibility afforded by their joint implementation. Third, HRC was found to provide a direct positive contribution to lean's objective of the elimination of motion, waiting, and over-processing waste through the employment of simulation exercises and optimization algorithms that allow for task shortening, simplification, and sequence optimization. Fourth, as far as the waste of defects is concerned, the human–robot HRC interface was identified as an additional source of potential error. The importance of technologies like AR, VR, wearables, sensors, and cloud computing was highlighted in this context to ensure the intuitiveness of the collaboration and avoidance of miscommunication. Finally, regarding the lean waste of underused human skills, it became clear how HRC contributes to its elimination by releasing human operators from mundane tasks and thus allowing human creativity to be used in training, problem-solving, and knowledge transfer processes. Furthermore, machine-learning techniques and related robot-training paradigms typifying efficient HRC, such as learning from demonstration, were established as factors able to embed the culture of continuous improvement that pervades the lean paradigm.

This is, to the best of the author's knowledge, the first study that specifically addresses the analogies and synergies between lean's three different kinds of wastes and HRC's goals and also adds to the very limited literature addressing the interactions between automation and the lean paradigm in the field of construction.

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Confined Spaces in Buildings with High Indoor Radon Concentration: A Case Study Analysis with the Application of Constructive Remediation Measures

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Abstract: Radon is an increasingly common concern, mainly when it is found indoors exposing the users of the space to radiation. As a gas, radon is an element produced due to uranium decay; it emanates naturally from soil and is considered by the World Health Organization as the second most common cause of lung cancer. Several methodologies are available for mitigating the indoor radon concentration, with distinct improvements and efficiencies that need to be proved with on-site testing. The case study here presented analyzes the effect of applying a barrier membrane, covering the pavement of a ground floor room located in a historic building with a high occupancy rate, on an abnormal radon concentration evidenced by experimental data. After the barrier membrane installation, a new long-term monitoring campaign (3 months) was carried out to assess indoor radon concentration. The obtained results showed that the barrier membrane lowered the indoor radon concentration by 90%. However, the radon exposure level remained higher than the recommended level to enable safe occupation and the regular use of space. Nevertheless, as the reduction in the radon concentration was very significant by the adoption of a barrier membrane, the combination of this technical solution with other mitigation methodologies, namely including the adoption of mechanical ventilation procedures, can become a very efficient solution for radon remediation, reducing the number of air changes per hour (ACH) from 30–60 to 4–6.

Keywords: indoor radon concentration; mitigation measures; historical buildings retrofitting; radon barrier membranes

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1. Introduction

Radon is a naturally occurring radioactive gas, with no color or smell; radon inhalation is the largest source of exposure to ionizing radiation in the population, contributing to more than 40% to the effective dose [1–4]. Prolonged exposure to indoor radon is the second leading cause of lung cancer, after tobacco, and the leading cause in non-smokers [5–7]. According to the literature, smokers and ex-smokers are at increased risk from the combined action of tobacco and radon [8]. However, there is no consistent evidence of a relationship between radon exposure and other types of cancer or disease [9–13]. Radon produces radioactive particles in the air people breathe, which are trapped in the airways and emit radiation that can cause lung damage, increasing the risk of lung cancer owing to prolonged exposures [14,15]. According to the World Health Organization (WHO), radon exposure is estimated to cause between 3% and 14% of lung cancers worldwide [16,17]. Across Europe, an estimated 9% of lung cancer deaths are due to radon exposure, accounting for around 2% of all cancer deaths [18,19].

Despite radon being everywhere, outside and inside buildings, certain areas are more prone to have high indoor radon levels [20,21]. Information about these areas can be obtained from radon susceptibility maps that are generally produced from wide-range surveys based on extensive radon gas monitoring campaigns that are an indicator of the level of susceptibility to indoor radon [22,23]. Based on the evidence, it is consensually assumed that the only way to know the radon concentration is by measuring it [24,25].

Radon penetrates easily into enclosed spaces, such as the building's rooms, and can reach high indoor concentrations under some circumstances; the high concentrations can be aggravated with the reduction of natural ventilation through new window frames and shutter boxes, which result from rehabilitation works to improve energy efficiency, and are associated with the use of less gas permeable wall facades [26,27]. Additionally, there are frequent small cracks in buildings' floors and walls, formed due to causes related to differential foundations settlements, movements of thermal origin, or adjustments between construction elements, as well as some specific openings intentionally created for the passage of pipes and cables, and buildings expansion joints. The size and frequency of these cracks or gaps also depend on the finishing coat and the quality of construction [28–32]. These cracks are the path for radon to enter the building driven by the difference between atmospheric pressure within, which is generally lower than the pressure in the underlying ground [33,34]. In contrast, the temperature differences between the interior of the building (generally warmer) and the ground (usually cooler) result in a phenomenon commonly known as the chimney effect, and are effects of wind action [35].

The exposure to indoor radon can be reduced by implementing preventive measures in the construction phase of new buildings or through corrective or remediation measures for existing buildings [36–38]. The present work aims to analyze the effectiveness of the application of a radon barrier membrane on the floor of a compartment located in a historic building used as an academic building of a university institution, situated in a region with a granitic geological substrate, in which concentrations of indoor radon tend to be high. This building has limitations concerning interventions involving changes to the architectural nature, such as installing ducts for mechanical ventilation or opening windows, shutters, or other connections to the outside to promote natural or forced ventilation. In this way, the evaluation of the effectiveness of passive solutions of a constructive nature, as is the case of barrier membranes hidden under the floor, assumes a decisive role since it contributes to the reduction of the impact of other measures when it continues to be necessary to combine several methodologies to reduce the concentration of indoor radon.

2. Materials and methods

2.1. Framework

The Escola Superior Agrária de Ponte de Lima (ESA IPVC) is one of the six organizational units of the Instituto Politécnico de Viana do Castelo. The ESA IPVC campus is in the municipality of Ponte de Lima, in the parish of Refóios do Lima, in the Alto Minho region (Figure 1).

The ESA IPVC campus occupies approximately 17 hectares, distributed among agricultural production areas, animal production areas, experimental orchards, vineyards, olive groves, greenhouses, and academic buildings. Among the academic buildings, the main building, known as the Mosteiro de Refóios do Lima, stands out, which is classified as an architectural heritage and a national monument. For this reason, both the building and its surroundings have a set of restrictions regarding interventions of an architectural nature, or even recovery and rehabilitation.

Although there are few traces of the medieval period, the origins of the monastery building mostly date back to the twelfth century [39].

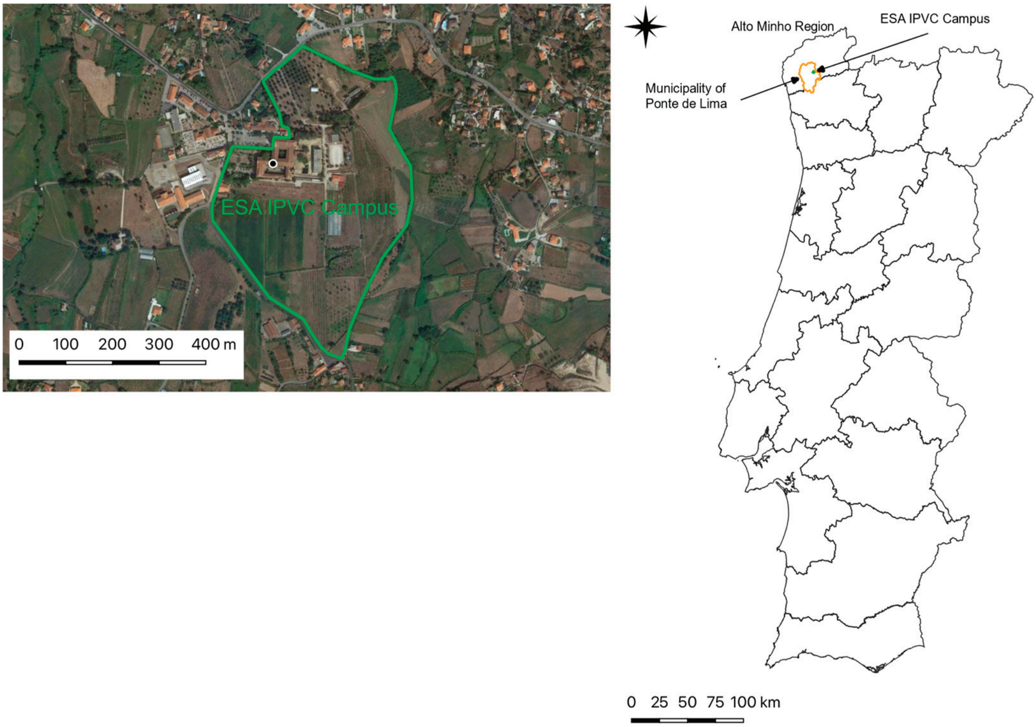

Figure 1. Location of the ESA IPVC campus. The dot on the building marks the position of the room where the indoor radon concentration measurements were taken.

However, the most brilliant construction took place between 1580 and 1810, with the beginning of the reconstruction of parts of the building, which should have been in ruins or at least extensively damaged. In 1770, the friars who inhabited the monastery were transferred to Mafra, by order of the Marquis of Pombal. The friars would eventually return to the monastery, where they continued to be involved in agricultural practice, which ended in 1834, with the extinction of religious orders in Portugal. After this period, the building passed into private ownership and began a long period of decay. In 1986, the building was acquired by the Municipality of Ponte de Lima, which began the recovery and rehabilitation of both the building, which was under the charge of the Architect Fernando Távora, and its surroundings, which were under the charge of the Landscape Architect Ilídio Alves Araújo. It was also during this period that the university institution was established in the building and the ESA IPVC campus was created. The main building is made up of two groups. The first group, from the second half of the 16th century, rests on primitive medieval foundations and includes a church, with the remaining structure built around a quadrangular central cloister. The second group, from the 18th century and later, has a set built around a patio, intended for agricultural tasks. The entire building is built in masonry, with granite serving as the main building material for the entire structure.

From a geological point of view, the region surrounding the ESA IPVC campus is made up of a relatively heterogeneous set of lithologies and structural features, as can be seen in Figure 2.

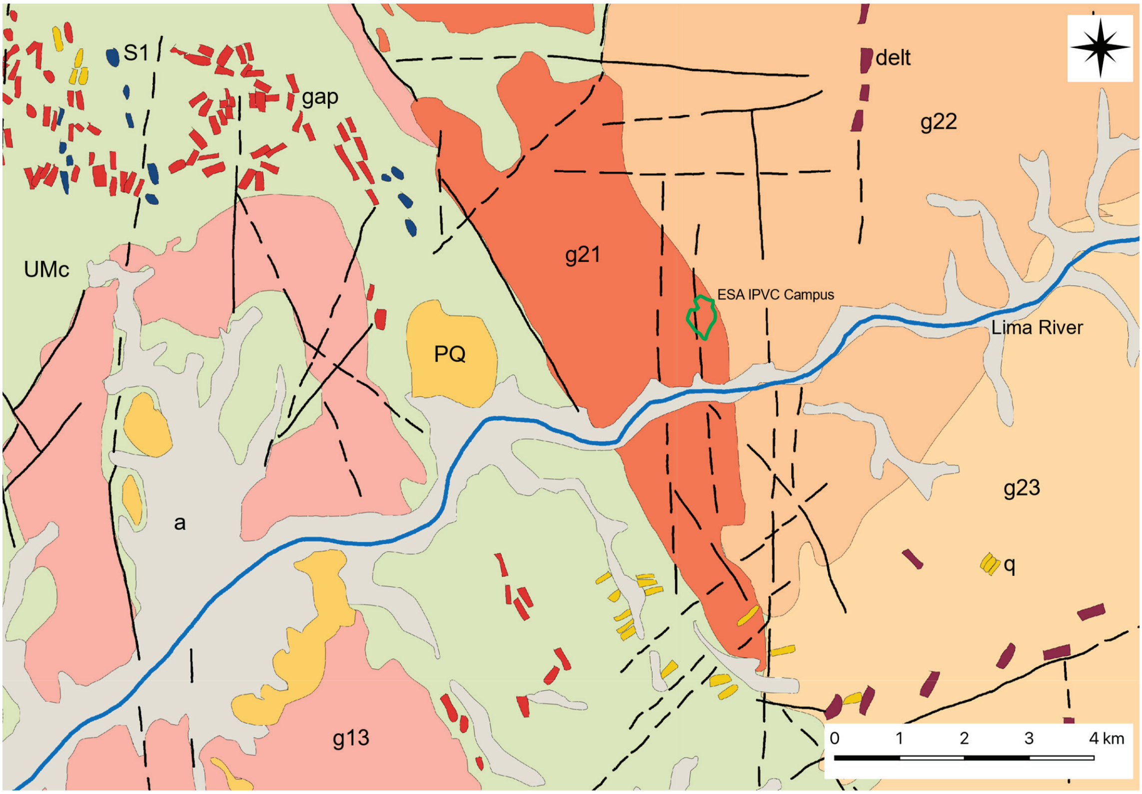

Figure 2. Geological framework of the Ponte de Lima region, where a–Fluvial and estuarine deposits, not current, accompany the channel of water courses, associated with current deposits; PQ–River and lake deposits are covered, or not, by periglacial solifluction deposits; g13–Medium-grained two-mica granite; g21–Porphyroid Granodiorite, biotitic, with highly developed megacrystals; g22–Porphyroid granite, coarse-grained, essentially biotitic; g23–Monzonitic granite, medium grain, porphyroid, with two micas, essentially biotitic; UMc–Pelites and psamites, skarns and vulcanites, black schists, gray quartzites and black schists with intercalations of ampelites and litites; S1–Phtanites, quartzites and black schists with intercalations of ampelites and litites; delt–Basic rocks; q–Quartz; and gap–Pegmatites and aplite-pegmatites (adapted from [40]).

The Lima River flows through this region, with an approximate orientation of ENE–WSW, and presents a predominance of granitoid rocks. The eastern sector presents lithologies associated with the Vigo-Régua ductile shear zone, where the clear separation caused by the structural accident (fault and probable fault), with NNW–SSE orientation, can be observed. In this eastern sector, extensive patches of coarse-grained porphyroid granite, essentially biotitic, occupy the northern part. Medium-grained, porphyroid, two-mica, essentially biotitic monzonitic granite occupies the southernmost part. In contact with the structural accident, there is also an important stain of biotitic porphyroid granodiorite, with highly developed megacrystals, completing the dominant group of syn-orogenic granites. In this eastern sector, there are also intrusions of masses and veins of quartz and basic rocks associated with structural accidents, but without reaching the frequency observed in the western sector of the area under analysis. The western sector is divided into two main groups, with medium-grained two-mica Hercynian granites occupying the central-south zone of this sector, surrounded by the parautochthonous Central Minho Unit, composed of pelites, psamites, and vulcanites, black schists, grey quartzites, and black schists with intercalations of ampelites and litites. The intrusion of quartz masses and veins, pegmatites, and aplite-pegmatites dots this western sector. There are also phthamites, quartzites, and black schists with intercalations of ampelites and litites from the group of carbonaceous schists of the Lower Silurian. The fluvial and lacustrine deposits covered or not, by periglacial solifluction deposits, from the early Quaternary and recent Pliocene, can be observed in some areas, mainly in the central-south region of the western sector, without occurring in the eastern sector. The fluvial and estuarine deposits (that do not accompany the channel of the rivers) are associated with current deposits from the Holocene to the actual period and are distributed by the two sectors, with a greater coverage in the western sector, associated with the enlargement of the bed of the river Lima.

Several structural accidents occur in the region under analysis, some of which are highlighted in Figure 3, with orientations tending to N–S and ENE–WSW, giving rise to blocks that move independently. These recent tectonic processes, probably of the Plio-Quaternary age, are of the compressive type and present with maximum stress in the E–W orientation.

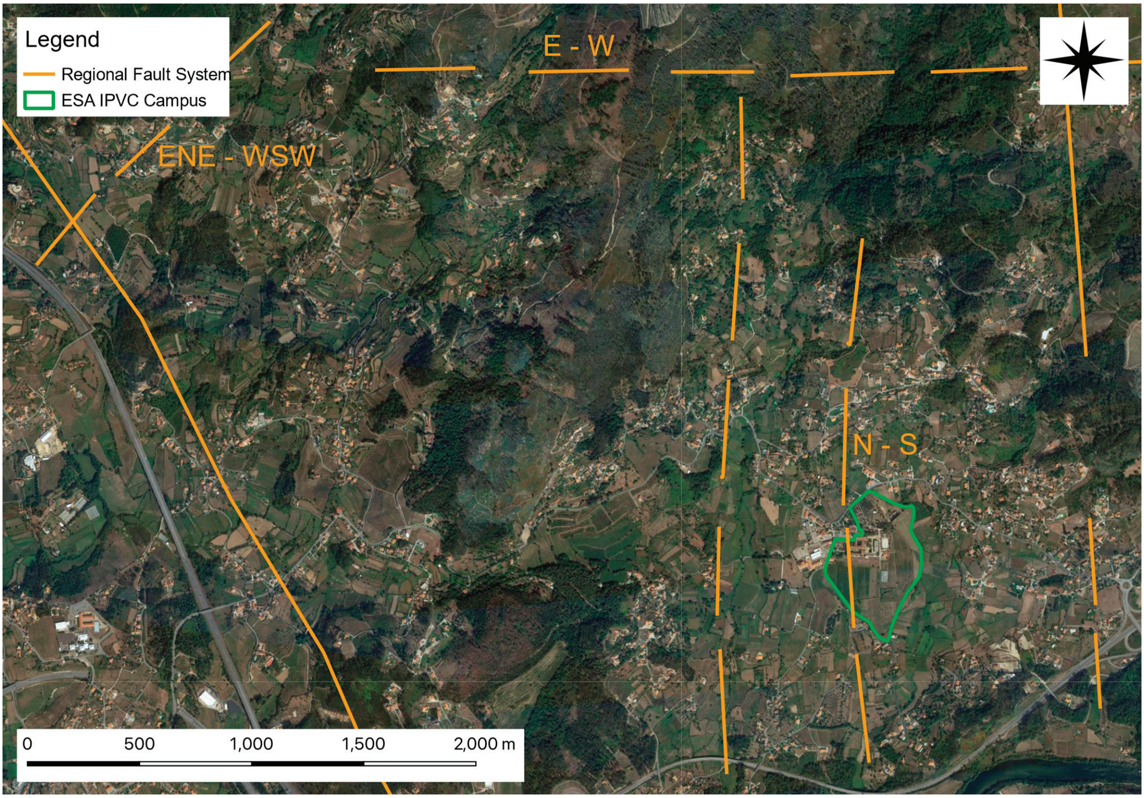

Figure 3. Scheme of the system of structural accidents that occur in the area under analysis, where fault systems and probable faults with N–S, ENE–WSW, and E–W orientation are identified (adapted from [40]).

This set of faults and probable faults, which create a mosaic of blocks with independent movements, together with the shear stress in the E–W direction cause a certain chaos in the structural set, which is extensively fractured. This situation may be the reason for the accumulation of indoor Rn; because if the lithological type that dominates the region is associated with a high structural discontinuity of rock massifs with high concentrations of uranium, the Rn gas can more easily and quickly flow to the surface and emanate into the interior of buildings or the outside air following the radioactive decay of this element.

2.2. Monitoring and Data Acquisition

Abnormal concentrations of indoor Rn were detected in certain places of the main academic building through periodic monitoring carried out in the short-term mode (7 days), to prevent and avoid the exposure of users and visitors to the building to excessive Rn concentrations. Following this periodic monitoring, certain compartments, located in cellars, presented anomalous values, reaching concentrations of more than 15,000 Bq·m^{-3} at certain peak moments. As these compartments were not being used for any specific purpose and did not have people inhabiting or visiting these components, it was decided to use these spaces as a testing area for the application of constructive remediation measures, such as the application of the barrier membranes.

In this sense, two campaigns were carried out to monitor the compartment. This compartment was located in the basement of the main academic building, with the floor (currently made of ceramic material) resting directly on the rock massif/ground. The compartment has an area of contact with the rocky substrate/soil of 12.6 m^2 and a volume of 34 m^3. Monitoring was performed using two AirThings Corentium Plus Radon Monitor probes and a model QRI, and the technical specifications are shown in Table 1.

Table 1. Technical specifications of the AirThings Corentium Plus Radon Monitor probes and the model QRI, used in the different phases of monitoring the indoor Rn concentration.

Rn sampling	Passive diffusion chamber
Detection method	Alpha spectrometry
Detector	1 silicon photodiode
Diffusion time constant	25 min
Measurement range	0–50,000 Bq.m^{-3}
Sampling rate	1 h
Operation environment	4 °C to 40 °C 5% RH to 85% RH non-condensing 50 kPa to 110 kPa
Temperature	0.336 °C resolution, ±1 °C accuracy
Humidity	0.5% RH resolution, ±4.5% accuracy
Barometric pressure	0.01 kPa resolution, ±1 kPa accuracy

Phase I monitoring was started on 13 March 2019 and was uninterruptedly performed until 13 June 2019, since the objective was to evaluate the Rn indoor concentration over a long-term period. After this period of monitoring, the Rn barrier membrane was applied. After completing this task, Phase II monitoring was carried out, which began on 3 September 2019 until 3 December 2019, according to the methodology that is outlined in Figure 4.

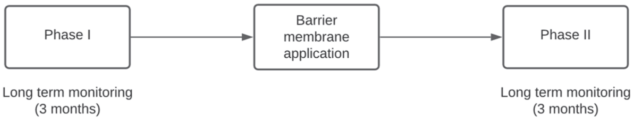

Figure 4. Temporal distribution of monitoring phases and other tasks.

3. Results and Discussion

The Rn concentration in the compartment was monitored using two probes, according to the procedure described above in Section 2.2. The measurement took place from 13 March 2019, starting at 5:23 pm, until 13 June 2019, ending at 4:23 pm, with 2181 measurements being obtained on each probe. Then, the data obtained in each of the probes were compared, to verify if there were significant differences between the two sets of data. For this purpose, the averages and variances of the two data groups were compared through the t-Student and F-Snedecor tests. In both situations, *p*-values greater than 0.5 were obtained, i.e., in both situations, the null hypothesis (H0) was not rejected, which means that there were no significant differences between the averages or variances of the two groups; the variances were supposedly equal. Thus, it was understood that it is possible to transform the two groups of data into one, by calculating the average of the two groups. The results obtained are summarized in Table 2.

Table 2. Summarized data obtained from the initial monitoring of Rn concentration, carried out from 13 March 2019 to 13 June 2019.

Monitoring Period	13 March 2019–13 June 2019
No. of measurements	2181
Average value	6479.6 Bq·m^{-3}
Standard deviation	3900.8 Bq·m^{-3}
Max. value	18,737.7 Bq·m^{-3}
Min. value	134.2 Bq·m^{-3}

As can be seen using the long-term data obtained (3 months), the results show extremely high values, ranging between 134.2 Bq·m^{-3} and 18,737.7 Bq·m^{-3}, indicating a high standard deviation (3900.8 Bq·m^{-3}) around the mean value (6479.6 Bq·m^{-3}). As the objective was to stabilize the concentration of Rn at values below 300 Bq·m^{-3}, we proceeded to distribute the obtained results in intervals of occurrence of 300 Bq·m^{-3} to be able to analyze the occurrence of the different values of Rn concentration throughout the analysis, as shown in Figure 5.

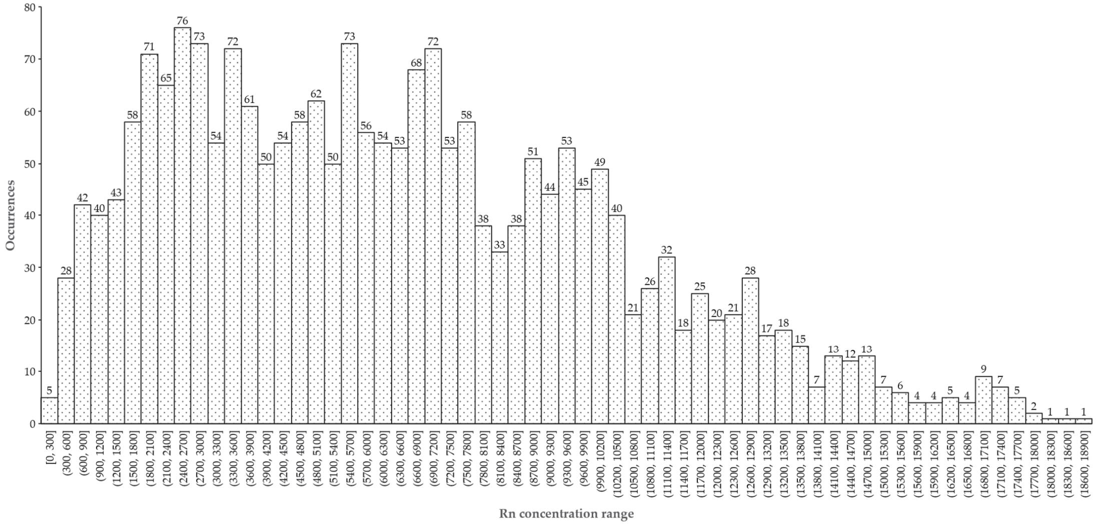

Figure 5. Distribution of results obtained in monitoring the Rn concentration by frequency intervals.

As can be seen from the distribution of the results, only five occurrences fall within the interval [0, 300] Bq·m^{-3}, corresponding to 0.2% of all measurements performed. In contrast, in the interval [300, 10,200] Bq·m^{-3}, there were 1891 occurrences, which correspond to 86.7% of the results obtained. In the interval [10,200, 18,900] Bq·m^{-3}, 285 results were included, corresponding to 13.1% of the total occurrences.

The results indicate the formation of a harmful environment in this space which, if intended for human use, would imply the need for 30–60 air renovations per hour (NR·h^{-1}) (Annex VI of Decree-Law No. 79/2006, of 4 April, available at https://files.dre.pt/1s/2006/04/067a00/

24162468.pdf, accessed on 10 October 2022). In other words, given that the compartment has a volume of 34 m^3, it would be necessary to extract 1020–2040 $m^3 \cdot h^{-1}$.

Given the high volume of air that would have to be renewed every hour, it was decided to use a constructive remediation solution, with the application of a barrier membrane. In this case, an Rn barrier membrane Monarflex RMB350, from Necoflex was applied. It is a membrane made from blends of virgin low-density polyethylene, with the specifications shown in Table 3.

Table 3. Technical specifications of Monarflex RMB350 (http://www.necoflex.is, accessed on 10 October 2022).

Elongation	19%
Tear resistance	405 N
Water vapor transmission	0.03 $g \cdot m^{-2} \cdot d^{-1}$
Color tone	Red (top side) and black (underside)
Thickness	0.35 mm

Figure 6 shows the initial state of the compartment floor and its appearance after the placement of the Rn barrier membrane. As can be seen in Figure 6b, it is important to finish at the base of the wall, to avoid points where Rn can cross owing to the bad placement of the mesh.


(**a**)
(**b**)

Figure 6. Placement of the Rn barrier membrane. (**a**) Floor before placing the barrier membrane; (**b**) Floor after placing the barrier membrane.

After placing the Rn barrier membrane, new monitoring was carried out. This monitoring was also carried out with two probes, according to the procedure described in Section 2.2, starting on 3 September 2019, at 5:49 pm, and ending on 3 December 2019, at 1:49 pm. In this monitoring campaign, in which two probes were also used, the data obtained were compared using the same methods used for the pre-application campaign of the barrier membrane. The results obtained with the t-Student and F-Snedecor tests were always higher than 0.5, not rejecting the null hypothesis (H0). Thus, there were no significant differences between the means of the two data groups, as well as between the presented variances, which are supposedly equal. These results validated the procedure of merging the two groups of data and using the average value.

Figure 7 shows the superposition of the results of monitoring the Rn concentration before and after the application of the barrier membrane.

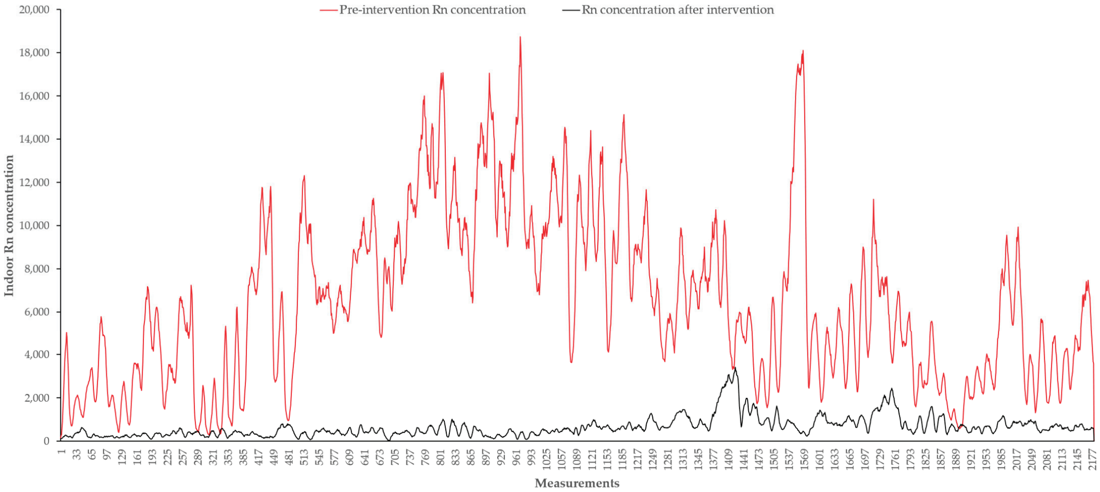

Figure 7. Results obtained before and after the application of the barrier membrane.

As can be seen, the difference between the results obtained in the two monitoring campaigns was significant. The results obtained in the post-application campaign are summarized in Table 4.

Table 4. Data obtained from monitoring the concentration of Rn after the application of the barrier membrane, carried out from 3 September 2019 to 3 September 2019.

Monitoring Period	3 September 2019–3 September 2019
No. of measurements	2181
Average value	634.4 Bq·m^{-3}
Standard deviation	475.0 Bq·m^{-3}
Max. value	3407.4 Bq·m^{-3}
Min. value	21.7 Bq·m^{-3}

Next, the results obtained were distributed by the classes of Rn concentration, for successive intervals of 300 Bq·m^{-3}, as shown in Figure 8.

The application of the barrier membrane caused a 90% reduction in the average values measured in the pre-intervention and post-intervention monitoring campaigns. However, as can be seen in the results presented in Figure 4, only 452 occurrences, corresponding to 20.7% of the measurements, were recorded in the interval [0, 300] Bq·m^{-3}. In other words, 79.3% of the measurements continued to record values above 300 Bq·m^{-3}. However, only 48 occurrences were recorded in the concentration range [2100, 3600] Bq·m^{-3}, corresponding to 2.2% of the total measurements, indicating the effectiveness of the barrier membrane in reducing the concentration of Rn. Thus, correction using a mechanical extraction system seems plausible considering the nature of the place (following the same legal document mentioned above), which could now be considered a cellar or a garage, with 4–6 NR·h^{-1}, and the flow to be extracted would be 136–204 m^3·h^{-1}.

Previous references have suggested the use of barrier membranes to reach an acceptable radon level, for example, the work presented by Rasmussen and Cornelius [41]. They used an adequate radon concentration of 100 Bq·m^{-3} in indoor air with several higher radon levels to evaluate the different radon barriers to prevent air penetration from the ground. In the current study, as the concentrations used were considerably lower, the barrier membranes used were almost entirely effective. The situation described in the current ESA IPVC case study is completely different because it is impossible to consider that the barrier membrane used can have a definitive effect on the indoor radon concentration of the compartment. As seen in the results presented in the previous section, the indoor radon concentration measured in the compartment after applying the barrier membrane dropped significantly. However, despite this decrease in the indoor radon concentration, it still presents values well above the limit that can be considered acceptable, as it continues to be above 300 $Bq \cdot m^{-3}$ during a significant part of the period in which the monitoring occurred.

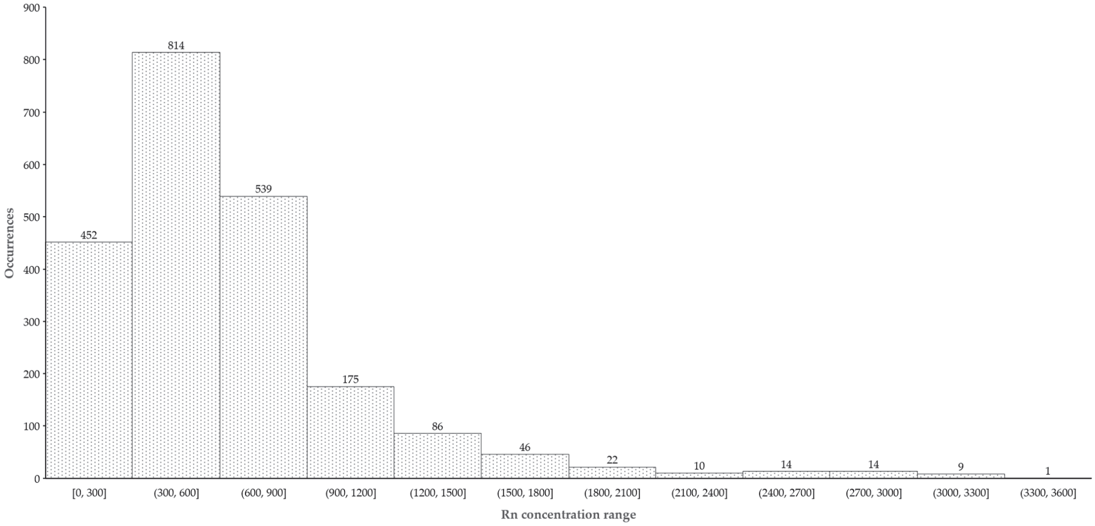

Figure 8. Distribution of the results obtained after monitoring the Rn concentration considering the frequency intervals.

Although in the current case study by ESA IPVC, the result is not entirely satisfactory, the situation may be related to other factors, as presented by Jelle et al. [42], including the fact that radon transport into buildings might be dominated by diffusion, pressure-driven flow, or something in between depending on the current values of the various parameters. These authors conclude that, from the results they obtained, most radon transport from the building ground to the indoor air is due to air leakage driven by pressure differences through the construction.

Thus, in the specific situation of the current ESA IPVC case study, the measured values continue to represent a problem. However, as demonstrated previously, with the application of the barrier membrane, the indoor radon concentration reached a result that can already be mitigated using active methods, namely, through mechanical ventilation. Despite this possibility and considering the conclusions of the study conducted by Jelle et al. [42], it is convenient to ensure that there is no circulation of radon gas through the building, as the pressure differences may be driving air with high concentrations of radon to the compartment. Thus, despite the high efficiency of the barrier membrane in blocking the transport of radon from the ground to the indoor air, it may be necessary to replicate the process on the entire floor of the building in direct contact with the ground for the measure to be fully efficient; this will help avoid the accumulation of high radon concentrations in other compartments, which later migrate and uniformize the concentration of radon throughout the floor.

4. Conclusions

Radon gas is a radioactive gas that naturally occurs owing to the decay of uranium. When released into the atmosphere, radon poses no threat whatsoever. However, when released into buildings, radon can become concentrated, posing a risk to occupants and users of the space who may be exposed to high radon concentrations. Several mitigation processes are already available to counteract the gas concentration inside buildings. The effectiveness of each of the existing measures depends significantly on the starting point and combining more than one solution is often necessary. As demonstrated by the case study analyzed in the present work, using barrier membranes, even in extreme situations with very high indoor radon concentrations, can significantly reduce radon concentration. Despite a reduction of approximately 90% of the initial concentration, the monitoring carried out after the barrier membrane application still shows a radon concentration above the recommended values considering the presence of users. However, using a mechanical ventilation system becomes much more feasible than using a barrier membrane considering that the number of air changes per hour is considerably lower. These issues are of increasing importance, because, in addition to the concern with the safety of building users, the concern with energy efficiency becomes increasingly urgent as a pillar of the management of service buildings, as is the case of the academic building of ESA IPVC.

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Data Availability Statement: The data are available upon request to the corresponding author.

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Conflicts of Interest: The authors declare no conflict of interest.

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High Indoor Rn Concentration Mitigation in a Heritage Building: Case Study Analysis of the Applied Constructive Measures

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Abstract: Indoor radon (Rn) concentration is pointed out by the World Health Organization (WHO) as the second leading cause of lung cancer. Adopting mitigation measures based on ventilation procedures is an effective solution for most cases. However, the occurrence of abnormal concentrations of indoor Rn in heritage buildings, where most interventions are restricted, may lead to alternative remediation techniques. In these cases, constructive mitigation measures, such as the use of barrier membranes on the floor or specific coating mortars on the walls, can be adequate solutions. In the current investigation, two constructive measures were applied and analyzed sequentially. The preliminary long-term monitoring campaign registered extremely high indoor Rn concentration measurements. The application of a barrier membrane covering the floor of the test compartment allowed a 90% reduction in the average Rn concentration, but it nevertheless remained substantially above the recommended value of 300 $Bq \cdot m^{-3}$. Subsequently, a coating mortar was applied on the walls. The combined measures contributed to a total reduction of 94% in the average indoor Rn concentration, which remains slightly above the recommended exposure limit. Despite the verified reduction and the apparent effectiveness of the measures, it is still necessary to carry out more monitoring campaigns to test their general applicability.

Keywords: indoor Rn concentration; constructive mitigation measures; Rn barrier membrane; anti-Rn slurry coating

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1. Introduction

The significance of buildings conservation and rehabilitation assumes growing importance in the valuation of built heritage [1]. This importance covers not only a theoretical and methodological approach but also assuming a practical and organizational focus [2]. The buildings' improvement that results from retrofitting must respect a multiplicity of values ranging from those of a cultural, historical, and social scope to those of an environmental and safety scope [3]. New issues and challenges emerge concerning intervention in buildings, which include a wide range of typologies, needs, problems, and values—tangible and intangible—and the development of norms, materials, diagnostic instruments, study methods and practices of intervention, management, and maintenance [4]. Furthermore, on the one hand, the ways in which built heritage is perceived by societies have evolved throughout time not only because of the gradual and active involvement of communities as an interested party but also due to the demand for a transformation that enables the adaptation to new uses, functions, and requirements [5]. On the other hand, the current socioeconomic pressure on historical heritage, associated above all with the progressive climate emergency and environmental crisis, brings added challenges around the care to be taken through the act of conserving and rehabilitating [6,7].

Based on this approach, a classified building of public interest housing a higher education institution was subject to a retrofitting process to promote Rn mitigation. Under this program, a technical room on the ground floor of the building was intervened in three evolutive stages: (i) in the first stage, the pavement was fully covered with a Rn protection membrane; (ii) in the second stage, the surrounding walls were coated with a Rn protection mortar; (iii) in a third stage, the cracks of doors and windows were sealed to prevent Rn migration from other adjacent rooms. This compartment works as a pilot to test Rn remediation solutions so that the most successful can be incorporated into the entire building.

Odorless, colorless, and tasteless, Rn is a radioactive gas formed by the decay of uranium, which is an unstable element, causing through this process the release of energy [8]. Rn is found in soil and granite-based building materials, and in Portugal, it is more common to find it in the northern areas and on the borders with Spain [9]. Rn is the greatest natural source of exposure of populations to ionizing radiation, and if this happens for prolonged periods, it can become a public health problem [10,11]. According to the World Health Organization (WHO), it is, in many countries, the second leading cause of lung cancer (after tobacco) [12–16]. Although it can be found on kitchen worktops, fireplace stones, concrete, and mortars incorporating granite aggregates, Rn enters the buildings through pipes or directly from the ground and walls of support and through cracks, gaps, and fissures [17]. In this case, the remediation procedures must involve not only covering all cracks and holes in pavements and walls in contact with the foundation soil but also allowing good air circulation daily by employing natural or mechanical ventilation [18–23].

To assess Rn risk exposure, rooms are generally classified according to the type of construction, with emphasis on the type of foundation or room elements in contact with the ground (basements totally or partially installed underground or ground floors concrete slabs laid directly on the ground) or floors raised above the ground over a space. The room classification is important since the Rn concentration is usually higher in rooms located close to the foundation soil, mainly in basements generally used as cellars, pantries, technical rooms, storerooms, and garages, that is, as spaces of less permanent or frequent occupancy. To evaluate Rn risk exposure, Decree-Law No. 108/2018 establishes in Portugal the legal regime for radiological protection, transposing Directive 2013/59/Euratom, which sets basic safety standards relating to protection against the dangers resulting from exposure to ionizing radiation. Namely, this applies to human activities in the presence of natural radiation sources leading to a significant increase in the exposure of workers or the population, to sources that lead to the presence of Rn inside buildings, external exposure to radiation from construction materials, and situations of prolonged exposure to this gas. With the entry into force of Decree-Law No. 108/2018, which took place on 2 April 2019, the Portuguese Environment Agency (APA) became the new competent authority in this matter.

In this way, the main objective of this research is to assess the result of the implementation of a set of Rn mitigation measures designed to remediate extraordinarily high indoor Rn levels in an ancient building, listed as National Architectural Patrimony, in a scenario where the use of mechanical ventilation systems for Rn mitigation is strongly constrained. For that, a room specifically selected on the ground floor of a building of heritage and architectural interest working as a school building was subject to a comprehensive indoor Rn assessment in three different stages by using long-term Rn tests over 3 months: (i) the first stage, including measurements performed before the implementation of any Rn mitigation measure; (ii) a second stage in which the in situ measurements were implemented after the pavement floor was covered by a Rn membrane barrier; (iii) and a third state comprehending measurements after the adoption of a wall cladding made of a Rn-proof mortar. The main purpose of this study is to analyze the impact of the adopted mitigation measures on indoor Rn concentration in a building located in the Alto Minho region northwest of Portugal, in which Rn monitors were installed on the ground floor. The monitored room is laid on a granite substratum bedrock, and the pavements, walls, and partitions are mainly built also with granite elements materials.

2. Literature Review

The assessment of the health status of buildings necessarily includes the quantification of air quality parameters, which include the assessment of indoor Rn concentration since this radioactive element has been classified as harmful to health. Despite being generally associated with granite-type geological substrates, thus enhancing the probability of high indoor concentrations occurring in buildings, its presence can also occur in other types of substrates. Soils and rocks with lower emanation potential can also lead to high concentrations of indoor Rn, especially if combined with building characteristics that are conducive to the concentration of the gas inside, namely, for example, due to the lack of ventilation that promotes renovation of air or that presents an architectural configuration that works as a trap for the retention of the gas inside. Rizo-Maestre and Echarri-Iribarren [24], in a study carried out in Alicante (Spain), analyzed the indoor Rn concentration in underground buildings implanted in clayey soils, demonstrating that despite the Rn emanation potential of these soils being considerably lower than that of that what happens in granitic soils, the structure of the building enhances the accumulation of Rn in its interior. In this study, the authors identified Rn concentrations in the building selected for the study as five times higher than those registered in other similar buildings, demonstrating that the constructive typology of the buildings also plays a determining role in the concentration of indoor Rn.

Despite the growing interest in the topic, the number of works available on mitigation measures cannot be considered abundant. In fact, searches in the main bibliographic databases, such as *SCOPUS* or the *Web of Science*, mainly present works related to assessment. Studies related to mitigation actions, such as those presented by Sicilia et al. [25], in which the authors address the theme of transport, concentration patterns, and Rn mitigation techniques applied to confined spaces, tend to present solutions related to the ventilation of indoor spaces. In this specific case, the authors studied the effects of pressurizing and depressurizing the compartments on the Rn concentration, demonstrating that the introduction of fresh air diluted the Rn concentration, and the slight increase in the pressure reduced the entry of gas by the advection mechanism. The authors concluded that the depressurization technique was the least effective mitigation technique since this method contributes to the negative pressure created in the compartment facilitating the emanation of Rn from the soil. As a corollary of this study, the authors recommend that before applying any mitigation technique, it is necessary to study the space to be remediated and the possible impact on neighboring spaces, which is in the same line of several other authors [26–33].

The authors point to similar recommendations, continually reinforcing the need to ventilate spaces as a corrective measure so that, as recommended by Rizo-Maestre and Echarri-Iribarren [34], it is necessary to also account for the areas considered to have a low presence of Rn gas to achieve healthy constructions. These authors, who studied the high risk of low indoor air quality in poorly ventilated buildings, reinforced once again the need to establish procedures for the ventilation of spaces, especially in cases where, despite the geological substrate not being potentially rich in Rn, there are still conditions that enhance the accumulation of gas. Along the same lines, Martin Sánchez and Nuevo [35], in the study carried out on actions for remediation in areas with a large concentration of indoor Rn, analyzed working places in the region of Extremadura (Spain). As corrective measures, ventilation protocols were indicated as well as other measures, such as changing the location of the workstation or limiting the time spent in the most exposed places. Furthermore, as also concluded by Rizo-Maestre and Echarri-Iribarren [36], they reinforced the role of the constructive typology as one of the factors to be considered for the concentration of indoor Rn.

As seen from the available works, the focus has been on mitigation measures directed toward the ventilation of spaces. One of the first references reporting the use of barrier membranes is found in the study presented by Groves-Kirby et al. [37], where the authors compared the concentration of indoor Rn in houses with and without the placement of barrier membranes. Based on the obtained results, the authors recommended that mandatory testing be introduced for all new dwellings in Rn-affected areas. In the following years, other authors, such as Cosma et al. [38], Muñoz et al. [39], Khan et al. [40], Burghele et al. [41], Gong et al. [42], Gaskin et al. [43], and Sainz et al. [33], presented case studies of the application of barrier membranes, including comparative analyses between different types of materials. Concerning anti-Rn mortars, most studies were found to refer to their existence, but no case studies were found where their effectiveness was analyzed. No study investigated the use of two different constructive mitigation measures, justifying the novelty of the case study analyzed in this work.

3. Materials and Methods

3.1. Framework

To carry out this study, we selected a historic building called Mosteiro de Refóios do Lima, located in the parish of Refóios do Lima, municipality of Ponte de Lima, in the Alto Minho region (northern Portugal). The building, currently occupied by the Escola Superior Agrária of the Polytechnic Institute of Viana do Castelo (ESA IPVC), is classified as a national monument of architectural interest. Figure 1 shows the location of the building as well as its general overview. In its framework, the university campus of ESA IPVC has a total area of 17 hectares distributed by the main academic building, where the present study was carried out, as well as agricultural annexes, university residences, and agricultural production areas for animal exploitation. The main academic building, which dates to the 12th century, but has undergone various interventions and renovations over time and was built essentially in masonry using granite stone exploited in the abundant quarries in the region. The entire region is rich in several types of granitic rocks, with lithology dominating the region.

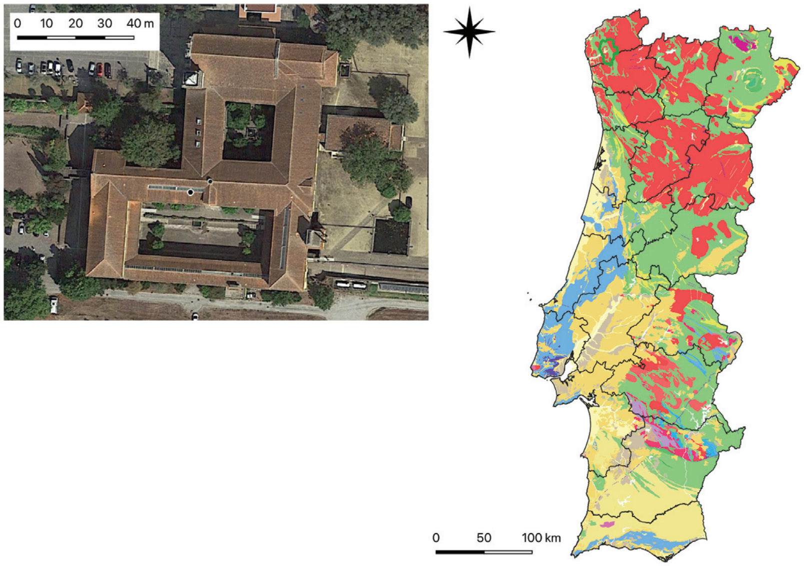

Figure 1. Location of the ESA IPVC academic building. The green circle shows the location of the municipality of Ponte de Lima. The simplified geological representation of Portugal shows the distribution of the granitic rocks (red) and the associated metamorphic rocks (light green) usually associated with high indoor Rn potential. The black dot in the main building highlights the position of the room where the indoor Rn concentration measurements were taken.

In fact, in the region, there is an abundance of granite-type lithologies, namely, two-mica granites with feldspar megacrystals (locally known as "horse tooth"), which are deeply fractured by a system of faults with N-S orientation. This intense fracture of the rocks must be the origin of the high concentrations of Rn that are verified in the region, where the Rn emanation potential is very significant, greatly contributing to the high concentrations of indoor Rn [44,45]. The original builders implemented the structure respecting the topography of the land so that it evolves as in terraces along the slope. The main entrance is at a level that accompanies the entire N exposure, while the opposite side, exposed to S, is at a lower level by about 6 m, culminating in an interior patio flanked by buildings now for educational use but which once functioned as storage rooms. Figure 2 shows a section (A,B) with N-S direction. It is schematically demonstrated that the compartment selected for carrying out the present monitoring study of the indoor Rn concentration is in direct contact with the geological substrate (soil and rock) on the pavement and partially on the walls. View (A) refers to the main entrance of the building, exposed to the N, and view (B) presents the opposite facade, exposed to the S, where it is visible the difference in level between Floor-1 and the inner patio with a difference of six meters in the level.

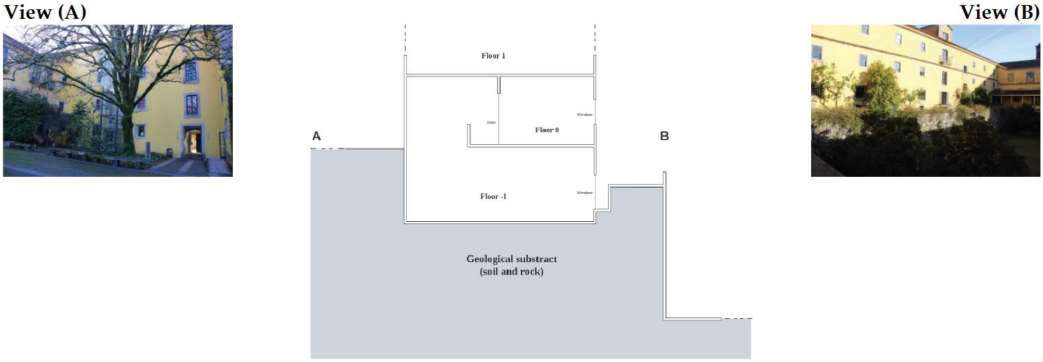

Figure 2. Section of the implantation of the building on the geological substratum. Views from each side of the main academic building of ESA IPVC, where view (**A**) refers to the main entrance of the building, exposed to the N, and view (**B**) presents the opposite facade, exposed to the S, where it is visible the difference of six meters between Floor -1 and the inner patio.

3.2. Monitoring and Data Acquisition

Indoor Rn concentration monitoring was carried out in a compartment located on Floor-1 of the ESA IPVC academic building. The compartment in question is located in the SW corner of the building, with the floor laid over the geological substrate and at least two walls in contact with the geological substrate. The compartment, which currently does not have any use involving the presence of people, may have been used as a storage room in the past and occupies an area of 12.6 m^2 and a volume of 34 m^3. Monitoring occurred between 13 March 2019 and 16 November 2021, as shown in Figure 3. Figure 4 shows the sequence of works carried out in the different phases.

Monitoring took place in three phases, which correspond to the indoor Rn concentration measurement campaigns, interspersed with the tasks of placing constructive measures for Rn migration, namely the application of the barrier membrane and the mortar. Phase II comprises an additional monitoring campaign to ascertain the impact of air circulation through the door that separates the compartment from the rest of Floor-1. Thus, Phase I corresponds to the preliminary assessment with the subsequent application of the barrier membrane. Phase II comprises the indoor Rn concentration assessment, followed by sealing the compartment door and a new indoor Rn concentration assessment campaign. Phase III begins with applying the coating mortar on the compartment walls and the subsequent assessment of the indoor Rn concentration. For the assessment of the indoor

Rn concentration, two AirThings Corentium Plus Rn Monitor probes, model QRI, were used. The two identical probes were used in all monitoring stages, so it is assumed that the error associated with the measurements is always similar. Table 1 presents the technical specifications of the probes used in the monitoring campaigns.

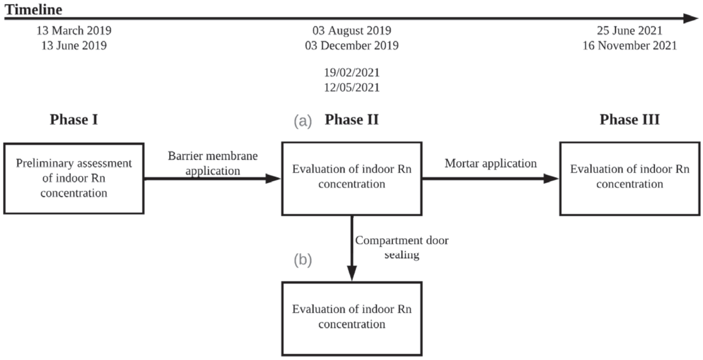

Figure 3. Organization of the works carried out during the monitoring process of the indoor Rn concentration in the compartment selected for the present case study.

Figure 4. A sequence of works carried out. (**a**) Initial appearance before the execution of the tasks; (**b**) barrier membrane application; (**c**) sealing of the outer compartment door; (**d**) application of mortar to the compartment walls.

Table 1. Technical specifications of the AirThings Corentium Plus Rn Monitor probes, model QRI, used in the different phases of monitoring the indoor Rn concentration.

Rn Sampling	Passive Diffusion Chamber
Detection method	Alpha spectrometry
Detector	1 silicon photodiode
Diffusion time constant	25 min
Measurement range	0–50,000 Bq·m^{-3}
Sampling rate	1 h
Operation environment	4 °C to 40 °C 5% RH to 85% RH non-condensing 50 kPa to 110 kPa
Temperature	0.336 °C resolution, ±1 °C accuracy
Humidity	0.5% RH resolution, ±4.5% accuracy
Barometric pressure	0.01 kPa resolution, ±1 kPa accuracy

The purpose of using the two probes to monitor the indoor Rn concentration was to check that there were no errors associated with the equipment. After each monitoring campaign, the data were analyzed by comparing the means and variances of each group. For this purpose, the Student's *t*-test was used to compare means, and the F-Snedecor statistical test was used to compare variances. For each of the four measurement campaigns, the results obtained by applying the Student's *t*-test and F-Snedecor tests were consistently higher than 0.5, not rejecting the null hypothesis (H0). In this way, it is concluded that there are no statistically significant differences between the means of the two data groups and no differences between the variances, which are supposedly equal. As there are no statistically significant differences, the data sets can be merged by determining the average value of each corresponding pair of measurements, starting to use only one data set for each phase of the indoor Rn concentration monitoring campaigns.

4. Results and Discussion

The results obtained in the three stages of the indoor Rn concentration monitoring, already transformed by merging the sets acquired by the two probes, are presented in Table 2.

Table 2. Summarized data obtained from the monitoring phases of indoor Rn concentration, carried out from 13 March 2019 to 16 November 2021.

	Phase I	**Phase II (a)**	**Phase II (b)**	**Phase III**
Monitoring period	13 March 2019 to 13 June 2019	3 August 2019 To 3 December 2019	19 February 2021 To 12 May 2021	25 June 2021 To 16 November 2021
Nr. of measurements	2205	2180	1970	3457
Average value	6459 Bq·m^{-3}	637 Bq·m^{-3}	9052 Bq·m^{-3}	373 Bq·m^{-3}
Standard deviation	3883 Bq·m^{-3}	475 Bq·m^{-3}	2572 Bq·m^{-3}	207 Bq·m^{-3}
Min. value	134 Bq·m^{-3}	22 Bq·m^{-3}	59 Bq·m^{-3}	4 Bq·m^{-3}
Max. value	18,738 Bq·m^{-3}	3407 Bq·m^{-3}	15,312 Bq·m^{-3}	1129 Bq·m^{-3}

Phase I monitoring, which took place between 13 March 2019 and 13 June 2019, accounted for a total of 2205 measurements at one-hour intervals, with an average indoor Rn concentration of 6459 Bq·m^{-3} and a standard deviation of 3853 Bq·m^{-3}. Such a high standard deviation indicates an equally high variance of the values obtained, evidenced by the minimum value recorded, 134 Bq·m^{-3}, and the maximum value recorded, 18.738 Bq·m^{-3}. In other words, there was a difference of 18.604 Bq·m^{-3} between the lowest and highest values for the indoor Rn concentration inside the compartment, indicating a significant fluctuation in the results. When carrying out the distribution of measurements obtained by successive intervals of 300 Bq·m^{-3}, it was verified that only four values fall within the interval (0; 300) Bq·m^{-3}. Only 0.002% are below the recommended threshold for occupant exposure, while 99.998% are above the recommended exposure value. Figure 5 shows the distribution of results obtained by categories with successive increments of 300 Bq·m^{-3}.

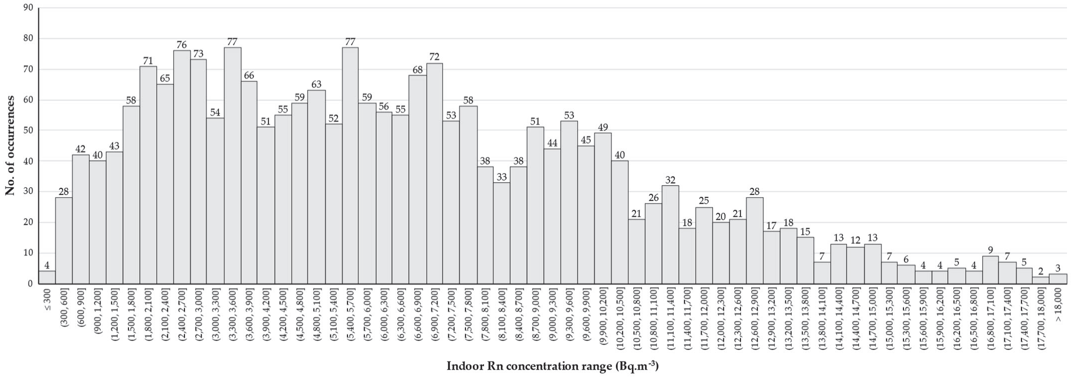

Figure 5. Distribution of measurements made in the preliminary assessment of Rn concentration in the compartment.

As can be seen from the distribution of results in the previous figure, the need to apply a mitigation measure to correct the indoor Rn concentration becomes evident. In this specific case, given the situation of structural confinement in which the compartment is located, there is no possibility of natural ventilation since the compartment does not have any opening to the outside except for the access door. However, using the door to ventilate the space does not seem to be recommended since it could contribute to increasing the Rn concentration in cabinets occupied by ESA IPVC administrative services staff. Thus, the option fell on the use of a barrier membrane to be applied over the floor to prevent the entry of Rn and its accumulation inside the compartment. In this case study, it was decided to use a Monarflex RMB350 barrier membrane with the technical specifications shown in Table 3.

Table 3. Technical specifications of Monarflex RMB350 (http://www.necoflex.is, accessed on 10 October 2022).

Elongation	19%
Tear resistance	405 N
Water vapor transmission	0.03 g·m^{-2}·d^{-1}
Color tone	Red (top side) and black (underside)
Thickness	0.35 mm

After applying the barrier membrane and also covering the baseboards of the walls, a new monitoring of the indoor Rn concentration was carried out, which took place from 3 August 2019 to 3 December 2019, totaling 2180 measurements with an interval of an hour. The results show an average value of 637 Bq·m^{-3}, with a standard deviation of 475 Bq·m^{-3}. In addition, at this stage, the high variance of the results obtained became evident, with a minimum recorded value of 22 Bq·m^{-3} and a maximum value of 3407 Bq·m^{-3}. As can be seen in Figure 6, the distribution of measurements by successive intervals with increments of 300 Bq·m^{-3} already presents a configuration different from that previously observed in Phase I, with the results being distributed in a more balanced way and already showing a significant reduction in the indoor Rn concentration. As can be seen, the average value registered shows a decrease of 90.14% compared to the average value verified in the preliminary assessment of Phase I.

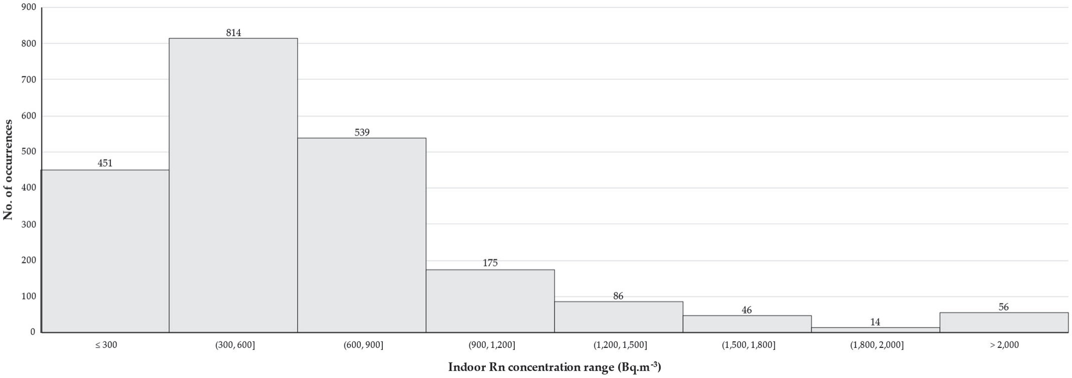

Figure 6. Distribution of measurements performed in the evaluation of the Rn concentration in the compartment after application of the barrier membrane.

In fact, after applying the barrier membrane, it appears that 20.69%, corresponding to 451 occurrences, are within the interval (0; 300) Bq·m^{-3} and that only 2.57%, corresponding to 56 occurrences, are in the class >2000 Bq·m^{-3}. Most of the results, 76.71%, corresponding to 1674 occurrences, are included in the interval (300; 2000) Bq·m^{-3}. However, despite the significant decrease in the indoor Rn concentration, it was observed that in most situations, the values continued to be above the recommended value of 300 Bq·m^{-3} although no longer showing the peaks of 18,000 Bq·m^{-3} recorded in Phase I. In this way, the effectiveness of the barrier membrane in mitigating the concentration of indoor Rn can already be confirmed. However, it is still not at the recommended value for human exposure.

In the course of these results obtained in Phase II, it was considered suitable to confirm the impact that the compartment door could have on the final balance of the indoor Rn concentration through the circulation of air from other compartments. That is, we proceeded to verify whether the concentration of indoor Rn still registered in the compartment could be related to Rn coming from adjacent compartments and not just from the floor and walls of the compartment. For this purpose, the compartment access door was sealed with the same barrier membrane used to insulate the floor.

Phase II(b) monitoring took place between 19 February 2021 and 12 May 2021, with a total of 1970 measurements with an interval of one hour, with an average value of 9052 Bq·m^{-3} being recorded and with a standard deviation of 2572 Bq·m^{-3}. Once again, the variance of the results is very high, with a minimum recorded value of 59 Bq·m^{-3} and a maximum value of 15,312 Bq·m^{-3}, that is, presenting results similar to those verified in the preliminary monitoring carried out in Phase I. However, when analyzing the evolution of the results through their projection in the graph shown in Figure 7a and comparing it with the evolution of the results obtained in the preliminary evaluation assessment, which is shown in Figure 7b, the different disposition of the results obtained is notable, indicating a cumulative tendency. This tendency is confirmed through the distribution of the results obtained by the class intervals, as seen in Figure 8.

As can be seen, the frequency distribution of occurrences is concentrated in the intervals between (4200; 14.100) Bq·m^{-3}, indicating a particular cumulative trend in the concentration of indoor Rn. Even at first glance, the distribution of the results may show an approximation to a normal distribution of the data obtained. However, by applying the one-sample Kolmogorov–Smirnov test to all data sets, with the null hypothesis being that the distribution of the data is normal, it was confirmed that none of the data sets follows the normal distribution since the significance levels obtained are more significant than 0.05 in all situations, rejecting the null hypothesis. Although they do not follow a normal distribution, the data obtained in Phase II(b) are the closest to this distribution, as shown in

Figure 9c, indicating that this difference concerning the other sets of data may be associated with the cumulative trend caused by the confinement of the compartment.

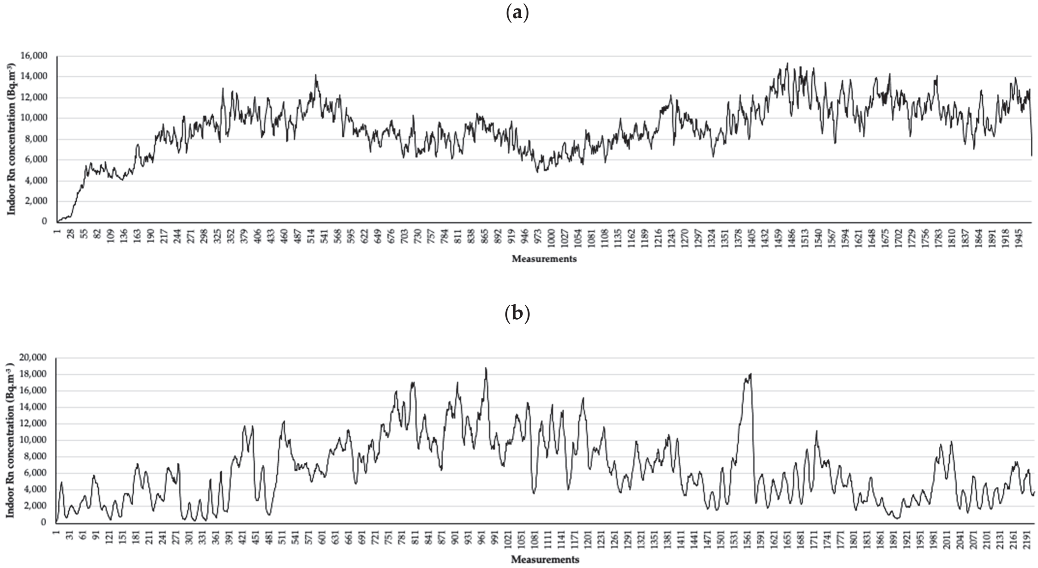

Figure 7. Evolution of indoor Rn concentration measurement results. (**a**) After compartment door sealing; (**b**) results of the preliminary assessment in Phase I.

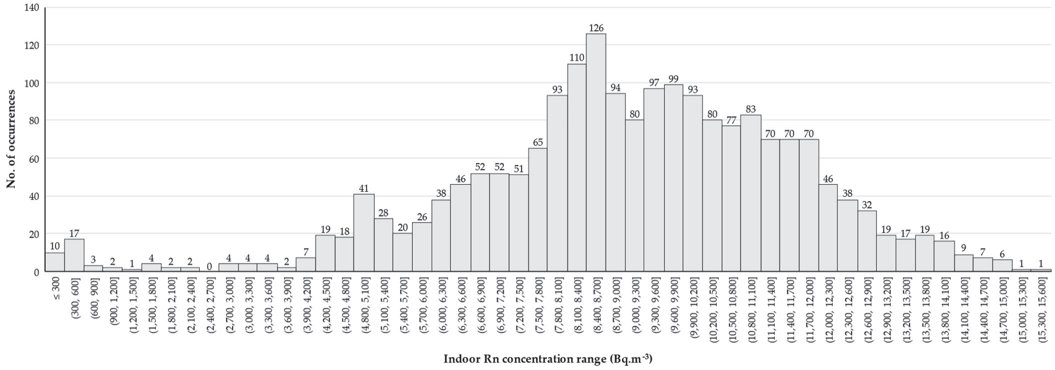

Figure 8. Distribution of indoor Rn concentration measurements in the compartment after sealing the door.

It will most likely be the compartment that contributes to the transfer of Rn to the adjacent compartments through the access door if conditions of pressure differences or displacement of air masses are verified. This situation also confirms that applying the barrier membrane does not eliminate the emanation of Rn, justifying the adoption of additional mitigation measures, such as applying a coating mortar for the walls. In the present situation, it was chosen to use an anti-Rn slurry coating. The selected option is a two-component permanently elastic polymer cement sealing suspension intended for waterproofing various concrete and reinforced concrete construction elements and whose technical specifications are presented in Table 4.

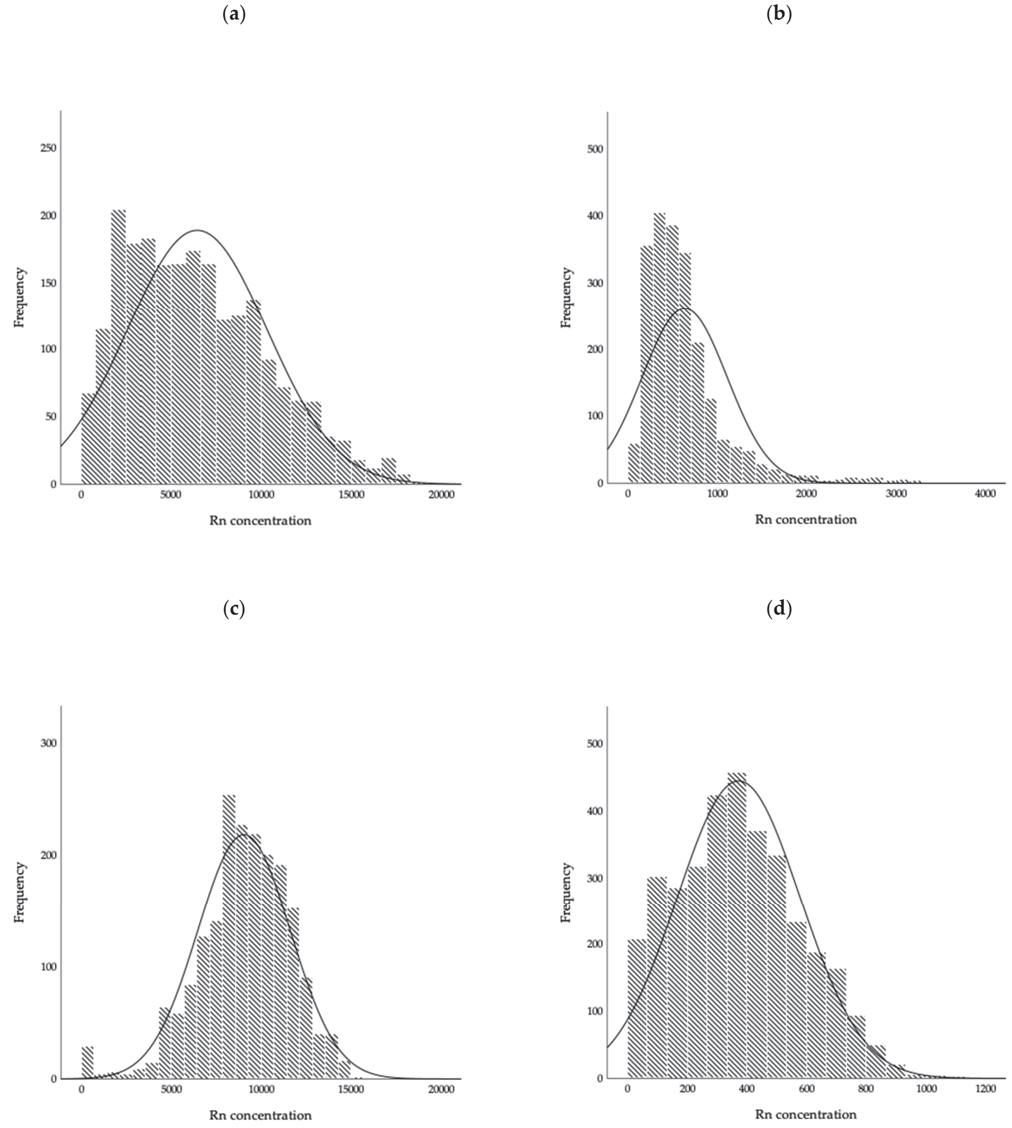

Figure 9. Histograms of the frequency distribution of occurrences. (**a**) Preliminary Phase I Assessment; (**b**) evaluation after application of the barrier membrane in Phase II(a); (**c**) evaluation after sealing the compartment door in Phase II(b); (**d**) evaluation after applying the coating mortar in Phase III.

Phase III occurred between 25 June 2021 and 16 November 2021, totaling 3457 measurements, with an interval of one hour, an average value of 373 Bq·m^{-3}, and a standard deviation of 207 Bq·m^{-3}. There is still significant variance in the results, with a minimum value of 4 Bq·m^{-3} and a maximum value of 1129 Bq·m^{-3}. However, despite the results' variability, the range is much smaller than those seen in previous phases. Frequency analysis, shown in Figure 10, demonstrates a very significant reduction in the concentration of indoor Rn after applying the coating mortar on the walls, with a decrease of 41.44% concerning the monitoring carried out after the application of the barrier membrane.

Table 4. Physical and mechanical parameters of WATERFIN PV (http://www.betosan.cz, accessed on 6 December 2022).

Color of Dry Component	Non-Standard Grey/White
Color of the Liquid Component	White
Color of coating	Grey/White
Minimum film-generating temperature of liquid component (°C)	>1
Tensile strength (MPa)	>1.5
Yield ability (%)	>30
Vapor resistance (m)	<4
Water tightness (under both negative and positive effects of water pressure)	>8 bars (80 m water column)
Coefficient of Rn diffusion D ($m^2 \cdot s^{-1}$)	$9.4 \times 10^{-12} \pm 0.5 \times 10^{-12}$

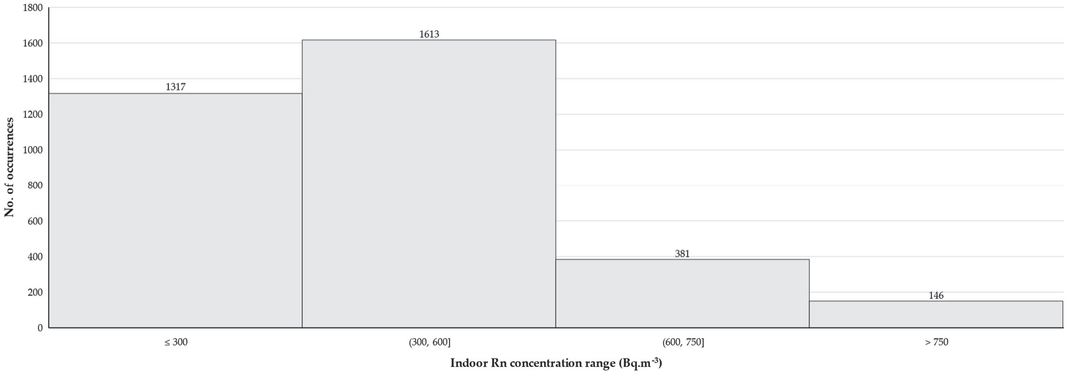

Figure 10. Distribution of measurements taken in the evaluation of Rn concentration in the compartment after mortar application.

After applying the coating mortar to the compartment walls, about 38.90%, corresponding to 1317 occurrences, coincided with the interval (0; 300) Bq·m^{-3}, while 4.22%, corresponding to 146 occurrences, coincided with the class >750 Bq·m^{-3}. However, 57.68%, corresponding to 1994 occurrences, were still above the recommended value for human exposure in the interval (300; 750) Bq·m^{-3}.

The combination of the two constructive measures in the present case study corresponds to a reduction of 94.23% of the concentration of indoor Rn in the compartment. As can be seen in Figure 11, which shows the superimposition of the evolution of the data collected in the different stages of monitoring the concentration of indoor Rn after the application of constructive measures, a very significant attenuation of the levels of Rn in the indoor air is confirmed.

Despite the reduction of about 94% of the indoor Rn concentration, the results obtained continue to show a tendency for the occurrence of values above the recommendation of 300 Bq·m^{-3}. However, although the results remain above 300 Bq·m^{-3}, this does not mean that the recommended measures are not efficient but rather that these types of actions may present different levels of effectiveness depending on whether they are applied in extreme situations, as is the case shown in this state, or in more common situations, in which the registered values are lower. It is also important to consider the possibility that these constructive measures are more efficient if applied in cases where new buildings are constructed, in locations where the Rn emanation potential is recognizably high, and in conjunction with other types of measures, namely, the existence of airboxes and ventilation systems, both natural and forced, to promote indoor air renewal and dispersion of Rn concentration. At the same time, the adoption of measures for the continuous monitoring of the indoor Rn concentration, namely through IoT systems, will allow the anticipation of the moments in which the indoor Rn concentration exceeds the recommended values, transforming it into a risk situation for the users of indoor spaces.

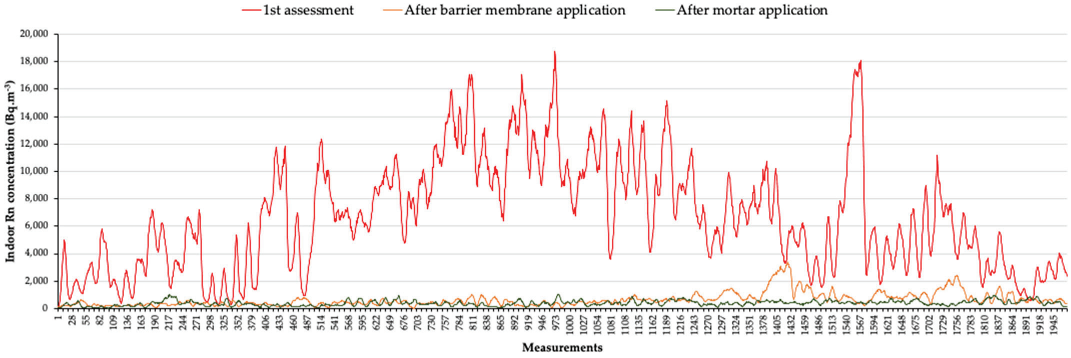

Figure 11. Evolution of the data collected in the different indoor Rn concentration monitoring phases.

5. Conclusions

The remediation of problems related to indoor air quality in buildings is increasingly a concern for the occupants of these spaces because, when associated with this air quality, health problems can be associated. Exposure to Rn is identified by the World Health Organization (WHO) as the second leading cause responsible for the occurrence of lung cancer, so the exposure of occupants of buildings with high concentrations of indoor Rn is a source of growing concern, both in buildings intended for housing, such as in-service buildings. However, if, in most cases, the solution involves natural or mechanical ventilation of spaces, other situations where air renewal procedures are not possible require other constructive measures to be taken. The application of constructive measures, such as opening windows or installing forced ventilation systems, may not be allowed, as these are buildings of architectural and heritage interest that are classified as monuments, with restrictions on interventions and renovations. For this reason, the use of measures applicable indoors, such as barrier membranes, which can be hidden under the floor, and wall-covering mortars, which can be hidden under paint or another type of finish, can contribute to mitigating the concentration of indoor Rn and reducing the dose of natural radiation to which occupants are exposed. In the case analyzed, a 94% reduction in the abnormal values of the indoor Rn concentration was achieved with the combination of two constructive measures. Despite the effectiveness of the measures used, the concentration of indoor Rn was still higher than the recommended value, which makes it necessary to carry out new tests and monitoring campaigns in other scenarios with different levels of concentration of indoor Rn as a way of validating the effectiveness of this type of constructive solution in a generalized way.

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buildings

Article

Productivity Analysis and Associated Risks in Steel Structures

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Abstract: Construction can be analyzed at industry, firm, project, and activity/task levels. Given that there are differences between the concepts of productivity and uses of productivity data, depending on the level of analysis, there is no single meaning of construction productivity, except of an output/input ratio. Furthermore, there is little knowledge in the extant literature about steel structure productivity, sustainability, and risks. Moreover, through the investigation of the grey literature, i.e., the national or European reports on construction productivity, the indexes given are at aggregate levels. This paper aims to fill this gap and provide a holistic approach to the levels of productivity, sustainability, and the risks involved in the construction process in several steel structure types from similar projects constructed by a company that has operated within the field of steel structures for several decades. From a homogeneous database of 71 steel structure projects constructed in the last decade, several curves are derived concerning productivity per work phase. For this research, productivity is construed as a ratio of output/(cycle time). Through a literature review and interviews with experienced site engineers, a risk registry was compiled by the authors concerning sixteen (16) risks encountered in the construction process. The TOPSIS multi-criteria analysis program is used for the prioritization of risks and the @RISK program for the probabilistic cost analysis of the identified risks.

Keywords: steel structures; productivity; risk analysis; Monte Carlo simulation; TOPSIS method; @Risk

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1. Introduction

The construction sector has often been berated for its low productivity [1]. Remarkably, McKinsey research [2] reveals that about USD 10 trillion is spent on construction-related goods and services every year but the sector’s annual productivity growth has only increased 1% over the past twenty years. Higher productivity could create USD 1.6 trillion of additional value added, meeting half the world’s infrastructure need. Studies that collect and analyze quantitative data regarding productivity are very important for both firms in the construction industry and government policies. Through the investigation of the grey literature, such as European financial reports or OECD reports on construction productivity, the indexes given are at aggregate levels [3,4]. The construction sector is highly fragmented; therefore, studies that investigate each sector’s productivity are of utmost importance in order to investigate labor productivity in conjunction with construction methods and the related risks.

There is little knowledge in the extant literature about steel structure productivity, sustainability, and risks. Although the literature is rich in research concerning general productivity in the construction sector and models for the analysis and estimation of this measure [5–9], there is a paucity of studies referring to steel structure construction productivity as a ratio of output/(cycle time). Furthermore, risk identification is a tedious task that presupposes a rich registry followed by an in-depth analysis in order to estimate the cost of a sustainable solution or the cost of resilience. This study’s contribution, using a large homogeneous database of 71 steel structure projects (Appendix A), aims to fill this gap by providing a holistic approach to productivity at the project level and per work phase, and the associated risks. This objective is accomplished by developing: (i) curves of productivity for different steel structures at the work phase level, (ii) a risk registry through a literature review and interviews with experience engineers in the field, (iii) an analytical hierarchy list of the identified risks using the TOPSIS multi-criteria analysis program, and (iv) cost quantification reports of these risks through their analysis with @RISK.

2. Literature Review

A literature review plays a very important role in research because it helps in collecting and consolidating the existing information of the specific field under investigation and in identifying gaps [10]. Searching of peer-reviewed articles was performed using the Web of Science (WoS) Core Collection and Scopus bibliographic databases, which are the two most widely accepted and well-recognized databases for high quality literature reviews [11]. Furthermore, the authors extended their research into EU, OECD, and national databases to identify non-peer-reviewed "grey literature", such as government, national, and international reports and guides. The time span was set as 2000–2023.

Our research found that no articles were published dealing with construction productivity issues or the related organizational risks of steel structures. In 2015, Naoum [12] conducted a literature review of productivity in construction sites covering a period of 1970–2014, with a total number of 119 productivity-related articles and reports. Their results give no information regarding the type of projects investigated; their approach is more descriptive since it is focused on the factors affecting productivity on sites without giving any quantifiable indexes.

More recently, Dixit et al. [13] attempted to summarize the evolution of research in construction productivity using a systematic literature review from papers published from 2006 to 2017. Their research analyzed 101 papers. In their study, factors and attributes affecting productivity were presented and seven main areas of development in construction productivity were identified, namely, tools and consumables, coordination, drawing management, material availability, labor skills, training, and rework. Nevertheless, in their research there was no classification in terms of the type of projects investigated and no metrics were given regarding productivity.

Teizer et al. [14] investigated the training methods in order to increase productivity of ironworkers employed in the construction of steel structures. They proposed a remote data sensing and visualization technology in order to capture the sequence of works of workers involved in steel structure construction. They identified productivity and safety issues that workers or trainees might not be aware of in their natural work environment. No data were provided on productivity and their sample included the erection of steel girders.

In 2019 Liew et al. [15] proposed a steel concrete composite system for modular construction of high-rise buildings compared to conventional construction methods to increase productivity and thus decrease labor costs. Their research investigated methods of modular construction and provided a stepwise methodology for high-rise buildings to improve productivity and safety, and reduce cost, manpower, and wastage on site.

The construction industry, including its productivity, is one of the most significant sectors that supports the economic development of a country. Specifically, the construction sector is the engine of growth for a country since it creates a flow of services and goods with other sectors [2,3]. Therefore, every attempt to provide consolidated indexes of productivity is very important since it can help public organizations and companies to accurately estimate time and cost, and to search for methods for the improvement of these metrics. This research attempted to fill the gap in the literature and provide, for the first time, specific indexes of productivity for steel structures of ten different types of projects, with eight phases of construction for each type, and the organization risks related to these projects.

3. Materials and Methods

3.1. Productivity in Steel Structures

Every construction project is made up of a sequence of unique, complex, and interrelated activities aimed at achieving a specific technical purpose within the constraints of cost, time, and the quality specifications required [16].

These activities can be grouped into the following basic phases in steel structures:

Various Steel Tasks include packing, measuring, transporting the materials on site, loading and unloading the materials, and foundation construction.

A registry was developed with 71 projects (Figure 1).

Productivity was recorded for each basic phase (Table 1) for each type of steel structure (Table 2), and finally per employee, according to Equation (1):

$$(kg/h)_{i.j.} = \frac{kg_{i.j.}}{h_{i.j.}} \tag{1}$$

where:

$(kg/h)_{i\cdot j\cdot}$: Kilograms per hour of each project for each one of the basic phases of steel structures.

$kg_{i.j}$.: Kilograms of each project for each one of the basic phases of steel structures.

$h_{i.j}$.: Hours of each project for each one of the basic phases of steel structures.

i: projects.

j: the basic phases of steel structures.

Figure 1. (**a**) Airport, (**b**) roof canopy, (**c**) pedestrian bridge, (**d**) bridge railing.

Table 1. Basic phases of steel structures.

Basic Phase
Design
Cutting Long Beams
Cutting Forming Sheets
Montage (Assembly)
Welding
Paint
Erection
Various Steel Tasks

Table 2. Main types of steel structures.

Main Types of Steel Structures
Industrial Area
Residence—Rooms for Rent
Hotel
Airport
Hospital
Warehouse
Business Center
Roof–Canopy
Pedestrian Bridge
Steel House
Bridge Railing
School
Mezzanine
Various Constructions

Steel Structures are divided into two basic weight categories. These are the beam weight and the sheet metal weight; the sum of these two constitutes the total weight.

3.2. Risk Analysis in Steel Structures

Risk is defined as follows [17]:

ISO 31000 recognizes that everybody operates in an uncertain world. Whenever a goal is established, there is always the possibility that things will not go according to the plan. Each step has a risk element that needs to be addressed and every result is uncertain.

According to ISO 31000, "*The risk is the*" *effect of the uncertainty on the Company's objectives*, "*resulting in a negative deviation from what is expected or positive due to the timely and effective action of Risk Management*."

This problem is further enhanced when construction projects are involved. The dynamic environment of construction projects imposes an even greater necessity for the early estimation of any possible risks in order to reassure the successful delivery of the project. The risks associated with steel projects were investigated through interviews with the project managers and superintendents of the 71 steel projects under analysis. Table 3 summarizes the most common risks that were highlighted by the construction experts.

Table 3. Risk register.

A/A	Risk
RI.1	Failure to deliver materials on time
RI.2	Equipment failure
RI.3	Resignation of a person from a "key" position
RI.4	Revaluation of Materials in a project with "locked" prices
RI.5	Inability to collect (agreed) receivables
RI.6	Not significant worker accident
RI.7	Significant worker accidents
RI.8	Tax rate increase
RI.9	Competition
RI.10	Investment failure
RI.11	Bad weather
RI.12	Change in Plans—Delayed Responses
RI.13	Fire—Destruction of factory
RI.14	Increased Administration Expenses
RI.15	Decreased Profit
RI.16	Improper Estimation of Budget

A two-step approach was followed to analyze the identified risks. To do this, @Risk software (version 7.0, Denver, CO, USA) was used for the quantitative analysis of risks and the TOPISIS multicriteria analysis program was used to prioritize risks.

Based on PMI 2000 [18], all risks can be grouped according to their probability of risk occurrence and their consequence. For all the identified risks, a probability of occurrence and the consequence probability in monetary values were set. Furthermore, in order to prioritize these risks, the Entropy-TOPSIS methodology was used, as analytically described below [19,20].

To perform the analysis through the @Risk program, the following steps were followed:

Step 1

For each risk determined in the risk register table, an estimated probability of occurrence and the occurrence consequence in monetary values were defined.

Step 2

The probabilities of occurrence, which usually have a discrete distribution, were defined and a continuous distribution for the consequence was also determined in this step.

Step 3

The outcome of these two distributions, namely, the "consequence" and the "number of risk occurrence", yields the level of importance of each risk.

Step 4

Using Monte Carlo simulation, a number of simulations were performed (for this research the number of iterations was set to 5000) in order to export probability distributions for the consequences and the number of occurrences.

Further to the analysis, to implement the TOPSIS method, three parameters were used. These were probability (P), severity (S), and vulnerability (V). Vulnerability is described as the intrinsic properties of a system that make it susceptible to a risk source that can lead to an event with a consequence [19,21]. All three parameters are expressed on a scale from 1 to 9; for example, 1 stands for "*occurrence probability out of risk very low*", whereas 9 stands for "*occurrence probability of risk very high*" [20].

Through interviews with the project managers of each of the 71 projects, a risk register (Table 4) encompassing the values (P), (S), (V) was produced.

Table 4. Risk—risk register table with values P, S, and V.

A/A	Risk	P	S	V	Rank
RI.1	Failure to deliver materials on time	3	3	5	12
RI.2	Equipment failure	3	5	3	7
RI.3	Resignation of a person from a "key" position	3	5	3	8
RI.4	Revaluation of Materials in a project with "locked" prices	5	3	7	6
RI.5	**Inability to collect (agreed) receivables**	**3**	**7**	**7**	**2**
RI.6	Not significant worker accident	5	1	3	11
RI.7	**Significant worker accidents**	**3**	**7**	**5**	**3**
RI.8	Tax rate increase	1	1	7	16
RI.9	**Competition**	**3**	**7**	**5**	**4**
RI.10	**Investment failure**	**3**	**7**	**9**	**1**
RI.11	Bad weather	3	3	3	14
RI.12	Change in Plans—Delayed Responses	3	1	1	15
RI.13	Fire—Destruction of factory	1	5	5	9
RI.14	Increased administration expenses	1	9	7	5
RI.15	Decreased profit	3	3	7	10
RI.16	Improper estimation of budget	3	3	5	13

The entropy method [19,20] was used to apply weights for each value as analytically described below:

First the table is normalized:

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{2}$$

The entropy is then calculated:

$$e_j = -h \sum_{i=1}^{m} r_{ij} \ln r_{ij} \tag{3}$$

where $j = 1, 2, \ldots, n$, and

$$h = \frac{1}{\ln(m)} \tag{4}$$

where m is the number of alternatives.

The weight is then calculated:

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{n} (1 - e_j)} \tag{5}$$

where:

x_{ij}: Decision table entries
r_{ij}: Normalized value
e_j: Entropy
h: Value depending on the number of alternatives
w_j: Weight of each criterion
m: Number of alternatives

After the weights were attributed to each risk, the TOPSIS method was used to rank the risks (Table 4, last column) by applying the following formulas:

$$\overline{x}_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{n} x_{\text{ij}}^{2}}} \tag{6}$$

Then multiplication was performed with the weight of each criterion:

$$V_{ij} = \overline{x_i}j \cdot w_j \tag{7}$$

Then, the best scenario $V_j{}^+$ and the worst scenario $V_j{}^-$, were found from V_{ij}.

$S_i{}^+$ and $S_i{}^-$ were then calculated through the mathematical formulas:

$$S_i^+ = \left(\sum_{j=1}^{m} \left(V_{ij} - V_j^+\right)^2\right)^{0.5} \tag{8}$$

$$S_i^- = \left(\sum_{j=1}^{m} \left(V_{ij} - V_j^-\right)^2\right)^{0.5} \tag{9}$$

So the result of each criterion is equal to:

$$P_i = \frac{s_i^-}{s_i^+ + s_i^-} \tag{10}$$

The percentage of each criterion can then be calculated through the mathematical formula:

$$Pi\left(\frac{0}{0}\right) = \frac{P_i}{\sum_{j=1}^{n} P_i} \tag{11}$$

Finally, the risks are prioritized in descending order from the highest to the lowest p value, where:

x_{ij}: Normalized matrix values
V_{ij}: Weighted normalized matrix values
$V_i{}^+$: Ideally better value than alternatives
$V_i{}^-$: Ideally worse value than alternatives
$S_i{}^+$: Euclidean distance from ideal best value
$S_i{}^-$: Euclidean distance from ideal worst value
P_i: Result of each criterion
P_i(%): Percentage of each criterion

4. Results and Discussion

4.1. Productivity in Steel Structures

Table 5 summarizes the productivity per main task and main project type from the 71 steel structure projects; as noted in Section 3.1, the productivity is given per employee.

The following remarks can be made:

- The most productive project type for the Design phase is Hospital, at 990 kg/h, while the least productive project type for the Design phase is Residence—Rooms for Rent, at 257 kg/h.
- For the Cutting Long Beams phase, Airport exhibits the highest productivity, at 425 kg/h, while the least productive project type for the basic Cutting Long Beams phase is Bridge Railing, at 64 kg/h.
- For the Cutting Forming Sheets phase, Mezzanine is the most productive, at 57 kg/h, while the least productive project type is Bridge Railing, at 18 kg/h.

- The most productive project type for the basic Montage (Assembly) phase is Business Center, at 428 kg/h, while the least productive project type is Pedestrian Bridge, at 115 kg/h.
- For the Welding phase, Business Center is the most productive project, at 296 kg/h, while the least productive project type is Footbridge, at 89 kg/h.
- For the basic Paint phase, Mezzanine presents the highest productivity, at 512 kg/h, while the least productive project type for the basic Paint phase is Pedestrian Bridge, at 204 kg/h.
- For the basic Erection phase, Hospital is the most productive project, at 212 kg/h, while the least productive project type is Bridge Railing, at 44 kg/h.
- For the basic Various Steel Tasks phase, Airport is the most productive project, at 1545 kg/h, while the least productive project type is Bridge Railing, at 138 kg/h.
- The average productivity of all types of projects and phases is 378 kg/h.
- Overall, the least productive type of project on average is Pedestrian Bridge, at 173 kg/h.
- Finally, the most productive type of project on average is Airport, at 528 kg/h.

Table 5. Productivity—Summary table of productivity by work phase for each project type.

TYPE	kg/h DSGN	kg/h CTBM	kg/h PLAT	kg/h ASMB	kg/h WELD	kg/h PANT	kg/h ERCTC	kg/h VARS	kg/h AVG
Industrial Area	686	289	37	244	206	345	102	373	316
Residence—Rooms for Rent	257	204	36	166	180	360	83	377	215
Hotel	948	232	29	184	163	441	81	271	327
Airport	989	425	50	308	205	294	131	1545	528
Hospital	990	249	41	256	166	279	212	230	334
Business Center	621	283	56	428	296	293	199		348
Roof-Canopy	242	219	35	160	275	390	100	228	228
Pedestrian Bridge	375	171	31	115	89	204	105	183	173
Bridge Railing	638	64	18	233	204		44	138	219
School	492	234	41	294	242	472	112	343	310
Mezzanine	367	271	57	266	224	512	102		280
Average	787	311	41	254	198	342	116	682	378

Figure 2 depicts in detail the average productivity per project and work phase.

Airports are the most productive type of project because they are structures that have a very heavy frame and comprise large repetitive sections.

Pedestrian Bridges have low productivity mainly in the Assembly and Welding phases. This is because these structures do not consist of elongated elements that are welded with plates and then erected with bolts, like classic steel structures. Instead, they comprise several combined elongated elements, and with plates are connected to each other during the Assembly and Welding phase to become a block, which demands more labor.

Bridge Railings have reduced productivity, especially during the Cutting Long Beams and Erection phase. This is mainly because decorative railings usually consist of round CHS hollow sections, which are more laborious to cut. They also include more laborious cuts, due to the particularity of their geometry. Regarding the rest of the main work phases and Erection, their reduced productivity is because they are not standardized tasks and need a different approach each time.

The generally low productivity in Residence—Rooms for Rent is because they have a light frame and require roughly the same hours of work, so the kg/h ratio is reduced.

Industrial Areas and Business Centers generally have slightly increased productivity during the Welding stage. This is because they are made up of heavier cross-sections than residential buildings, but large public works such as Airports and Hospitals have roughly the same frame but have significantly fewer requirements in terms of weld thickness and control requirements.

Finally, by determining the cost/h and having calculated the productivity per work phase and project type, several comparisons could be derived for the "unit cost" per work phase per project type.

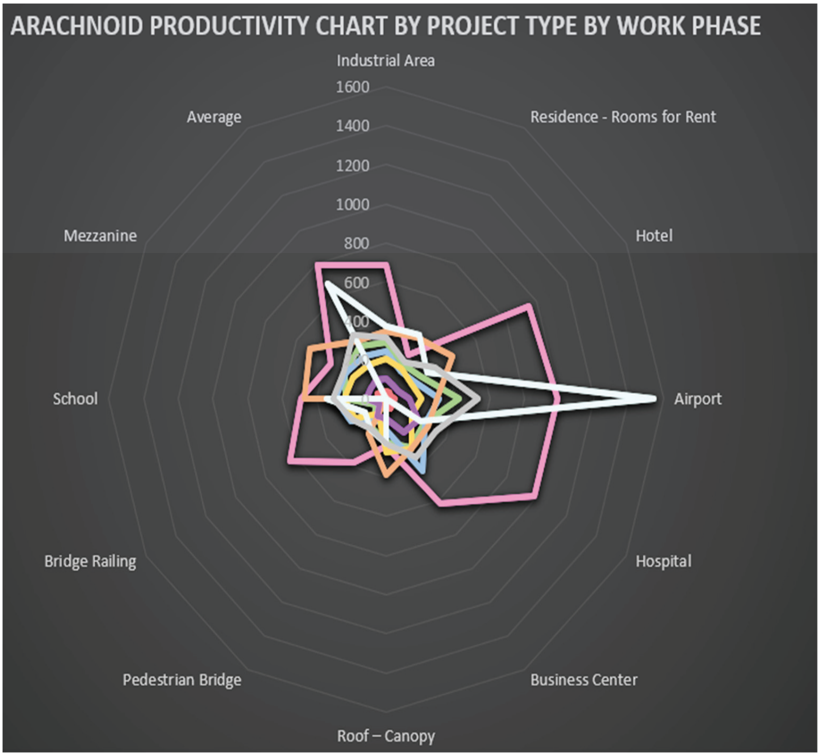


Figure 2. Productivity—Arachnoid diagram of average productivity by project type by work phase.

4.2. Risk Analysis in Steel Structures

Business risks cannot be accurately predicted with a single value in terms of their consistency and using a probability deterministic model. In such cases, it is appropriate to use the probabilistic model because:

1. It enables us to define a reasonable range of values regarding both the probability of occurrence of the risks and their consequences [22],
2. It introduces the concept of interaction of input variables in a computational environment.

The result of the probabilistic method is the calculation of the probability distribution of each examined output variable (e.g., cost of risks, number of occurrences of risks).

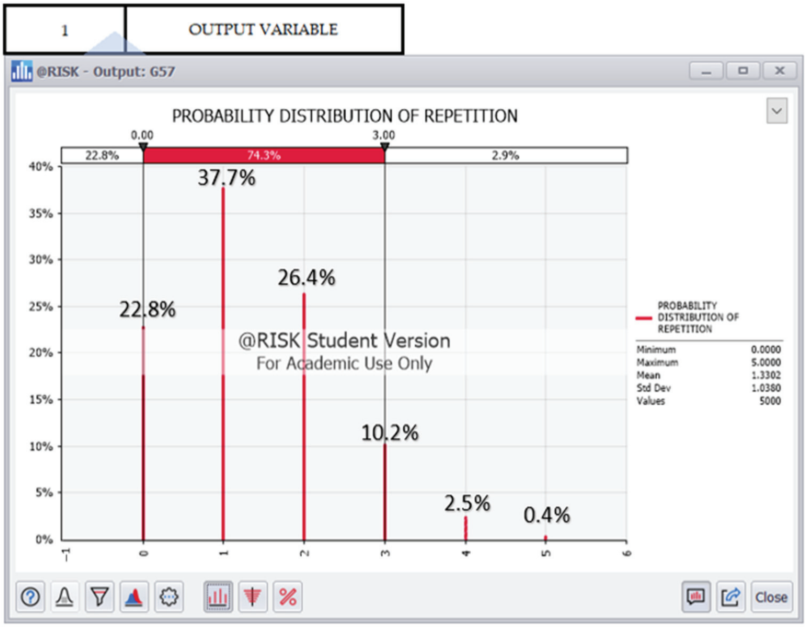
Table 6 shows the risk severity level. The monetary values for each risk were determined from the historical data and the experience of the projects' managers and superintendents of the 71 projects under analysis.

Table 6. Risk—Risk severity level of each of the risks individually.

A/A	Risk	Consequence Probability Distribution	Probability Distribution of Repetition	Risk Severity Level
RI.5	Inability to collect (agreed) receivables	231,250 €	0	0 €
RI.7	Significant worker accidents	253,333 €	1	253,333 €
RI.9	Competition	200,333 €	0	0 €
RI.10	Investment failure	178,500 €	0	0 €
RI.14	Increased administration expenses	445,000 €	0	0 €

Using @Risk software, the following results were extracted, and the diagrams presented better depict this information.

- Exact and Cumulative Distribution Probability Diagram of Total Number of Hazard Occurrences (Repetitions) (Figure 3)



Minimum	0.0000
Maximum	5.0000
Mean	1.3302
Std Dev	1.0380
Values	5000

Figure 3. Risk—risk recurrence probability distribution chart.

- ○ There is a 22.8% chance that no risk will occur;
- ○ There is a 37.7% chance that only one risk will appear;
- ○ There is a 26.4% chance that 2 risks will appear at the same time;
- ○ There is a 10.2% chance that 3 risks will appear at the same time;
- ○ There is a 2.5% chance of 4 risks appearing at the same time;
- ○ There is a 0.4% chance of 5 risks appearing at the same time;
- ○ The probability of 4 or 5 risks appearing simultaneously (2.5% or 0.4% respectively);
- ○ The cumulative probability of 4 and 5 risks occurring at the same time is 2.9%;
- (a) The maximum number of simultaneous risks appearing is 5.

- Diagram of Exact and Cumulative Total Risk Cost Probability Distribution (Figure 4)

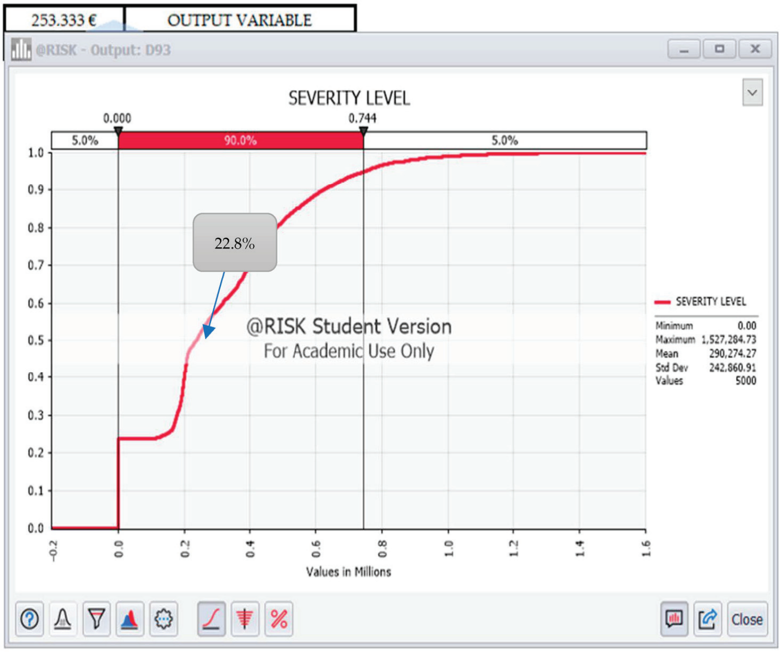


Figure 4. Risk—risk severity level cumulative chart.

- ○ There is a 22.8% chance that no costs of risks will occur;
- ○ The maximum cost that can be incurred from the random combination of all the main risks considered is EUR 1,527,284.73;
- ○ There is a cumulative probability of 95% that the total burden of the business will rise to EUR 744,000 and only a probability of 5% that the cost of the business will range from EUR 744,000 to 1,527,284.73;
- ○ There is only a 5% cumulative probability that costs of risks will be greater than EUR 786,000 and a 95% probability that costs will be less.

- Total Cost of Risk Tornado Diagram (Figure 5)

From the above diagram, the risks with the highest cost are in descending order are:

- ○ Significant worker accidents;
- ○ Inability to collect (agreed) receivables;
- ○ Increased administration expenses;
- ○ Competition;
- ○ Investment failure;

- Tornado Diagram for the Total Number of Risk Occurrences (Figure 6)

The tornado chart above shows the occurrence number of each risk separately, and the risk having the highest probability of occurrence. These risks in descending order are:

- ○ Significant worker accidents;
- ○ Inability to collect (agreed) receivables;
- ○ Competition;
- ○ Investment failure
- ○ Increased administration expenses.

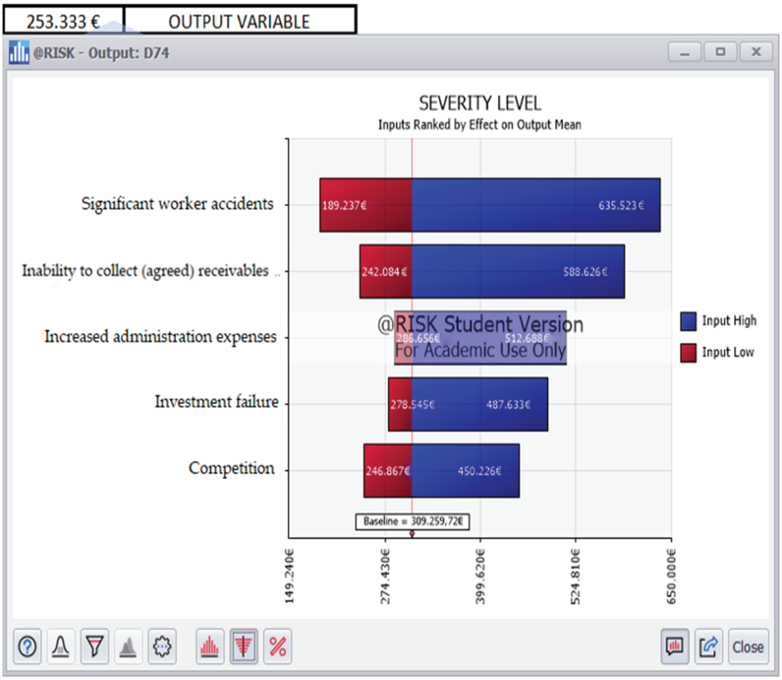


Figure 5. Risk—risk severity level.

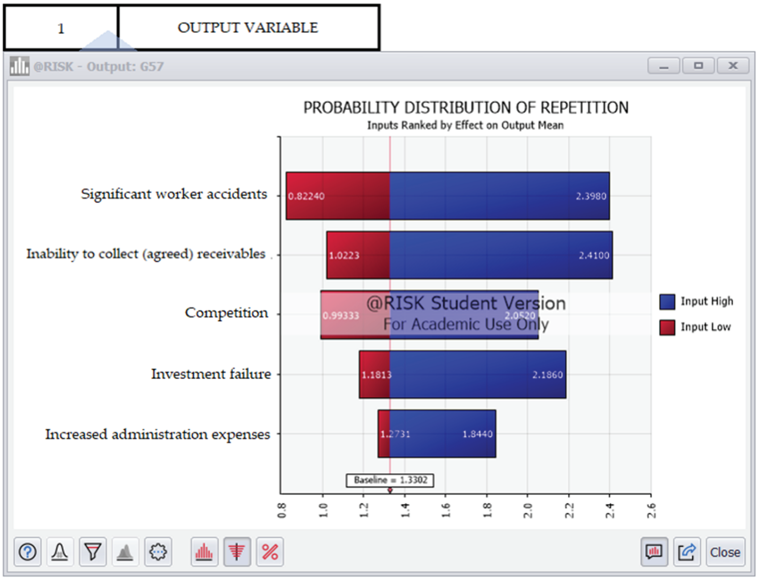


Figure 6. Risk—tornado chart for total risk occurrence number.

The most important risks according to the TOPSIS entropy method are the five risks that were analyzed above. These risks reflect the importance in relation to the weights given by the interviewees, and are presented, in descending order, in Table 7 and Figures 7 and 8.

Table 7. Most important risks according to the TOPSIS entropy method.

A/A	Risk	Score	%	Rank
RI.10	Investment failure	0.6934	9.42	1
RI.5	Inability to collect (agreed) receivables	0.6746	9.17	2
RI.7	Significant worker accidents	0.6448	8.76	3
RI.9	Competition	0.6448	8.76	4
RI.14	Increased administration expenses	0.6141	8.34	5

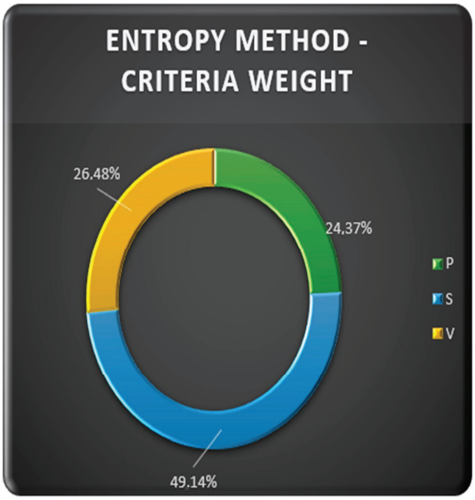


Figure 7. Risk—entropy method—criteria weights.

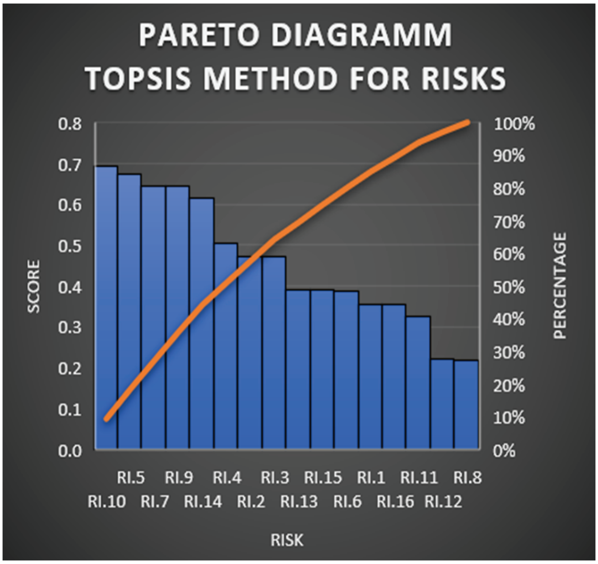


Figure 8. Risk—Pareto diagram using TOPSIS method for risks.

5. Discussion and Conclusions

5.1. Discussion

As noted by Dixit et al. [13], productivity is commonly defined as a ratio of a volume measure of output to a volume measure of input use. The productivity could be measured at various levels, but three main measures exist: industry or sector level, project level, and activity or process level measurement. Nevertheless, project-based productivity comparisons are preferred because they could help construction entities to discover the area of improvement. Moreover, productivity curves could help construction managers to better estimate construction time and cost by allocating the adequate human resources to the "critical" project activities. This has become particularly imperative in recent years because, according to a McKinsey Report [2], construction productivity reached a deadlock. From the investigation of the extant literature, there is no publication in this sector regarding productivity curves at the project level and per construction phase. The majority of articles approach the productivity level, either by measuring the productivity of a case study or via a hierarchy of the factors of poor productivity, in a descriptive way without giving numbers or providing curves for comparisons. This paper aims to fill this gap by providing a holistic approach to the levels of productivity at the project level and per construction phase in order to help construction companies that undertake steel projects to better estimate their time and costs of construction. Furthermore, this research goes a step further by investigating and quantifying the most common risks that these types of companies encounter during construction. Data were gathered on 71 steel projects constructed in the last decade by the same constructor who has operated in the steel structure sector for several decades. This fact ensured that the data are homogeneous in terms of any exogenous risks of noise (i.e., different approaches of labor costs attribution, etc.). The analysis distinguished eight basic phases of steel structure construction: (i) Design, (ii) Cutting Long Beams, (iii) Cutting Forming Sheets, (iv) Montage (Assembly), (v) Welding, (vi) Paint, (vii) Erection, and (viii) Various Steel Tasks. For each phase, the productivity was recorded per employee in kg/h for fourteen main types of steel structures: (i) Industrial Area, (ii) Residence—Rooms for Rent, (iii) Hotel, (iv) Airport, (v) Hospital, (vi) Warehouse, (vii) Business Center, (viii) Roof—Canopy, (ix) Pedestrian Bridge, (x) Steel House, (xi) Bridge Railing, (xii) School, (xiii) Mezzanine, and (xiv) Various Constructions. It was concluded that Airports are the most productive type of project since they are structures with a very heavy frame and large repetitive sections. At the other extreme are Pedestrian Bridges, which have low productivity, especially during the Assembly and Welding phase, which encompasses laborious tasks. The information given by the calculation of the productivity index per project and per phase of construction could assist contractors to accurately estimate the "unit cost" (cost/kg) per work per phase and per project, and result in more valid and secure comparisons when selecting or prioritizing construction projects.

Furthermore, even when the indexes are valid and the comparisons can be accurately made, there are always several risks that companies have to face in their daily routine. Therefore, this research proceeded a step further by developing a risk registry based on the historical data of the 71 steel structure projects and the experience of the project managers and superintendents of these projects. Sixteen risks were identified, and through their analysis, five risks were characterized as "*most important*" and were analyzed further in terms of occurrences, severity, and vulnerability: (i) RI.10—investment failure, (ii) RI.5—Inability to collect (agreed) receivables, (iii) RI.5—Significant workers accidents, (iv) RI.9—Competition, and (v) RI.14—Increased administration expenses. Furthermore, probability curves were created for capturing the relevant costs for mitigation.

Although this is the first attempt made in the sector to provide figures for productivity, thus enabling valid and safe comparisons and hierarchizing the associated risks, the sample is country based. Therefore, any comparisons should be made taking into account the country's conditions of wealth and construction maturity. Future work could include the enhancement of data incorporating more projects and the inclusion of other international projects in the sector.

5.2. Conclusions

To ascertain where the major problem lies, we have to look at construction subsectors. According to a McKinsey Report [2], better planning can boost productivity. To this end, this study offers curves of productivity as a basis for better planning based on past experience.

In general, studies that analyze productivity and risks related to steel structures are non-existent. This is a first attempt to address this gap in the extant literature by presenting, through a large and homogeneous database of 71 steel projects of various types, productivity and risks associated with this kind of structure. Through face-to-face interviews with project managers and superintendents, a homogeneous database was created. The results of the analyses aim to help projects managers and companies in this sector to better estimate their costs and risks associated with their work, and thus result in a better profit margin and more valid and secure comparisons when selecting or prioritizing construction projects.

Productivity is given in terms of unit cost per employee. The analysis revealed that among the fourteen different types of steel projects investigated, Airports is the most productive type, and Pedestrian Bridges rank at the bottom of the list with an average index of productivity of 378 kg/h. Furthermore, the investigation of the risks related to this kind of structure showed that, of the sixteen risks identified, five were classified as "high" risks that should be investigated in terms of their consequences and occurrence. These risks are: (i) significant worker accidents, (ii) inability to collect (agreed) receivables, (iii) competition, (iv) investment failure, and (v) increased administration expenses. Moreover, the TOPSIS entropy method revealed that the same risks are more important and ranked them by taking into account (a) probability, (b) severity, and (c) vulnerability weights. The highest score was for "*investment failure*" and the lowest was for *"increased administration expenses"*.

The proposed approach can be enriched in the future by incorporating additional data from other steel projects or international projects in this sector, thereby producing more valid and robust results.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to cost sensitive reasons.

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Abbreviations

DSGN	Design
CTBM	Cutting Long Beams
PLAT	Cutting Forming Sheets
ASMB	Montage (Assembly)
WELD	Welding
PANT	Paint
ERCT	Erection
VARS	Various Steel Tasks

Appendix A

Table A1. The main characteristics of the projects.

A/A	Types	Area (m^2)	Height (m)	Floors	Comments
321	Industrial Area	747 m^2	7.00 m	1	Steel Building with Panel
1	Residence—Rooms for Rent	200 m^2	9.00 m	3	Composite Multistorey Building
2	Business Center	960 m^2	6.00 m	1	Steel Building with Panel
3	Industrial Area	477 m^2	5.70 m	-	Steel Building with Panel
4	Roof-Canopy	999 m^2	1.0–9	-	Various Many Small Steel Structures
5	Residence—Rooms for Rent	139 m^2	2.50 m	1	Steel Frame of House
6	Airport	5.240 m^2	5.0–15	1	Various Steel Structures
7	Residence—Rooms for Rent	75 m^2	2.40 m	1	House with Metal Steel and Dry Construction
8	Mezzanine	-	-	-	Steel Mezzanine
9	Residence—Rooms for Rent	218 m^2	4.00 m	1	Steel Frame of House
10	Residence—Rooms for Rent	60 m^2	6.00 m	2	Steel—Concrete Frame of House
11	Residence—Rooms for Rent	280 m^2	11.50 m	5	House with Steel—Concrete Frame and Dry Construction
12	Industrial Area	1.395 m^2	9.90 m	2	Steel—Concrete Building with Panel for Overlay
13	Various Constructions	-	-	-	Various Many Small Steel Structures
14	Airport	5.720 m^2	5.00 m	1	Steel—Concrete Frame of Building
15	Industrial Area	516 m^2	7.20 m	1	Steel Building with Panel
16	Industrial Area	503 m^2	6.00 m	1	Steel Building with Panel
17	Various Constructions	-	-	-	Various Many Small Steel Structures
18	Industrial Area	67 m^2	5.00 m	1	Steel Building with Panel
19	Airport	278 m^2	4.64 m	1	Steel—Concrete Frame of Loft
20	Industrial Area	1.175 m^2	7.00 m	1	Steel Building with Panel
21	Industrial Area	869 m^2	7.57 m	1	Steel Building Addition with Panel
22	Airport	1.075 m^2	15.23 m	-	Steel Building
23	Residence—Rooms for Rent	92 m^2	3.40 m	1	Steel Frame of House
24	Various Constructions	8 m^2	8.70 m	3	Steel Frame of Elevator
25	Airport	3.680 m^2	2.6–11	1 + 2	Various Steel Structures
26	Hotel	1.150 m^2	11.00 m	2	Steel—Concrete Frame of Hotel
27	Industrial Area	440 m^2	5.50 m	1	Steel Roof with Panel
28	Various Constructions	20 m^2	1.00 m	1	Steel Structure
29	Residence—Rooms for Rent	254 m^2	12.60 m	3	Steel—Concrete Frame of Hotel
30	Various Constructions	52 m^2	3.00 m	1	Steel Interior Reinforcements of Existing Home
31	Industrial Area	1.825 m^2	1.00 m	1	Steel Building with Panel
32	Roof-Canopy	200 m^2	-	-	Reconstruction of a Steel Roof with Panel
33	Hotel	4.023 m^2	18.00 m	3	Steel Frame of a Composite Hotel
34	Roof-Canopy	168 m^2	1.20 m	1	Steel Roof with Panels

Table A1. *Cont.*

A/A	Types	Area (m^2)	Height (m)	Floors	Comments
35	Airport	250 m^2	4.60 m	1	Steel Building
36	Roof-Canopy	108 m^2	5.50 m	1	Steel Roof with Panel
37	Airport	240 m^2	4.70 m	1	Various Many Small Steel Structures
38	Various Constructions	-	-	-	Various Many Small Steel Structures
39	Various Constructions	330 m^2	12.00 m	3	Steel Reinforcement of an existing building
40	Pedestrian Bridge	60 m^2	1.00 m	-	Steel Open Pedestrian Bridge
41	Industrial Area	425 m^2	5.00 m	1	Steel Building with Panel
42	Industrial Area	593 m^2	9.85 m	2	Steel frame of Composite Building
43	Industrial Area	420 m^2	4.50 m	1	Steel Building with Panel
44	Industrial Area	850 m^2	5.00 m	1	Steel Additions with Panel
45	Hospital	2.289 m^2	4.05 m	1	Steel frame of Composite Building
46	Roof-Canopy	120 m^2	4.89 m	1	Steel Building with Panels
47	Residence—Rooms for Rent	303 m^2	3.00 m	1	Steel House with dry construction on an existing conventional
48	Hotel	1.164 m^2	13.25 m	4	Steel frame of Composite Building
49	Residence—Rooms for Rent	126 m^2	8.30 m	2	Steel Frame of House
50	Industrial Area	36 m^2	9.50 m	1	Steel Building with Panel
51	Roof-Canopy	165 m^2	3.80 m	1	Steel Roof
52	Industrial Area	609 m^2	18.80 m	5	Steel Building with Panel
53	Various Constructions	120 m^2	3.50 m	1	Various Small Steel Structures
54	Various Constructions	60 m^2	8.00 m	2	Various Small Steel Structures
55	Industrial Area	819 m^2	7.50 m	2	Steel Additions with Panel
56	Industrial Area	196 m^2	4.15 m	1	Steel Building with Panel
57	Residence—Rooms for Rent	110 m^2	5.84 m	2	House with Steel Frame and Dry Construction
58	Residence—Rooms for Rent	237 m^2	3.41 m	1	House with Steel Frame and Dry Construction
59	Industrial Area	603 m^2	7.50 m	1	Steel Additions with Panel
60	Bridge Railing	1.128 m^2	4.70 m	1	Steel Decorative Bridge Railing
61	Industrial Area	3.039 m^2	7.60 m	2	Steel Building with Panel
62	Pedestrian Bridge	480 m^2	3.90 m	1	Steel Closed Pedestrian Bridge with Panel
63	Industrial Area	224 m^2	4.50 m	1	Steel Building with Panel
64	Industrial Area	536 m^2	7.00 m	2	Steel Building with Panel
65	Industrial Area	719 m^2	5.60 m	1	Steel Additions with Panel
66	Industrial Area	136 m^2	11.92 m	2	Steel Building Open for Silo
67	School	887 m^2	7.20 m	2	Steel Building with Panels
68	Mezzanine	77 m^2	3.00 m	-	Steel Mezzanine
69	Industrial Area	1.432 m^2	7.28 m	1	Steel Additions with Panel
70	Residence—Rooms for Rent	43 m^2	3.00 m	1	House with Steel Frame and Dry Construction
71	Bridge Railing	840 m^2	4.00 m	1	Steel Decorative Bridge Railing

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Machine-Learning-Based Consumption Estimation of Prestressed Steel for Prestressed Concrete Bridge Construction

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Abstract: Accurate prediction of the prestressed steel amount is essential for a concrete-road bridge's successful design, construction, and long-term performance. Predicting the amount of steel required can help optimize the design and construction process, and also help project managers and engineers estimate the overall cost of the project more accurately. The prediction model was developed using data from 74 constructed bridges along Serbia's Corridor X. The study examined operationally applicable models that do not require indepth modeling expertise to be used in practice. Neural networks (NN) models based on regression trees (RT) and genetic programming (GP) models were analyzed. In this work, for the first time, the method of multicriteria compromise ranking was applied to find the optimal model for the prediction of prestressed steel in prestressed concrete bridges. The optival model based on GP was determined using the VIKOR method of multicriteria optimization; the accuracy of which is expressed through the MAPE criterion is 9.16%. A significant average share of 46.11% of the costs related to steelworks, in relation to the total costs, indicates that the model developed in the paper can also be used for the implicit estimation of construction costs.

Keywords: material consumption; prestressed concrete bridges; machine learning; multicriteria optimization; compromise ranking; vikor

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1. Introduction

The development of a society and the state is highly dependent on the development of traffic and the state of the traffic infrastructure. The traffic infrastructure consists of many bridges, viaducts, culverts, and other facilities and is constantly expanding. In the entire past millennium to the 20th century, fewer bridges were built than now in one decade [1]. More than two million bridges are currently in use throughout the world [1]. Over 80% of the bridges built are concrete-girder bridges, with a significant share of prestressed concrete bridges. Many construction activities accompany the construction of bridges on roads, significant earthworks, geotechnical works, construction of the bridge structure itself, works on signaling, lighting, and construction of culverts and accompanying facilities.

A subset of artificial intelligence known as machine learning (ML) enables computer systems to learn from their past performance and advance accordingly. It entails analyzing and discovering patterns in data using statistical models and algorithms, followed by utilizing these patterns to create forecasts or conclusions regarding brand-new data. In numerous types of research in construction, it is applied to the random forest, AdaBoost, gradient boost regression trees, support vector regression, extreme gradient boosting, and ANN algorithms. Some successful implementations of these algorithms in predicting the behavior of elements in construction are listed in the works of Tang et al. (2022), Feng et al. (2023), and Zhao et al. (2023) [2–4].

A sufficiently accurate estimation of resources is essential when analyzing various technical solutions for bridges when detailed data on designed bridges are unavailable. In addition, the availability of information about the resources needed for the construction of bridges in the initial stages of the project enables the entire project to be seen more comprehensively to provide initial construction cost estimates for funding acquisition purposes and also from the aspect of maintenance through the analysis of the whole life cycle of the project. Recent thorough reviews of the literature and content evaluations of construction cost prediction models by Tayefeh Hashemi et al. (2020) and Antoniou et al. (2023) have shown that numerous models offering cost estimates and/or material consumption estimates at various design stages have been provided by researchers, mostly for buildings, but also for power generation or network construction, road construction, rail and road tunnels, and bridges [5,6].

One of the most detailed comparative studies related to the consumption of resources in bridge construction was done in 2001 by Flyvbjert et al. [4]. The total value of the analyzed projects in North America and Europe was over USD 90 billion. The results indicated that the average percentage error in cost estimation for bridges and tunnels is 33.8%, while the total average error for all analyzed projects is 27.6%. One of the important conclusions is the subjectivity in the assessment of resources in the construction of construction facilities [7].

An analysis of the consumption of resources, concrete, prestressed steel, and reinforcing steel, and equations for their assessment in the construction of prestressed bridges are provided by Men in 1991 in the book *Prestressed Concrete Bridges* [8]. The analysis is based on records of resource consumption during the construction of 19 prestressed concrete bridges in Switzerland. The cost of building bridges, as well as the consumption of resources during construction, is given as a function of the variable defined as the geometrical average-span length.

In 2001 Marcous et al. [9] worked on a preliminary quantity estimate of highway bridges using artificial-intelligence methods. On the basis of 22 prestressed concrete bridges across the Nile River in Egypt, artificial neural-network models were developed. In terms of testing the accuracy of the model, cross validation was used. As a result, it was found that the error of the created model in estimating the weight of prestressed steel is 11.5%.

The Egnatia Motorway, a 680 km long modern highway that serves five ports and six airports and connects the major cities of Northern Greece, is one of the largest civil engineering projects ever undertaken in Europe. A number of Greek researchers have used data from the Egnatia Motorway's bridges to develop their models for estimating bridge material consumption and construction costs. It is one of the original fourteen priority projects of the European Union and constitutes part of the Trans-European Network for Transport [10].

More specifically, Fragkakis et al., in 2011 [11], worked on a parametric model for estimating resources in the construction of concrete-bridge foundations. Their database included complete data on 78 structures and 157 pier foundations. The coefficient of determination exceeds 77% in all prediction models. Antoniou et al. [12,13] worked on a model for estimating highway bridge-underpass costs and material consumption. The research was based on data from 28 closed-box sections and six frame underpasses from the Egnatia Motorway and the E65 Motorway in Greece. Their first study [12] provided consumption values of reinforcing steel per m^3 of used concrete and the so-called theoretical volume of the structure. This new variable is described as the product of the length, width, and overhead clearance height of the local road that needs to be reconfigured to pass underneath the freeway. The same research team proceeded to develop more accurate linear regression models for forecasting the costs of underpass bridges, concrete consumption, and reinforcing steel consumption, depending on two input variables, i.e., the bridge surface area and the theoretical volume. As a result, satisfactory values of the coefficient of determination for cost estimation, consumption of concrete, and consumption of reinforcing steel of 0.80, 0.85, and 0.70, respectively, were obtained [12,13]. Similarly, Antoniou et al. [14] provided an analytical formulation for early cost estimation and material consumption of road overpass bridges in 2016. The database included data on 57 completed overpasses on the Egnatia Motorway. The research defined linear models for cost estimation, reinforcing steel consumption, and prestressing steel consumption. In the model for forecasting the consumption of prestressing steel, linear models are given for assessment depending on the deck surface area as an input variable and depending on the theoretical volume of the bridge, whose coefficient of determination value is 0.85 and 0.73, respectively. In this case the theoretical volume of the bridge is defined as the deck length multiplied by its width multiplied by the average pier height. In order to promote the use of prefabrication in the design and construction of highway concrete bridges in countries with nonwell-established relevant standards, Antoniou and Marinelli used multilinear regression analysis [15]. They proposed a set of standard precast extended I beams suitable for use in the majority of the common motorway-bridge models. The data of 2284 total beams from 109 bridges built along the Egnatia Motorway and two of its perpendicular axes [15] form the basis of the suggested set of standard beams.

Marinelli et al. [16] in 2015 worked on researching the application of artificial neural networks for nonparametric bill-of-quantities estimation of concrete road bridges. The data used to develop the model consists of 68 motorway bridges constructed in Greece between 1996 and 2008. A neural network model was used for forward signal propagation, and three output variables were forecast: the volume of concrete, the weight of reinforcing steel, and the weight of prestressed steel. The model's accuracy expressed through the MAPE criterion was 11.48% for precast beams, 13.94% for cast in situ, and 16.12% for the cantilever construction method.

Kovačević et al. created a number of models in 2021 [17] for estimating the cost of bridges made of reinforced concrete (RC) and prestressed concrete (PC). The characteristics of the project and the tender documents were included in the database for the 181 bridges in Serbia's Corridor X that were finished. The research's best option was a model based on Gaussian random processes, and it had an accuracy of 10.86% by the MAPE criterion.

Kovačević and Bulajić carried out a study in 2022 [18] to predict the consumption of prestressed steel used in the construction of PC bridges using machine-learning (ML) techniques. In Serbia's Corridor X, the database contained data on 75 completed prestressed bridges. According to the specified criterion MAPE, the model's accuracy in determining the prestressed steel consumption per square meter of the bridge superstructure was 6.55%.

The application of artificial neural-network models (ANNs), models based on regression trees (RTs), models based on support-vector machines (SVM), and Gaussian processes regression (GPR) are all taken into consideration by Kovačević et al. [19] in order to estimate the concrete consumption of bridges based on a database for the 181 bridges in Serbia's Corridor X in 2022. The most precise model, with a MAPE of 11.64%, is produced by employing GPR in combination with ARD's covariance function, according to the study. Also, the application of the GPR ARD covariance function makes it possible to see the importance of each input variable to the model's accuracy.

The development of a model for forecasting the amount of steel in this research is significant for science for several reasons. The prediction of the prestressed steel amount for a concrete road bridge is important for cost estimation, structural integrity, and the efficiency of the design and construction processes. The amount of prestressed steel used in a bridge directly affects the cost of construction. Accurately predicting the amount of steel required can help project managers and engineers estimate the overall cost of the project more accurately.

In this research, the hypothesis is that it is possible to define a model for forecasting the amount of prestressing steel using machine learning methods that will be accurate and transparent enough for practical application and where the amount of prestressing steel can be obtained based on a narrow set of model input variables. The RMSE, MAE, R, and MAPE criteria were defined for evaluating the model, while an effort was made to find a model with less complexity. In addition, the aim was to find a model that would, to the greatest extent, simultaneously satisfy all of the set criteria but at the same time is not particularly bad according to any individual criterion from the defined criteria.

In addition, to the author's knowledge, the method for finding the optimal compromise solution VIKOR was applied for the first time for forecasting the amount of prestressing steel. In this way, implementing the VIKOR method, within the set of potential alternatives that are represented by individual models that have different accuracy according to the selected criteria, there is a solution that satisfies all criteria well overall but is the least bad according to individual criteria.

2. Methods

In order to calculate the amount of prestressing steel used in the construction of prestressed concrete road bridges, different ML approaches are presented and analyzed in this study. The use of artificial neural networks, models based on the regression trees, and multigene genetic programming (MGGP) models were examined.

2.1. Multilayer Perceptron (MLP) Neural-Network Models

Multilayer perceptron (MLP) neural networks are a type of feed-forward artificial neural network that is commonly used for supervised-learning tasks. They are called "multi-layer" since they contain one or more hidden layers in addition to the input and output layers. Due to their ease of implementation and ability to simulate a variety of complex functions, MLP neural networks are widely employed.

The basic structural element (Figure 1) of neural networks is a neuron. The neuron model consists of the following elements [20].

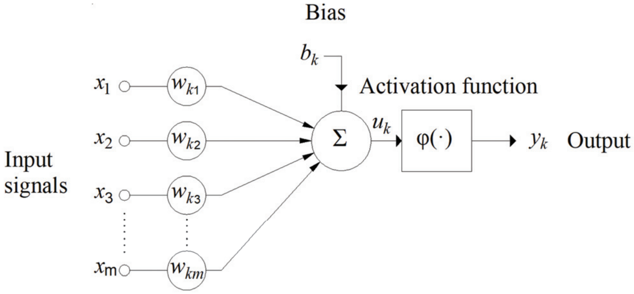


Figure 1. Artificial-neuron model [20].

- A collection of synapses that have corresponding weight values;
- Summarizing part, where inputs multiplied by appropriate weights are added;
- Appropriate activation function that restricts the neuron's output.

An artificial neuron consists of a group of weight coefficients that enter the body of a neuron, known as the node or unit, and a set of weights. Weights are connections with other neurons from the previous layer that then add up, and in the end, the bias value is added, which is independent of the other weights and serves to correct the sum. The following Equations (1) and (2) can mathematically explain this:

$$u_k = \sum_{j=1}^{m} w_{kj} x_j \tag{1}$$

$$y_k = \varphi(u_k + b_k) \tag{2}$$

where $x_1, x_2, \ldots, x_m$ are the corresponding input values of individual variables, and $w_{k1}, w_{k2}, \ldots, w_{km}$ are the corresponding weights for neurons k and b_k, the calculated bias.

A feed-forward neural network called a multilayer perceptron (Figure 2) consists of individual neurons grouped in at least three layers:

- Data enters the network at the input layer;

- All calculations using the data, weights, and biases are performed in the hidden layer;
- The output layer from which outcomes are obtained.

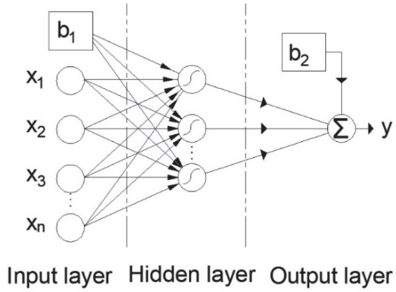


Figure 2. Multilayer perceptron (MLP) neural network [20].

If the MLP architecture with the property of universal approximator is used, the determination of the network structure is reduced to the determination of the number of neurons of the hidden layer since the number of input neurons is determined by the dimensions of the input vector and the number of output neurons is determined by the dimension of the output vector.

An MLP model with one hidden layer whose neurons have a tangent hyperbolic sigmoidal activation function, while the neurons of the output layer have a linear activation function, can approximate an arbitrary multidimensional function for a given dataset when there are a sufficient number of neurons in the hidden layer [17].

There are numerous recommendations regarding the approximate number of neurons in the hidden layer, some of which are listed in Table 1.

Table 1. Recommendations for the number of neurons in the hidden layer of a neural network.

	Number of Neurons in the Hidden Layer	**Reference**
1.	$N_H = (N_i + N_o)/2$	Ripley [21]
2.	$N_H = \sqrt{(N_i + N_o)}$	Kaastra [22]
3.	$N_H = 2 \times N_i$	Kannellopulas [23]
4.	$N_H = \frac{2}{3} \times N_i + N_o$	Heaton [24]
5.	$N_H = (4 \times N_i^2 + 3)/(\ N_i^2 - 8)$	Sheela [25]
6.	$N_H \leq min\left(2N_I + 1,\ \frac{N_S}{N_I+1}\right)$	Kovačević et al. [20]

Where N_I the is number of inputs, N_s is number of samples, and N_o is number of outputs.

In this paper, the upper limit of the number of neurons was adopted, and then different architectures of neural networks were examined, starting with one neuron in the hidden layer and finally with the number of neurons equal to the upper limit obtained by the expression in row 6 in Table 1.

2.2. Regression-Trees (RTs) Models

Regression trees (RTs) are a straightforward and understandable machine-learning model that may be used for regression and classification [20]. In each tree node, except for the leaves, the corresponding condition is examined. Whether the condition is met or not, one or the other branch of the tree goes to the next node. An example of a decision tree is given in Figure 3. For the corresponding input quantity, that is, the instance (a vector or matrix) of the problem under consideration and for which a prediction needs to be made, the corresponding condition at the root of the tree is first examined. Then, depending on the result, the instance follows the branch that corresponds to that result to the next node and repeats the process until it reaches the terminal leaf, whose value indicates the requested prediction. All instances of space initially belong to the same set, and then space is gradually split up into subsets.

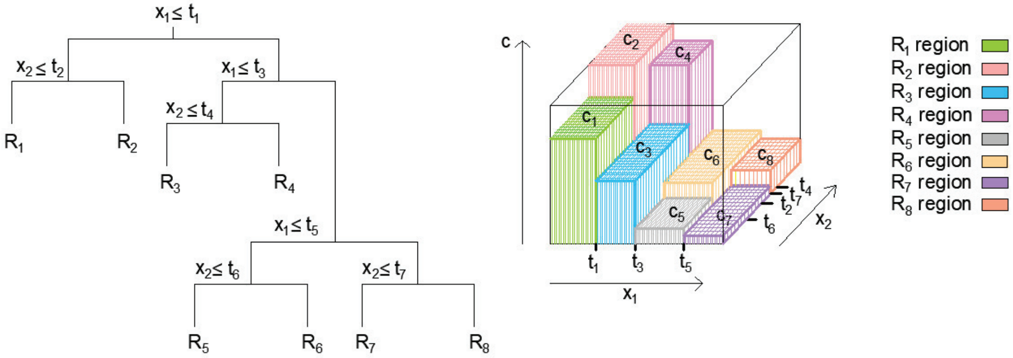


Figure 3. Example of segmenting variable spaces into regions (**left**), the creation of a 3D regression surface (**right**) [20].

The split variable *j* and split point value *s*, which serve as the location at which the division of space will be carried out, must be determined. Its value corresponds to the minimum value of the expression (3) that can be determined by examining all of the input variables in the model [26,27]:

$$\min_{j,\,s}\left[\min_{c_1}\sum_{x_i \in R_1(j,\,s)}(y_i - c_1)^2 + \min_{c_2}\sum_{x_i \in R_2(j,\,s)}(y_i - c_2)^2\right] \tag{3}$$

where $\hat{c}_1 = average(y_i\,|x_i \in R_1(j,\,s))$ and $\hat{c}_2 = average(y_i\,|x_i \in R_2(j,\,s))$.

After identifying the split variable *j* and the best-split point *s*, the process is maintained by further splitting these regions until a specific stop criterion is satisfied. This approach represents the so-called greedy approach since it only considers what is optimal in the current iteration, not considering whether that decision is also globally optimal [20,26,27].

According to the implemented binary recursive segmentation (Figure 3 (left)), each step involves splitting the input space into two parts and repeating the segmentation process. The resulting areas or regions should not overlap and encompass the whole space of predictors or input variables. In binary recursive partitioning, the output is characterized by the mean value in each of the two areas that make up the input space.

The Figure 3 shows the mean values for regions $R_1 - R_8$ denoted with $c_1 - c_8$ (Figure 3 (right)). Regions are defined using specific values $t_1 - t_7$, which represent the obtained optimal values for split point values s for split variables x_1 and x_2.

In this way, instead of one linear model for the entire domain of the considered problem, the domain is fragmented into a larger number of subdomains in which the corresponding linear model is implemented.

Deep regression trees are typically prone to overfitting since, by applying a large number of conditions, such trees can describe even irrelevant specificities of the data on which they were trained. Shallow trees typically have the problem of underfitting. Based on this, it can be concluded that the depth of the tree represents a regularization hyperparameter. The good side of decision trees is their interpretability. If the tree is small, its conditions clearly indicate the basis on which it makes decisions.

Moreover, each path through the decision tree from root to leaf can be seen as a single if–then rule, in which the condition represents the conjunction of all conditional outcomes along the path, while the final decision is the numerical value in the terminal leaf. Another advantage of using regression trees is that regression trees can combine categorical and continuous attributes.

2.3. Multigene Genetic-Programming (MGGP) Models

Genetic programming (GP) is a machine-learning method based on evolutionary principles applied to mathematical models of the problem under consideration [28]. The basic idea lies in the evolutionary principle that the biological individual best adapted to the environment survives. Analogous to that approach, individual prediction models can be considered biological individuals. The models that provide the most accurate forecast for the output-model variable can be considered the most adapted and survive and go into the next generation with other adapted models.

With the MGGP method [29–32], individuals are first created, making up the initial population (Figure 4). Then, each individual model is represented by one or more trees. The tree model is formed in the first iteration as a random selection of mathematical functions, constants, and model variables. Each tree represents one gene. Trees end with terminal nodes that are either model input variables or constants, while all other nodes are called functional nodes.

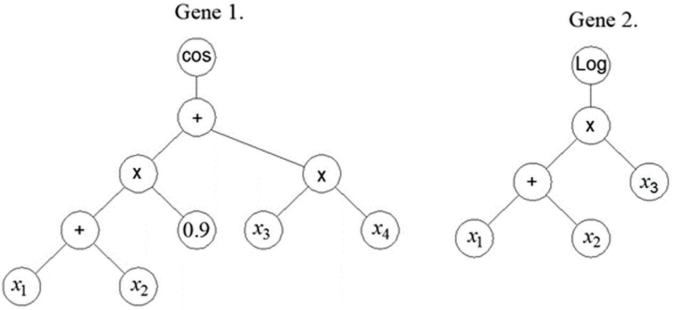


Figure 4. An example of an MGGP model that has two genes [17].

One prediction MGGP model consists of one or more trees or genes. After the formation of the initial population of a specific size, the models that are the most adapted, which in MGGP modeling means the models whose prediction differs the least from the target value, are selected. Those best models are then used to create the next population of models through crossover, mutation, and direct copying of individuals of the previous generation. In practical implementation, the selection is made, probabilistically based on the model's fitness value and/or complexity. The complexity of the model is based on the number of nodes and subtrees that can be formed from the given tree, which represents the so-called expressional complexity of the model.

A gene can either be replaced entirely during the crossover or partially changed [29–32]. If it is assumed that the individual model marked with J_1 (4) contains the following genes $[G_{1,1}\ G_{2,1}\ G_{3,1}\ G_{4,1}\ G_{5,1}]$ and if it is assumed that the other individual model marked with J_2 (5) contains the following genes $[G_{1,2}\ \ G_{2,2}\ \ G_{3,2}\ \ G_{4,2}\ \ G_{5,2}]$. Let us indicate by <> the genes that are randomly selected in both models with two cross sections:

$$J_1 : [G_{1,1} \ < \mathbf{G_{2,1}}\ \mathbf{G_{3,1}} > G_{4,1}\ G_{5,1}], \tag{4}$$

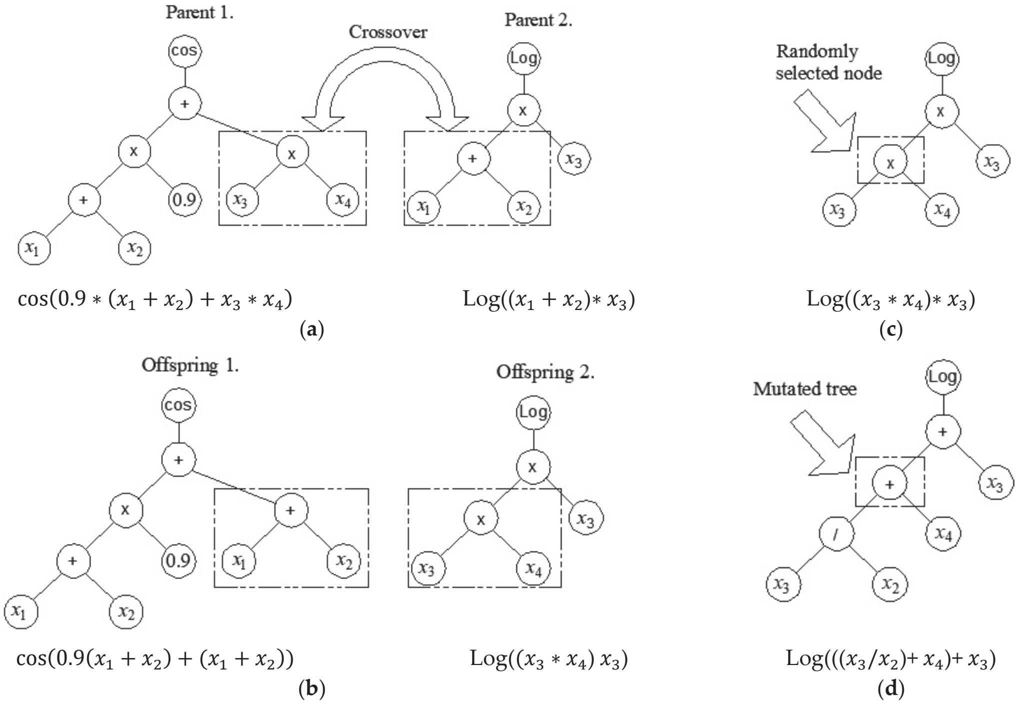
$$J_2 : \ [G_{1,2}\ \ G_{2,2}\ \ < \mathbf{G_{3,2}} > G_{4,2}\ \ G_{5,2}]. \tag{5}$$

The bolded portions of the model or entire genes covered by random cross sections are exchanged in the offspring O_1 (6) and offspring O_2 (7), which represents the so-called high-level crossover procedure [20].

$$O_1 : [G_{1,1}\ \ \mathbf{G_{3,2}}\ G_{4,1}\ G_{5,1}], \tag{6}$$

$$O_2 :[G_{1,2}\ \ G_{2,2}\ \ \boldsymbol{G_{2,1}}\ \boldsymbol{G_{3,1}}\ G_{4,2}\ \ G_{5,2}\ ]. \tag{7}$$

Crossover is also implemented at the level of one gene (low-level crossover), where the structure of a part of the gene changes (Figure 5a,b). However, only part of the gene may be exchanged (that is, only part of the tree is exchanged).



(**a**) (**c**) (**b**) (**d**)

Figure 5. Crossover and mutation operation in MGGP: (**a**) random selection of parent tree nodes; (**b**) exchange of parents' genetic material; (**c**) random node selection in tree mutation; and (**d**) mutation of a randomly selected part of a tree [20].

It is also possible to mutate at the level of a single gene in addition to crossover (Figure 5c,d). A mutation involves the random selection of one gene and one node within it. The relevant mutation is then carried out, adding a subtree that was randomly generated at the location of the chosen node. A specified number of iterations are made using the aforementioned processes.

The model obtained this way is pseudolinear since it represents a linear combination of nonlinear individual models in the form of a tree.

Mathematically, a multigene regression model can be represented by the following Equation (8):

$$\hat{y} = b_0 + b_1 t_1 + b_2 t_2 + \ldots + b_G t_G \tag{8}$$

where b_0 is the bias term, b_i is the ith scaling parameter, t_i is the $(N \times 1)$ vector of outputs from the ith tree (gene), and whose structure is represented by Figure 6.

With G, it is denoted the gene-response matrix, or $G = [\ 1\ t_1\ t_2\ \ldots\ t_G]$, whose dimensionality is $(N \times (G+1))$ and b is a vector of the coefficients $b = [b_0\ b_1\ \ b_2 \ldots\ b_G]$ is the dimensionality $((G+1) \times 1)$. Taking into account the above, the multigene regression model can be written in the following Equation (9):

$$\hat{y} = Gb \tag{9}$$

From the training data, the vector b is the least-squares estimate and it can be calculated using the following Equation (10):

$$b = \left(G^T G\right)^{-1} G^T y \tag{10}$$

Regular tournament selection, which solely employs RMSE or Pareto tournament, is used to choose individuals for breeding. Each individual in a Pareto tournament is chosen probabilistically based on their RMSE (fitness) score and expressional complexity. The procedure is successively repeated until a certain stopping criterion is reached.

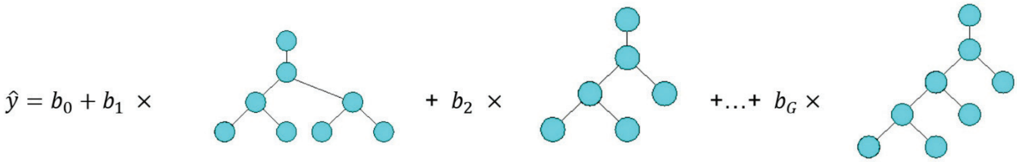


Figure 6. The general structure of the MGGP model [20].

2.4. Method for Multicriteria Compromise Ranking VIKOR

Very often, to solve various optimization problems, it is necessary to choose a solution that is evaluated based on a large number of criteria. Multicriteria decision-making (MCDM) approaches are used when selecting the best alternative from a list of potential alternatives due to their capacity to consider various and frequently conflicting criteria to create rankings of alternatives. Many different MCDMs have been adopted for decision making in the construction industry [33,34]. One of the ways to solve the problem is the VIKOR compromise programming method, which ranks the alternatives in such a way that they propose an alternative that ensures the maximum satisfaction of the majority of the defined criteria and, at the same time, is not particularly bad according to specific criteria [35–39]. It can be said that the proposed compromise solution is a compromise that satisfies both the majority and the minority criteria at the same time.

Compromise programming proposes establishing a reduced set of solutions to the problem of multicriteria optimization by employing the ideal point as a reference point in the space of criterion functions.

Suppose that there is an optimal solution x_i^*, ie. f_i^*, according to the i-th criterion (11):

$$f_i^* = \underset{x \in X}{ext} f_i(x), \ \ i = 1, 2, \ldots, n. \tag{11}$$

where *ext* represents the maximum if that criterion function represents something that is "good" that it is wanted to be maximized, such as profit, benefit, etc., or minimum if it represents something that is "bad" that it is wanted to be minimized, such as cost, something that is harmful, etc.

The vector $F^* = (f_1^*, \ \ldots, \ f_n^*)$, where n is the total number of criterion functions, $f_i(x)$ is the ideal solution to the problem of multicriteria decision making. In practice, it is rare that a potential solution is simultaneously optimal according to all of the individual criteria $f_i(x), i = 1, 2, \ldots, n$.

In real situations, it is necessary to find a solution closest to the ideal based on some adopted measure of distance. Therefore, in the VIKOR method, the measure of the distance from an ideal point defined by Equation (12) [33–37] is used:

$$L_p(F^*, F) = \left\{ \sum_{i=1}^{n} [f_i^* - f_i(x)]^p \right\}^{1/p}, \ 1 \le p \le \infty. \tag{12}$$

This metric represents the distance between the ideal point F^* and point $F(x)$ in the space of criterion functions. In order to emphasize the dependence on the parameter p, the metric $L_p(F^*, F)$ will be denoted by $R(F(x), p)$.

The solution $x^+(p) \in X$ which achieves the minimum of the function $R(F(x), p)$, is called the compromise solution of the multicriteria optimization problem with the parameter p [35–39].

The function $R(F(x),\ p)$ for $p = \infty$ has the following form (13):

$$R(F(x),\ \infty) = \max_i \left[f_i^* - f_i(x)\right]. \tag{13}$$

When the value of the parameter p tends to infinity, the problem of the distance from the ideal point is reduced to the mini–max problem.

In the case of compromise optimization, in the general case, it is necessary to determine the sequence for a particular set of alternatives $\{a_1,\ a_2, \ldots, a_{J.}\}$ According to the defined criteria $f_1, f_2, \ldots,\ f_n$.

The distance of some alternative a_j, concerning the ideal point in relation to all defined criteria (the criteria are considered in summary), is measured by the measure S_j, which is defined by the following Equation (14):

$$S_j = \sum_{i=1}^{n} \left[w_i\left(f_i^* - f_{ij}\right) / \left(f_i^* - f_i^-\right)\right], for\ p = 1), \tag{14}$$

where w_i represents the weight attached to some criterion f_i; f_{ij} represents the value of i-th criterion function for the alternative a_j; f_i^* represents the best value according to criterion i; and f_i^- represents the worst value according to criterion i ($i = 1, 2, \ldots, n$).

The distance of some alternative a_j, concerning the ideal point to certain individual criteria, is defined through the measure R_j, which is defined by the following Equation (15):

$$R_j = \max_i \left[w_i\left(f_i^* - f_{ij}\right) / \left(f_i^* - f_i^-\right)\right],\ \ (for\ p = \infty). \tag{15}$$

Using the defined measures S_j and R_j, the initially defined problem of finding the optimal solution concerning the defined criteria $f_i(x)$, $i = 1, 2, \ldots, n$, is reduced to a two-criteria problem of optimizing the distance from the ideal point.

The ideal alternative in the new two-criteria problem has the following goodness-measure values (16), (17):

$$S^* = \min_j S_j \ and\ R^* = \min_j R_j \tag{16}$$

$$S^- = \max_j S_j \ and\ R^- = \max_j R_j \tag{17}$$

The definitive measure of the optimality of an alternative is determined by the value Q_j, which represents the superposition of measures S_j and R_j, i.e., the balance between the fact that the better alternatives better meet the majority of criteria and have a minimal deviation from individual criteria, is determined by the Equation (18):

$$Q_j = v_1 QS_j + v_2 QR_j. \tag{18}$$

where v_1 is the weight of decision-making strategy satisfying the majority of criteria, v_2 is the weight of decision-making strategy taking into account the individual criterion, the distance values of individual alternatives are normalized in relation to measures S_j and R_j, i.e., $QS_j = \left(S_j - S^*\right) / \left(S^- - S^*\right)$, and $QR_j = \left(R_j - R^*\right) / \left(R^- - R^*\right)$. If both strategies have the same weight, then $\nu = v_1 = v_2 = 0.5$.

According to [35–39], the VIKOR approach only proposes the alternative that is in the first position on the compromise ranking list for $\nu = 0.5$ as a multicriteria optimal alternative (for specified weights w_i) if it also has:

- "sufficient advantage" over the alternative from the next position (condition U_1);
- "sufficiently firm" first position with weight change ν (condition U_2).

Alternative a' has a sufficient advantage for $\nu = 0.5$ over the following a'' from the ranking list if (19):

$$Q(a'') - Q(a') \geq DQ, \tag{19}$$

where DQ is the "priority threshold" $DQ = \min(0.25;1/(J-1))$, and J represents the total number of problem alternatives.

3. Dataset

This research analyzed the consumption of prestressing steel in prestressed concrete bridges (prefabricated or cast onsite). In order to create an appropriate model for assessment, it was necessary to create an appropriate database on prestressed bridges, for which data was collected on realized prestressed concrete bridges on Corridor X in Serbia. In addition, project and contract documentation was collected for 74 completed bridges on the highway and the connecting roads to the highway (Figure 7).

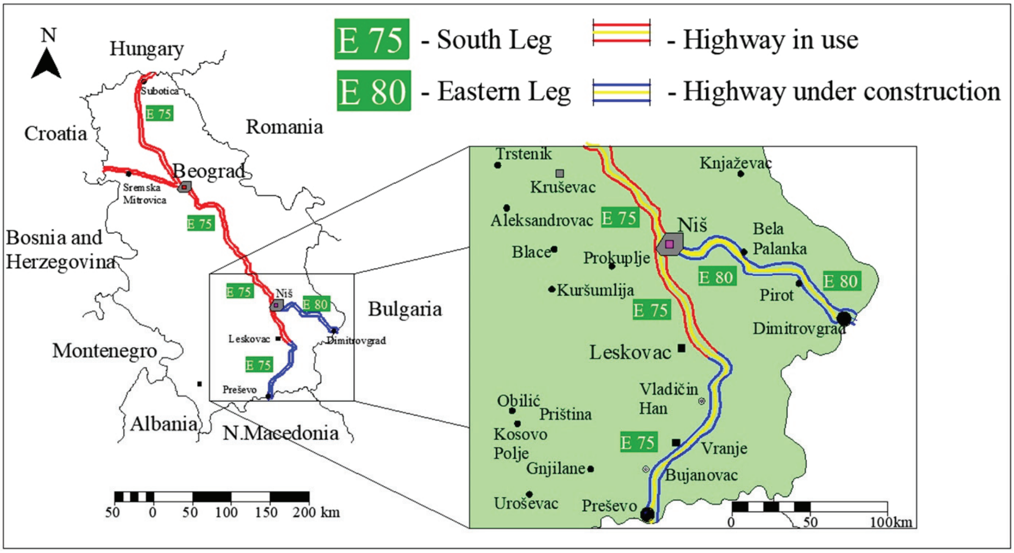


Figure 7. Eastern and southern legs of Corridor X in Serbia [17].

Most research uses a modified span variable. In this research, variables were introduced that take into account the maximum individual span, the average span, and the total length span of the bridge since it is very important for the model whether the bridge is made of a larger number of smaller spans or a smaller number of larger spans. In addition, sometimes, not all spans on the same bridge are the same. Since, in the case of bridges that have more spans, where a certain span can be slightly larger than the other spans (e.g., due to the river that the bridge spans), a variable describing the maximum span was introduced.

In addition, the dataset included bridges on the highway itself, but also a certain number of access bridges, so a variable was introduced that contains information about the width of the road. The variable that contains information about the width of the road implicitly contains information about the useful load. The bridges that were analyzed were located in a narrow geographical area, and there were no differences in terms of load, so the load was not treated as a separate variable.

The data was divided so that 70% of the total data was assigned to the training set, and the remaining 30% of the data that the model did not see was used for testing the model. When dividing the data, it was taken into account that these two sets of data should have similar statistical characteristics.

The data was divided by mixing the entire set using the integrated randperm Matlab function several times and then randomly separating the training and test set from it in the specified percentage while controlling the statistical indicators of the training and test set, which should be, ideally, in the case of the same, that is, in the practical research of similar values. A total of 52 datasets were used for model training. The remaining data from 22 datasets were not submitted to the model and were used for model evaluation.

For the input variables for the forecast model of prestressing steel per m^2 of the bridge superstructure, the following were taken: x_1—maximum individual bridge span (MIBS), x_2—average bridge span (ABS), x_3—total bridge span (TBS) length, x_4—bridge width (BW).

Based on project documents, the dependent variable PS, being the mass in kg of prestressed steel per m^2 of the bridge superstructure, is calculated. The statistical characteristics of the model variables are given in Table 2. The mechanical characteristics of the prestressing steel are given in Table 3.

Table 2. Mean, minimum, and maximum values of variables in the model used to estimate the prestressed steel consumption per m^2 of the bridge superstructure.

Variable	**Average Value**	**Minimum Value**	**Maximum Value**
Max. individual bridge span—MIBS [m]	31.58	18.00	49.00
Average bridge span—ABS [m]	30.74	17.60	44.91
Total bridge span—TBS [m]	161.33	21.20	628.74
Bridge width—BW [m]	12.81	8.40	17.80
Mass of prestressed steel (PS) [kg/m^2]	17.13	8.98	38.74

Table 3. Geometrical and mechanical rope characteristics [18].

		Nominal Values			**Guaranteed Values**			
Abbreviated Name	**Class**	**Diameter Ø [mm]**	**Tensile Strength [N/mm^2] fpk**	**Elastic Modulus kN/mm^2**	**Section Area [mm^2] Apk**	**Characteristic Breaking Force [kN] fpk**	**Characteristic 0.1% Proof Stress of Prestressing Fp0.1k Steel [kN]**	**Maximum Relaxation at a Force of 0.7 Fpk after 1000 h [2.5%]**
Y1770S7	A	15.2	1770	195	140	248	213	2.5
Y1860S7	B	15.2	1860		140	260	224	
Y1770S7	A	16.0	1770		150	265	228	
Y1860S7	B	16.0	1860		150	279	240	

By analyzing the correlation matrices of the considered variables of the model, it can be observed that there is a significant intercorrelation of the variables of the model. Significant intercorrelation of model variables significantly reduces the accuracy of linear regression models, and nonlinear machine-learning models are particularly suitable for modeling in these cases.

In the specific case, all the variables related to the span are correlated (MIBS, ABS, and TBS) by the amount of prestressing steel as an output variable. However, the variable bridge width (BW), which has a low correlation with the value (R = 0.08) with the output variable, is correlated with other input variables. The application of machine-learning methods is particularly suitable in such cases of synergistic effects of individual input variables.

Data related to the consumption of prestressing steel is a good indicator of the total costs. In the formed database of 74 bridges, the calculated share of steel works in the total costs was 46.11%, while the share of concrete works was 40.66%. A model that would focus on the prediction of the amount of steel could also be used for implicit cost estimation.

Histograms of model variables and mutual correlations with the correlation coefficient values are given in Figure 8. From Figure 8, it is noticeable that there is a significant intercorrelation between most of the input variables of the model.

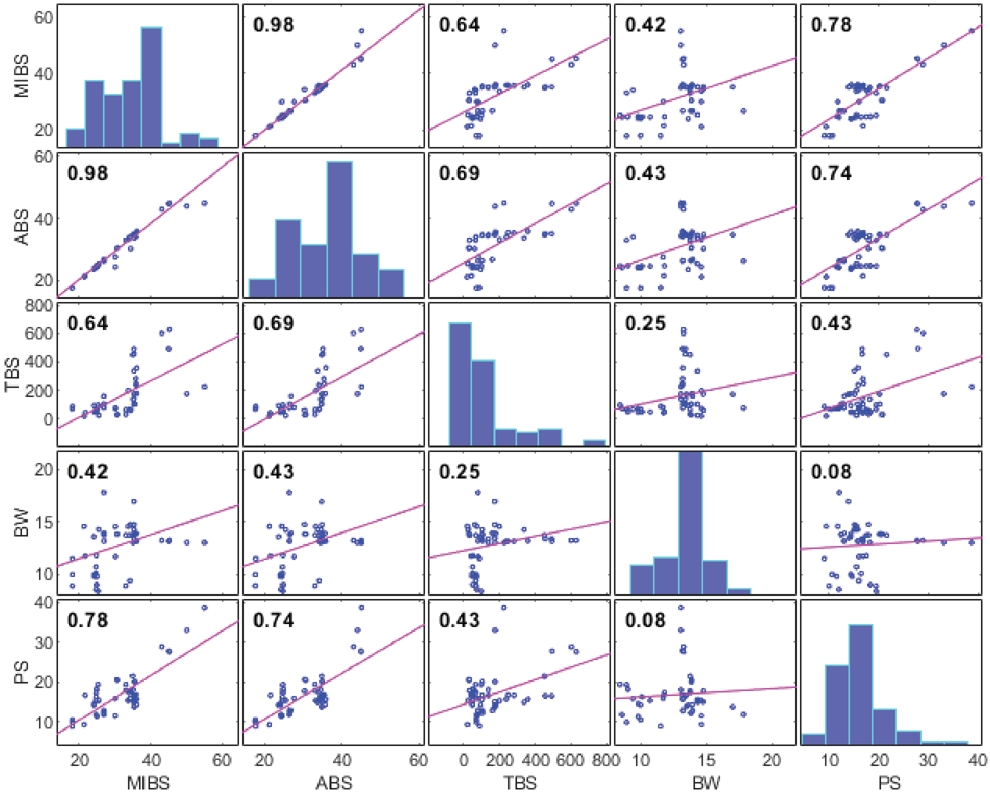


Figure 8. Correlation matrix of model variables.

In Table 3, the mechanical characteristics of the prestressed steel ropes are listed for the reason that the limitation of the developed model is that the amount of steel obtained by prediction refers to the prestressed steel of the given characteristics.

Criteria for Assessing Model Accuracy

In the research, all models were trained and tested under identical conditions. When determining the optimal model, the accuracy of the model according to the criteria RMSE, MAE, R, and MAPE was taken into account, though the complexity of the model was also taken into account. The applied systemic approach to modeling is given in Figure 9. The RMSE and MAE criteria are absolute criteria of model accuracy expressed in the same unit as the variable that is being modeled. MAPE and R criteria are relative criteria of model accuracy and have no unit.

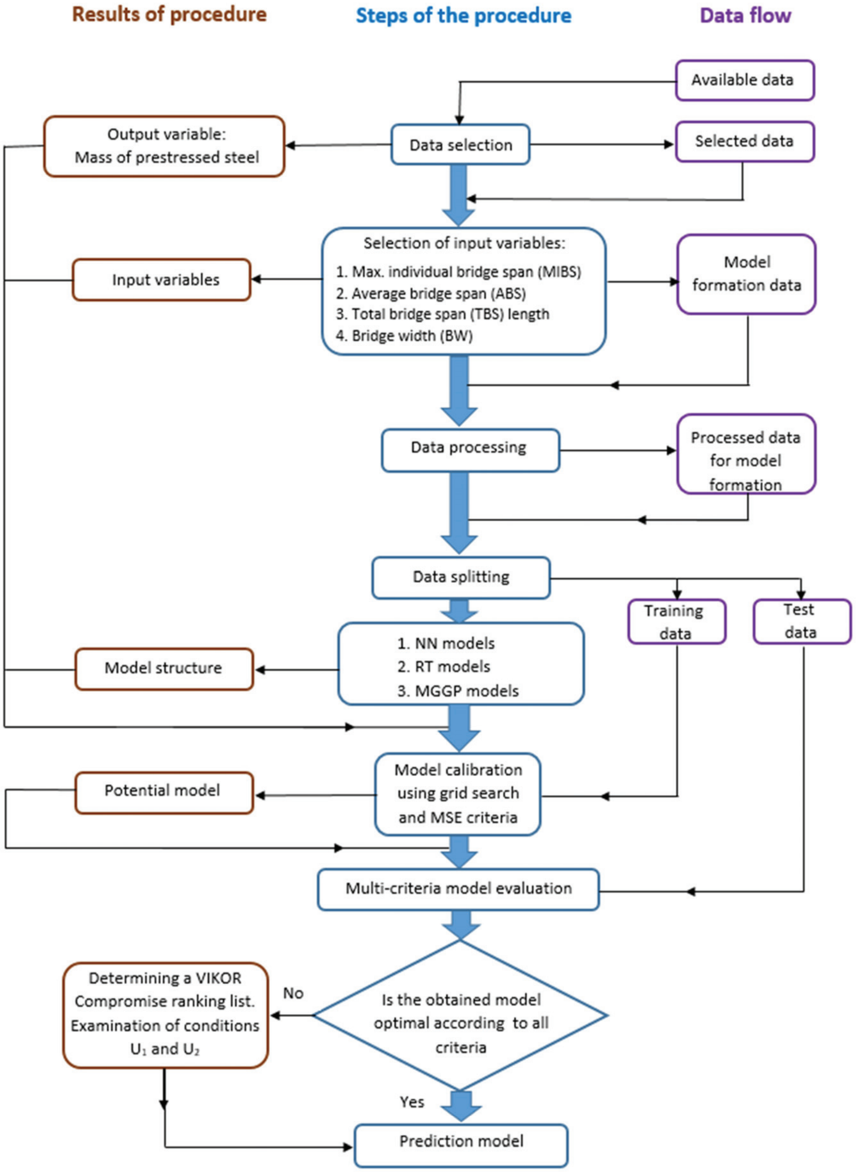


Figure 9. Systemic approach applied in research.

The RMSE criterion is defined by Equation (20) and is characterized by the fact that deviations from the target value are first squared, then averaged, and then their square root is found. With such a calculation, a greater emphasis on greater deviations is given.

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(d_k - o_k)^2} \tag{20}$$

where d_k is the target value, o_k is the modeled output, and N is the number of samples.

The MAE is used to estimate the model's mean absolute error and practically all deviations have the same weight. It is defined by the following Equation (21):

$$\mathrm{MAE} = \frac{1}{N}\sum_{k=1}^{N}|d_k - o_k\ | \tag{21}$$

The R coefficient, is a relative criterion for the evaluation of the model's accuracy. It is defined in dimensionless form by the following Equation (22):

$$\mathrm{R} = \sqrt{\left[\sum_{k=1}^{N}(d_k - \overline{d})(o_k - \overline{o})\right]^2 \times \left[\sum_{k=1}^{N}\left(d_k - \overline{d}\right)^2(o_k - \overline{o})^2\right]^{-1}} \tag{22}$$

where $\overline{o}$ is the predicted mean and $\overline{d}$ is the mean target value.

The mean absolute percentage error (MAPE) is a measure of prediction accuracy calculated in dimensionless form. The accuracy is expressed as a ratio determined by the following Equation (23):

$$\mathrm{MAPE} = \frac{100}{N}\sum_{k=1}^{N}\left|\frac{d_k - o_k}{d_k}\right| \tag{23}$$

When determining the optimal solution, the VIKOR method of multicriteria compromise ranking of alternatives was used to obtain a solution or model that will satisfy the majority of criteria, but will not be significantly bad, according to any defined individual criteria. In addition, the complexity of the model was taken as a criterion.

4. Results

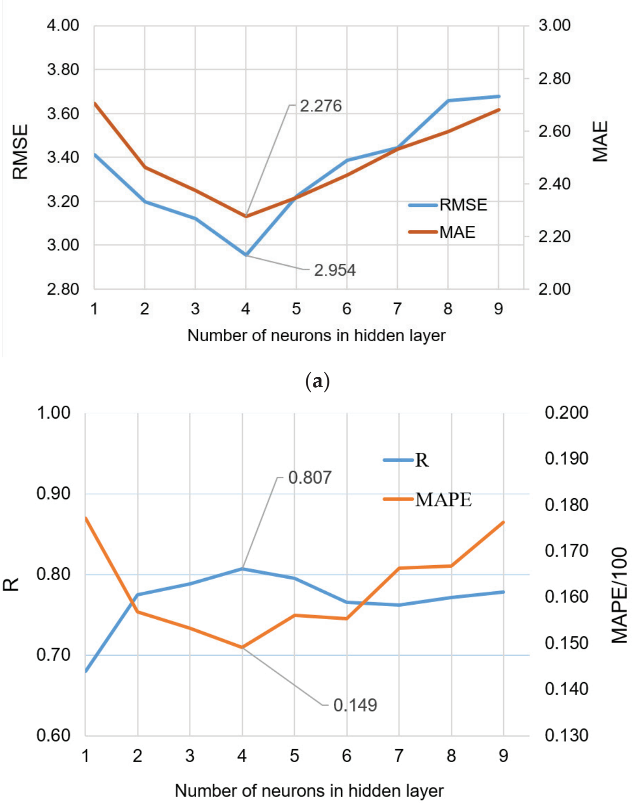
With the applied methods depending on the method, a different data-preparation procedure was applied. In the method of artificial neural networks, linear scaling in the interval [0, 1] was applied so that all of the variables were equal during model training and then rescaled, and an accuracy assessment was performed after the output variables were rescaled. No scaling was applied to regression tree models and models based on genetic programming.

The MLP neural network has a fixed number of neurons in the input and output layers, with four and one neurons, respectively. However, the number of neurons in the hidden layer was determined through experimentation and was limited to a maximum of nine neurons based on expression in row six in Table 1.

For determining the optimal number of neurons in the hidden layer, the network was trained multiple times with different numbers of neurons in the hidden layer ranging from one to nine, as illustrated in Figure 10. The adopted limit of nine neurons is large enough to satisfy all the recommendations indicated by the expressions in Table 1. By analyzing Figure 10, it can be seen that the thus-adopted range for the number of neurons is satisfactory and, within that range, the accuracy functions RMSE, MAE, and MAPE have minima, while R achieves maximum. The results of the training indicate that the best number of neurons in the hidden layer is four, which was determined by evaluating the network's performance using four quality criteria: RMSE, MAE, R and MAPE, as shown in Figure 10.

All models were trained within the Matlab program with default parameter settings. The LM algorithm was used.

The regression-tree model is built using a recursive binary-splitting process. Starting from the root node, the predictor variable that best separates the data into two subsets is selected using a split criterion mean-squared error (MSE). This process is repeated for each subset until a stopping criterion is reached. The splitting process continues until a set of leaf nodes is reached that provides predictions of the dependent variable. This research implements a minimum number of observations per node as the stopping criterion.



(**a**)

(**b**)

Figure 10. Comparison of the accuracy criteria for MLP-ANNs with different numbers of neurons in the hidden layer: (**a**) RMSE and MAE; and (**b**) R and MAPE.

The performance of the regression tree can be improved by tuning the hyperparameters, such as the maximum tree depth and the minimum number of observations per node. This involves trying different values of the hyperparameters and evaluating the performance of the tree on the testing set. The goal is to find the optimal hyperparameters set that provides the best predictions.

In this research, the RT model examined different values of the minimum amount of data per parent node ranging from 1 to 10 and the minimum amount of data per terminal leaf from 1 to 10. All the models thus obtained were evaluated in terms of the defined accuracy criteria RMSE, MAE, R, and MAPE on a defined test set of subdata.

It was found that the optimal model with a min parent size equal to four and a minimum amount of data per terminal sheet is two. The structure of the regression table is given in Figure 11.

With the MGGP model, the first population of random trees is generated to start the evolutionary process. In all models, a population of 1000 randomly generated trees was initially formed using a functional set composed of selected mathematical operators and randomly selected ephemeral random constant (ERC) values (Table 4). Within the MGGP model, the selection of the appropriate parameters in terms of crossover probability, mutation probability, and probability of the Pareto tournament, which determines the transfer of individuals to the next generation, is of crucial importance for creating the model. The ERC probability, which determines the probability of the appearance of certain values of constants from the range [−10, 10] in terminal leafs, is set to the value of 0.1, and the tournament size is set to the smallest value of two, which prevents premature convergence and ensures a greater diversity of individuals. The values for the number of genes were adopted in accordance with the recommendations of the authors of the GPTIPS 2.0 software with the maximum value of five, while the optimal depth of the trees was investigated experimentally.

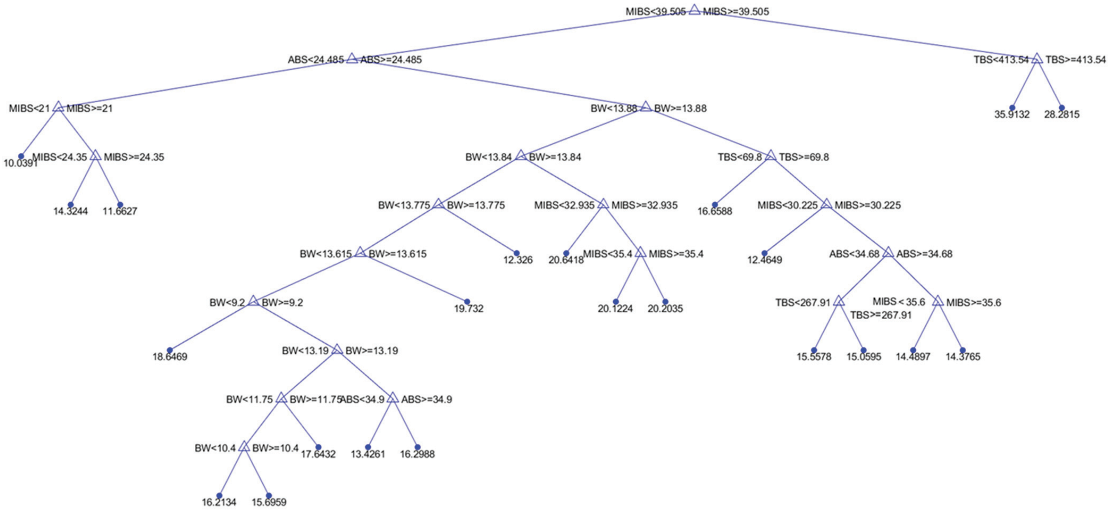


Figure 11. Graphic representation of the optimal regression tree model.

Table 4. Setting parameters for MGGP models.

Parameter	Setting
Function set	times, minus, plus, rdivide, square, exp, log, mult3, sqrt, cube, power
Population size	1000
Number of generations	100
Max number of genes	5
Max tree depth	6
Tournament size	2
Elitism	0.05% of population
ERC probability	0.1 (Integer 0.5)
Crossover probability	0.85 (High level 0.2, Low level 0.8)
Mutation probability	0.14
Probability of Pareto tournament	0.7

Each tree in the population is then evaluated simultaneously based on fitness expressed through RMSE and expressional complexity. The fittest individuals from the population are selected to be parents for the next generation. The selected parents are then combined through genetic operators such as crossover and mutation to produce offspring for the next generation, and a certain percentage of trees (0.05% of the population) went directly to the next generation.

The offspring replace the least-fit individuals in the population to create the next generation. The evolutionary process is continued until a stopping criterion is met, such as a maximum number of generations or a desired level of fitness. The complexity of the model was examined using the MGGP approach using various values of the number of genes and various tree depths.

In this research, the maximum number of generations was limited to 100, and the procedure was repeated ten times for each gene structure with a defined maximum depth of the tree, and the models were combined. Models with one to five genes whose tree depth varied from one to six were tested. A total of 30,000,000 MGGP models were tested.

In order to single out the optimal models, a graphic representation of the population of models obtained during 100 generations was used and presented on a two-dimensional graph, one axis of which is expressional complexity and the other axis is the value of $1 - R^2$. In this way, it is possible to define the so-called Pareto front composed of regression MGGP models that are not inferior in terms of expressional complexity and the $1 - R^2$ value, represented by green dots. Non-Pareto models are represented by blue dots.

It is of interest to further analyze these models on the test dataset in terms of the defined accuracy criteria RMSE, MAE, R and MAPE. In the specific case, e.g., model that has three genes and whose depth is six, the Pareto front is made up of 19 different models (marked green). The optimal model in the training set is represented by a green dot with a red border (Figure 12).

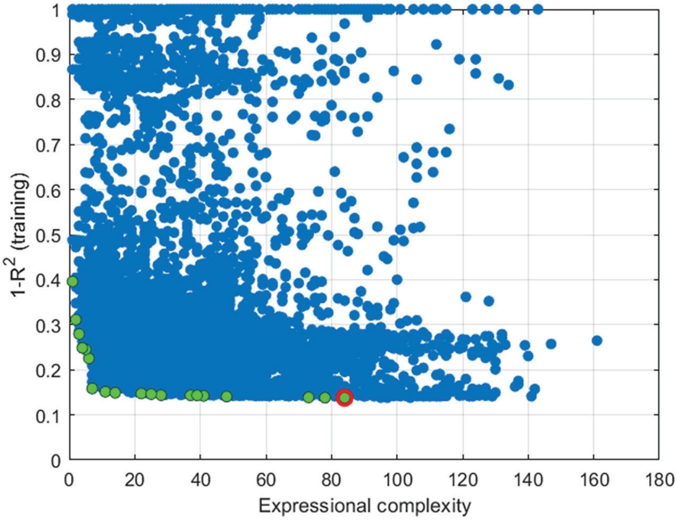
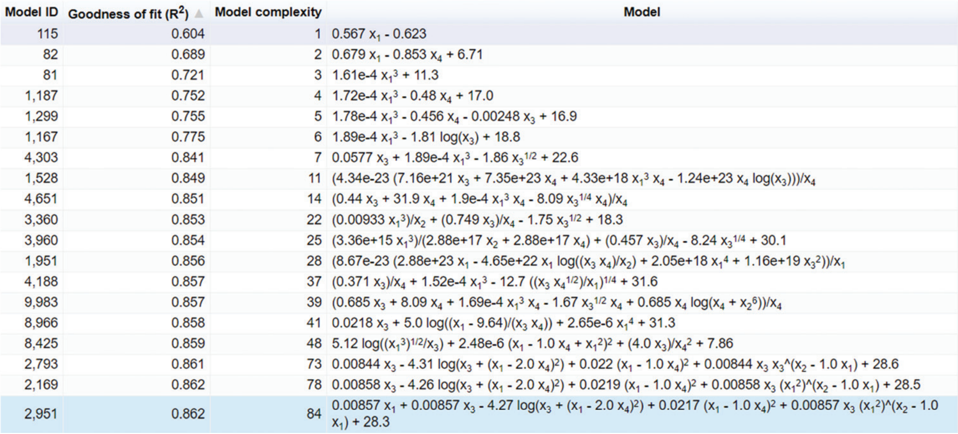


Figure 12. Pareto front of models in terms of model performance and model complexity for a model with 3 genes and depth of up to 6.

In total, more potential architectures of the MGGP model were analyzed, that is, models with one, then two, three, four and five genes. For each model, the depth varies from one to a maximum of six. Using the evolutionary process, it creates a total of one million models for each type of model, and only the best 10,000 were displayed on the Pareto front. The number of model types is 30 (since we have models of up to five genes whose depth is from one to six, that gives 5 × 6 = 30 model types).

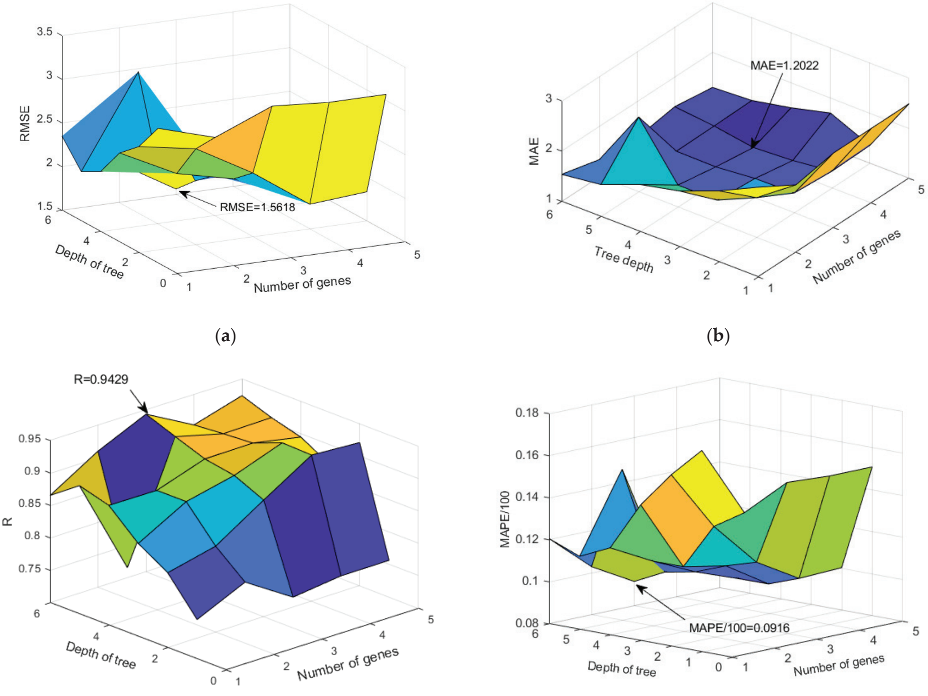
Figure 13 shows 19 Pareto optimal models out of a total of a million analyzed models that have a given structure of three genes (three trees) and whose tree depth is a maximum of six.

The results of all of the analyzed models in terms of the defined criteria are graphically presented in the Figure 14. It can be seen that in terms of RMSE and R criteria, the optimal model is composed of three genes whose tree depth is limited to six. Regarding the MAE criteria, the optimal model is composed of four genes whose depth is limited to four. While in terms of the MAPE criteria, it was found that the model with three genes and whose tree depth was limited to six was the most accurate. Regarding expression complexity, the optimal model is a model with four genes and a depth of up to three, whose expression complexity is the lowest and amounts to 39. The value of expression complexity is given automatically by the GPTIPS 2.0 software. Details regarding the model with four genes and whose tree depth is a maximum three are given in Appendix A (Figures A1–A3), while for the model with four genes whose tree depth is four, details are given in Appendix B (Figures A4–A6).



Model ID	Goodness of fit (R^2)	Model complexity	Model
115	0.604	1	$0.567\ x_1 - 0.623$
82	0.689	2	$0.679\ x_1 - 0.853\ x_4 + 6.71$
81	0.721	3	$1.61e\text{-}4\ x_1^3 + 11.3$
1,187	0.752	4	$1.72e\text{-}4\ x_1^3 - 0.48\ x_4 + 17.0$
1,299	0.755	5	$1.78e\text{-}4\ x_1^3 - 0.456\ x_4 - 0.00248\ x_3 + 16.9$
1,167	0.775	6	$1.89e\text{-}4\ x_1^3 - 1.81\log(x_3) + 18.8$
4,303	0.841	7	$0.0577\ x_3 + 1.89e\text{-}4\ x_1^3 - 1.86\ x_3^{1/2} + 22.6$
1,528	0.849	11	$(4.34e\text{-}23\ (7.16e{+}21\ x_3 + 7.35e{+}23\ x_4 + 4.33e{+}18\ x_1^3\ x_4 - 1.24e{+}23\ x_4\log(x_3)))/x_4$
4,651	0.851	14	$(0.44\ x_3 + 31.9\ x_4 + 1.9e\text{-}4\ x_1^3\ x_4 - 8.09\ x_3^{1/4}\ x_4)/x_4$
3,360	0.853	22	$(0.00933\ x_1^3)/x_2 + (0.749\ x_3)/x_4 - 1.75\ x_3^{1/2} + 18.3$
3,960	0.854	25	$(3.36e{+}15\ x_1^3)/(2.88e{+}17\ x_2 + 2.88e{+}17\ x_4) + (0.457\ x_3)/x_4 - 8.24\ x_3^{1/4} + 30.1$
1,951	0.856	28	$(8.67e\text{-}23\ (2.88e{+}23\ x_1 - 4.65e{+}22\ x_1\log((x_3\ x_4)/x_2) + 2.05e{+}18\ x_1^4 + 1.16e{+}19\ x_3^2))/x_1$
4,188	0.857	37	$(0.371\ x_3)/x_4 + 1.52e\text{-}4\ x_1^3 - 12.7\ ((x_3\ x_4^{1/2})/x_1)^{1/4} + 31.6$
9,983	0.857	39	$(0.685\ x_3 + 8.09\ x_4 + 1.69e\text{-}4\ x_1^3\ x_4 - 1.67\ x_3^{1/2}\ x_4 + 0.685\ x_4\log(x_4 + x_2^6))/x_4$
8,966	0.858	41	$0.0218\ x_3 + 5.0\log((x_1 - 9.64)/(x_3\ x_4)) + 2.65e\text{-}6\ x_1^4 + 31.3$
8,425	0.859	48	$5.12\log((x_1^3)^{1/2}/x_3) + 2.48e\text{-}6\ (x_1 - 1.0\ x_4 + x_1^2)^2 + (4.0\ x_3)/x_4^2 + 7.86$
2,793	0.861	73	$0.00844\ x_3 - 4.31\log(x_3 + (x_1 - 2.0\ x_4)^2) + 0.022\ (x_1 - 1.0\ x_4)^2 + 0.00844\ x_3\ x_3\hat{}(x_2 - 1.0\ x_1) + 28.6$
2,169	0.862	78	$0.00858\ x_3 - 4.26\log(x_3 + (x_1 - 2.0\ x_4)^2) + 0.0219\ (x_1 - 1.0\ x_4)^2 + 0.00858\ x_3\ (x_1^2)\hat{}(x_2 - 1.0\ x_1) + 28.5$
2,951	0.862	84	$0.00857\ x_1 + 0.00857\ x_3 - 4.27\log(x_3 + (x_1 - 2.0\ x_4)^2) + 0.0217\ (x_1 - 1.0\ x_4)^2 + 0.00857\ x_3\ (x_1^2)\hat{}(x_2 - 1.0\ x_1) + 28.3$

Figure 13. Original output from the GPTIPS 2.0 software with analytical expressions of the models that make up the Pareto front (models with 3 genes and a maximum depth of generated trees of up to 6).



(**a**) (**b**)

(**c**) (**d**)

Figure 14. Comparison of accuracy criteria for the MGGP model as a function of gene number and tree depth (**a**) RMSE, (**b**) MAE, (**c**) R, and (**d**) MAPE.

The specific analysis did not single out one model as the most accurate in terms of all defined criteria of accuracy, so a multicriteria analysis (Table 5) was used to rank the potential solutions. In order to select a multicriteria optimal solution, the approach was to try to select a solution that, to the greatest extent, satisfies all the criteria of accuracy, and does not have extremely bad criteria indicators, according to individual criteria.

Table 5. Values of criterion functions for individual models or alternatives.

Criteria	a_1 (Gene = 4, Depth = 4)	a_2 (Gene = 4, Depth = 3)	a_3 (Gene = 3, Depth = 6)	f_i^*	f_i^-
f_1 = RMSE	1.9531	1.7602	**1.5618**	1.5618	1.9531
f_2 = MAE	**1.2022**	1.2462	1.2843	1.2022	1.2843
f_3 = MAPE/100	0.0940	0.0941	**0.0916**	0.0916	0.0941
f_4 = R	0.9091	0.9268	**0.9429**	0.9429	0.9091
f_5 = expr.comp.	54	**39**	84	39	84

In addition, priority was given to finding a solution that has a lower complexity of expressions. The complexity of the expression is defined by the expressional complexity value given by GPTIPS 2.0 [27,28] software. As a methodological approach, the VIKOR method for finding compromise solutions was implemented. In this way, the search for a multicriteria compromise optimal solution was started.

When applying the VIKOR method, it was assumed that all criteria have the same weight, which is $w_i = 0.2$, ($i = 1, 2, \ldots, 5$). Since the criteria space is heterogeneous, i.e., criteria expressed in different units, all values are first scaled into the interval [0, 1]. The length of the range of the i-th criterion function is $D_i = f_i^* - f_i^-$, where for each i-th criterion, f_i^* corresponds to the best alternative system (or decision) and f_i^- the worst. For creating dimensionless functions (Table 6) with an interval range from criteria functions [0, 1], the following transformation is used here (20):

$$d_{ij} = T\left(f_i^* - f_{ij}\right) = \left(f_i^* - f_{ij}\right)/D_i \tag{24}$$

Table 6. Normalized and weighted normalized values of criterion functions.

Criteria	d_{i1}	d_{i2}	d_{i3}	$w_i d_{i1}$	$w_i d_{i2}$	$w_i d_{i3}$
f_1 = RMSE	1	0.5070	0	0.2	0.1014	0
f_2 = MAE	0	0.5359	1	0	0.1072	0.2
f_3 = MAPE/100	0.96	1	0	0.192	0.2	0
f_4 = R	1	0.4763	0	0.2	0.0953	0
f_5 = expr.comp.	0.3333	0	1	0.06667	0	0.2

Using the normalized values, the following metric values can be obtained:

$$S_j = \Sigma_{i=1}^{i=5} w_i d_{ij}; S_1 = 0.658667; S_2 = 0.503858; S_3 = 0.4;$$
$$R_j = \max_i \left[w_i d_{ij}\right]; R_1 = 0.2; R_2 = 0.2; R_3 = 0.2;$$

The VIKOR method introduces a modified measure R_j by adding to the value obtained in the previous expression a value of the quantity r_j, which is determined on the basis of the following relation:

$$r_j = \frac{S_j - R_j^-}{100}; r_1 = 0.004587;\ r_2 = 0.003039;\ r_3 = 0.002;$$

From here, the values of the modified measure R are obtained:

$$R_1' = 0.2 + 0.00458 = 0.204587;\ R_2' = 0.2 + 0.003039 = 0.200304; R_3' = 0.2 + 0.002 = 0.202;$$

Based on the defined metrics S and R, the problem is reduced to a two-dimensional one, and by adopting the same preference for satisfying the majority of criteria as for each individual criterion ($\nu = v_1 = v_2 = 0.5$), a compromise ranking list of solutions can be obtained (Table 7).

$$S^* = 0.4; S^- = 0.658667; R^* = 0.202; R^- = 0.204587;$$

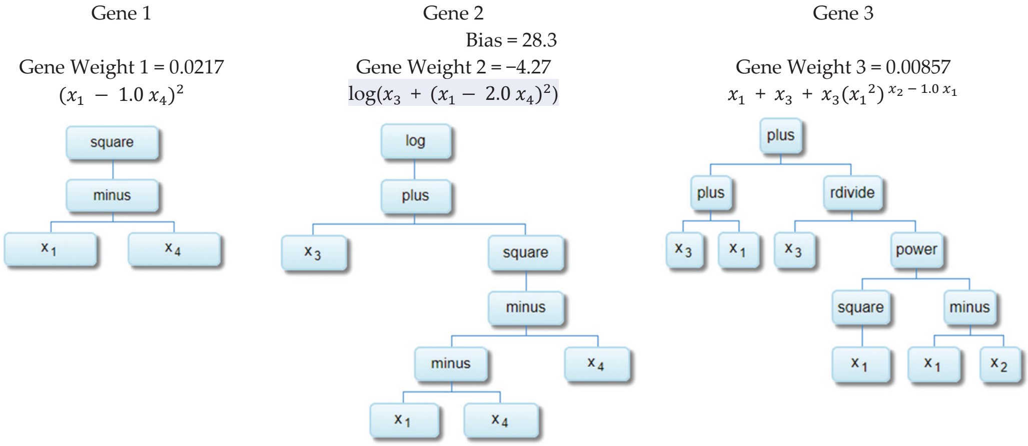
Table 7. Ranking of individual alternatives using the metrics of the VIKOR method.

a_i	R_i	R_i'	QS_i	QR_i	Q_i
a_1	0.658667	0.204587	1	1	1
a_2	0.503858	0.200304	0.401514	0.401623	0.401568
a_3	0.4	0.202	0	0	0

By analyzing Table 7. it can be seen that the final order of alternatives based on metric Q has the following order $a_3 \rightarrow a_2 \rightarrow a_1$. In order for alternative a_3 to be considered as the only compromise solution to the problem, it is necessary that the difference in Q measures for alternatives a_3 and a_2 be greater than the threshold value $DQ = 0.25$, which is satisfied in this case, so it can be considered that a_3 represents the only compromise solution to the optimization problem. In addition, a_3 satisfies both conditions U_1 and U_2. The accuracy of the proposed compromise solution, according to the adopted criteria, is given in Table 8 and its structure is as in Figure 15.

Table 8. Comparative analysis of results of different machine-learning models.

Model	RMSE	MAE	MAPE/100	R
ANN	2.9540	2.2760	0.1490	0.8070
Decision tree	1.7131	**1.1035**	**0.0766**	0.9341
MGGP (gene = 3, depth = 6)	**1.5618**	1.2843	0.0916	**0.9429**
MGGP (gene = 4, depth = 3)	1.7602	1.2462	0.0941	0.9268
MGGP (gene = 4, depth = 4)	1.9531	1.2022	0.0940	0.9091



$$y = 0.00857x_1 + 0.00857x_3 - 4.27\log(x_3 + (x_1 - 2.0x_4)2) + 0.0217(x_1 - 1.0x_4)2 + 0.00857x_3(x_1{}^2)^{x_2 - 1.0x_1} + 28.3$$

$x_1 =$ Max. individual bridge span [m]; $x_2 =$ Average bridge span [m]; $x_3 =$ Total bridge span [m]; $x_4 =$ Bridge width [m]; y = Mass of prestressed steel [kg/m^2]

Figure 15. Tree structure of the individual genes that comprise the optimal model (gene = 3, depth = 6).

Diagrams of modeled and actual values on the training set are shown in the Figure 16a), while the values of the modeled and actual values on the test dataset are shown in the Figure 16b).

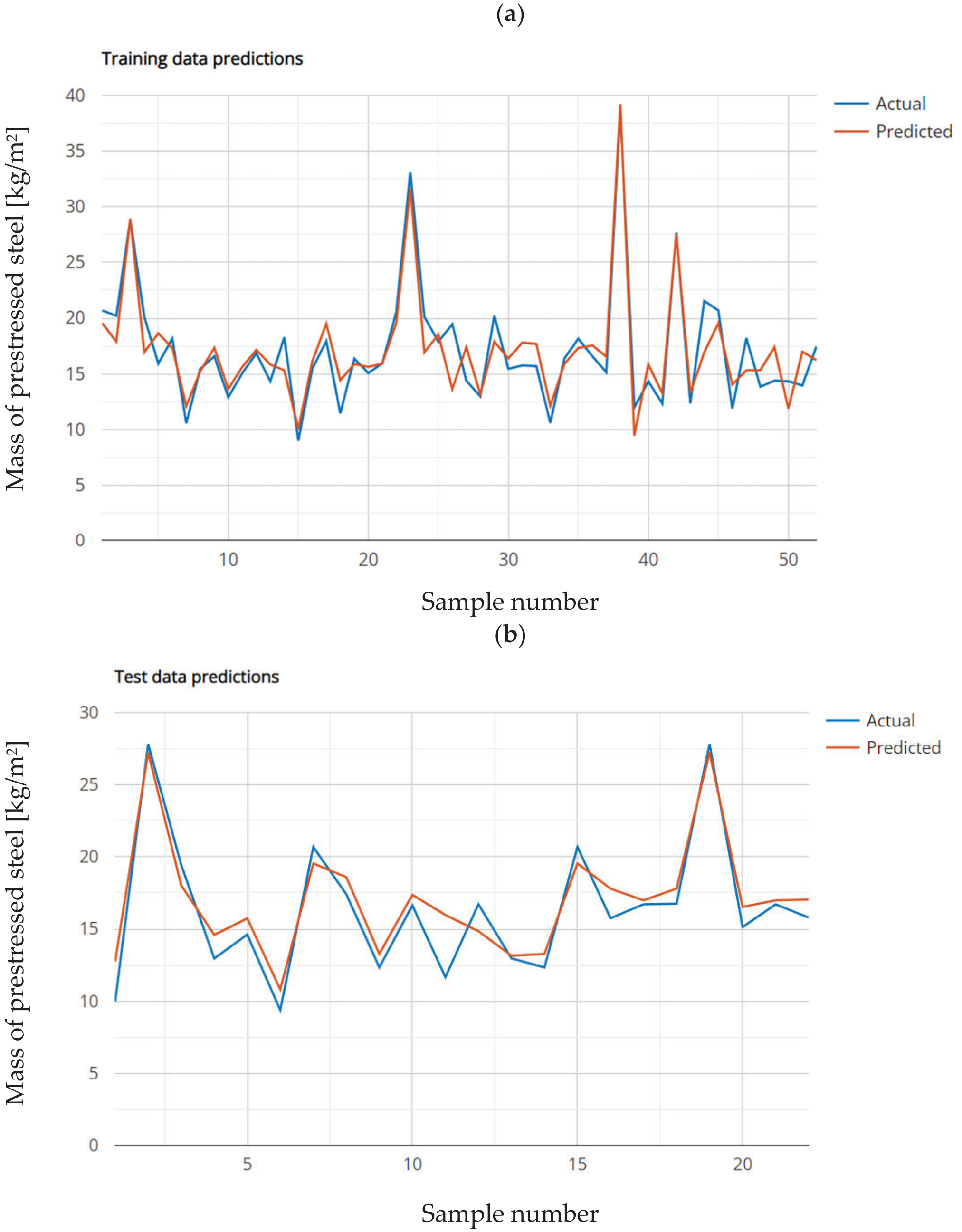


Figure 16. Graphic representation of modeled (optimal model gene = 3, depth = 6) and actual values of prestressed steel consumption: (**a**) training set, (**b**) testing set.

5. Conclusions

The paper defines models based on regression trees that can be used to forecast the amount of prestressed steel in the construction of prestressed concrete bridges. Defined models do not require the use of certain software or the possession of programming knowledge and can be very easily applied in practice. In addition, the analyzed models showed higher accuracy compared to neural network models recommended by many studies.

The application of defined symbolic models in the form of constitutive equations is quick. The structure of the model and its parameters are extracted directly from the data in this study, as opposed to the standard regression models, which first specify the model's structure before determining its parameters from the experimental data. The resulting model, which takes the form of scaled trees and represents a linear combination of nonlinear input transformations, can effectively simulate the challenging task of estimating the consumption of prestressed steel during the construction of prestressed concrete bridges.

The accuracy of the model expressed through the value of the MAPE error of 9.16%, as well as the high value of the correlation coefficient of 94.29%, was obtained.

The formed mathematical model recognized the span as a variable that implicitly contains information about the type of bridge construction (for example, precast beams or box girder). The representation of different types of construction was unbalanced, so this information could not be entered as an input. However, since the authors are working on increasing the database, it will be implemented in the future research.

In this research, MGGP models proved to be significantly simpler and more accurate than ANN models. There is a significantly larger number of ANN model parameters that need to be determined, significant analysis is required when determining the optimal structure, and their implementation requires some programming knowledge. The RT models that were analyzed have less complexity than the ANN model, however, the form of the model itself, being in the form of a complex tree, is not ideal for practical application. MGGP models have an advantage over both ANN and RT models in that their structure is determined by the data itself without any subjective action.

The model developed in the paper can be applied within the range of the dataset on which it was developed.

The limitations of the paper are that the bridges within the database were realized in a relatively narrow geographical area. In that area, there are no significant differences in bridge load (seismic load, wind load, etc.). If there are significant differences in model loading during model training, an additional input variable could be introduced to the training dataset that would include this.

Although the database of prestressed bridges, in this case, is composed of data on 74 completed bridges, it can be considered significant. Expanding the database would result in more data within the training and test dataset, which could define the model and its accuracy even more precisely.

The research applied in this paper has, in terms of results compared to previous research, produced a result that is generally better than the other researched models in terms of criteria of accuracy and complexity. Furthermore, the obtained model is straightforward and is in the form of a simple equation.

In the event of a significant increase in the database in future research, clustering methods could also be applied. The methodology developed in this work would be applied in individual clusters, and individual equations can be defined for each cluster type. The mentioned methodology can also be applied to the similar problem of determining constitutive equations in engineering and construction when we have enough experimental data for the problem we are considering.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

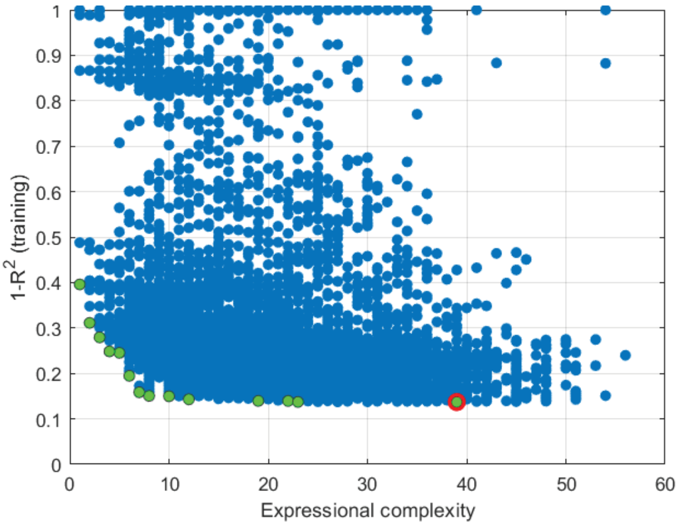
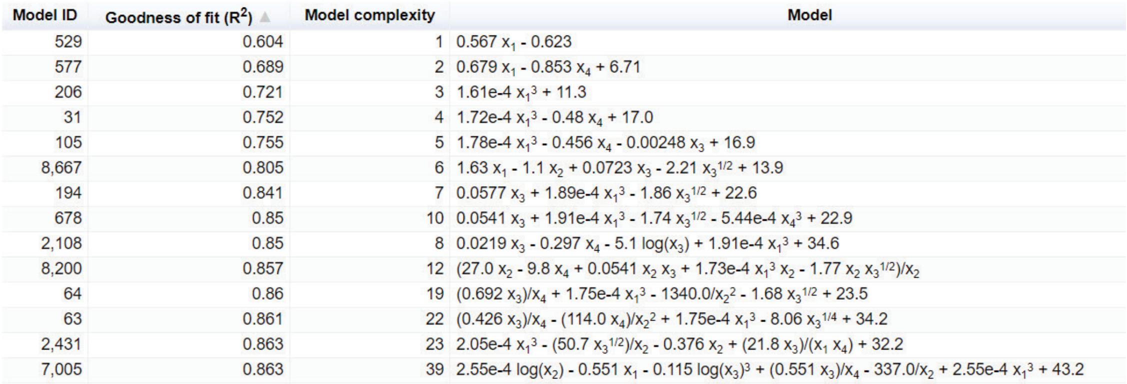


Figure A1. Pareto front of models in terms of model performance and model complexity for a model with 4 genes and depth up to 3.



Model ID	Goodness of fit (R^2) ▲	Model complexity	Model
529	0.604	1	$0.567\ x_1 - 0.623$
577	0.689	2	$0.679\ x_1 - 0.853\ x_4 + 6.71$
206	0.721	3	$1.61e\text{-}4\ x_1^3 + 11.3$
31	0.752	4	$1.72e\text{-}4\ x_1^3 - 0.48\ x_4 + 17.0$
105	0.755	5	$1.78e\text{-}4\ x_1^3 - 0.456\ x_4 - 0.00248\ x_3 + 16.9$
8,667	0.805	6	$1.63\ x_1 - 1.1\ x_2 + 0.0723\ x_3 - 2.21\ x_3^{1/2} + 13.9$
194	0.841	7	$0.0577\ x_3 + 1.89e\text{-}4\ x_1^3 - 1.86\ x_3^{1/2} + 22.6$
678	0.85	10	$0.0541\ x_3 + 1.91e\text{-}4\ x_1^3 - 1.74\ x_3^{1/2} - 5.44e\text{-}4\ x_4^3 + 22.9$
2,108	0.85	8	$0.0219\ x_3 - 0.297\ x_4 - 5.1\ \log(x_3) + 1.91e\text{-}4\ x_1^3 + 34.6$
8,200	0.857	12	$(27.0\ x_2 - 9.8\ x_4 + 0.0541\ x_2\ x_3 + 1.73e\text{-}4\ x_1^3\ x_2 - 1.77\ x_2\ x_3^{1/2})/x_2$
64	0.86	19	$(0.692\ x_3)/x_4 + 1.75e\text{-}4\ x_1^3 - 1340.0/x_2^2 - 1.68\ x_3^{1/2} + 23.5$
63	0.861	22	$(0.426\ x_3)/x_4 - (114.0\ x_4)/x_2^2 + 1.75e\text{-}4\ x_1^3 - 8.06\ x_3^{1/4} + 34.2$
2,431	0.863	23	$2.05e\text{-}4\ x_1^3 - (50.7\ x_3^{1/2})/x_2 - 0.376\ x_2 + (21.8\ x_3)/(x_1\ x_4) + 32.2$
7,005	0.863	39	$2.55e\text{-}4\ \log(x_2) - 0.551\ x_1 - 0.115\ \log(x_3)^3 + (0.551\ x_3)/x_4 - 337.0/x_2 + 2.55e\text{-}4\ x_1^3 + 43.2$

Figure A2. Original output from the GPTIPS 2.0 software with analytical expressions of the models that make up the Pareto front (models with 4 genes and a maximum depth of generated trees of up to 3).

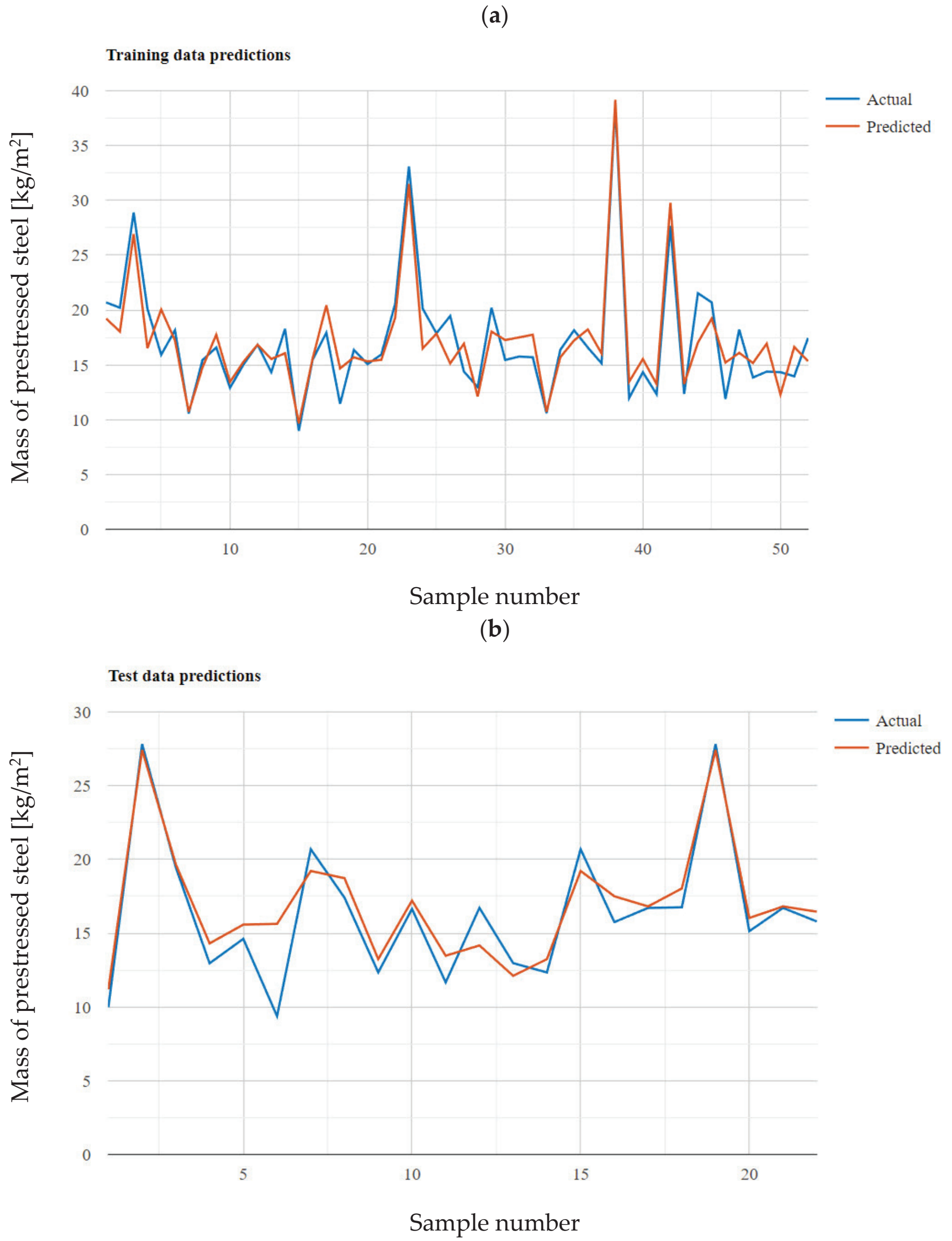


Figure A3. Graphic representation of modeled (model gene = 4, depth = 3) and actual values of prestressed steel consumption: (**a**) training set and (**b**) testing set.

Appendix B

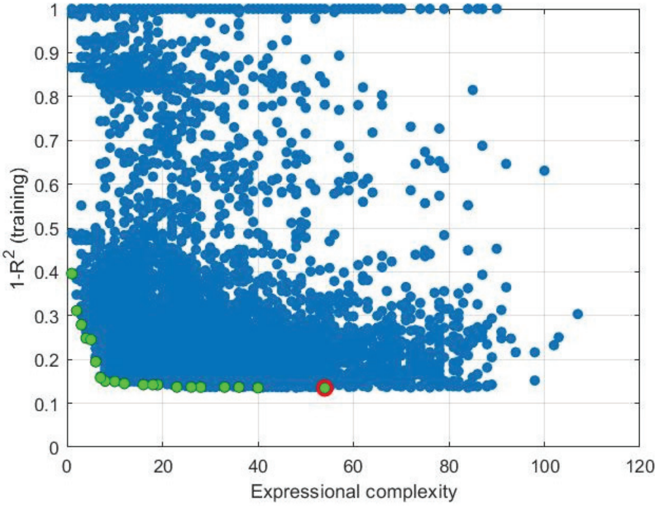
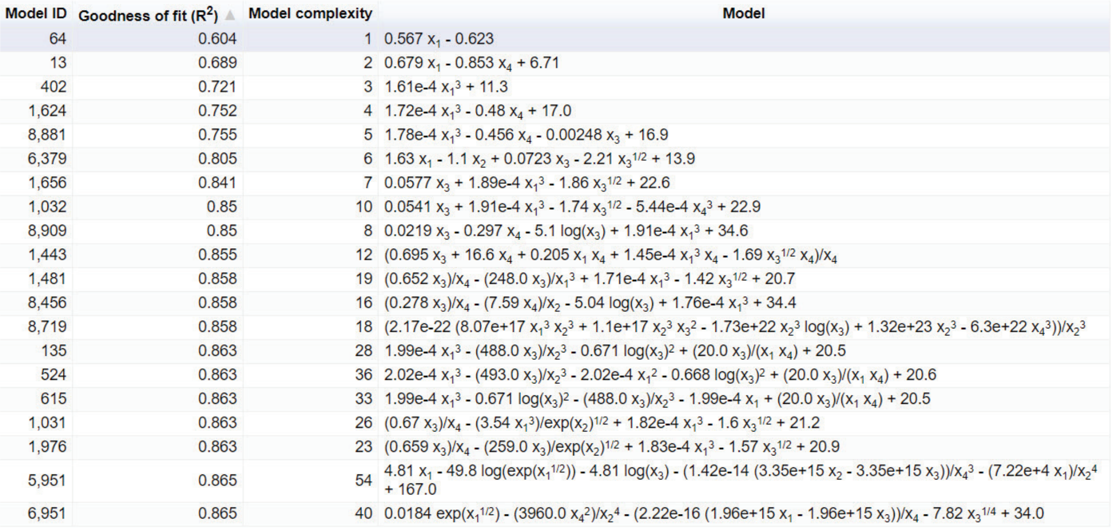


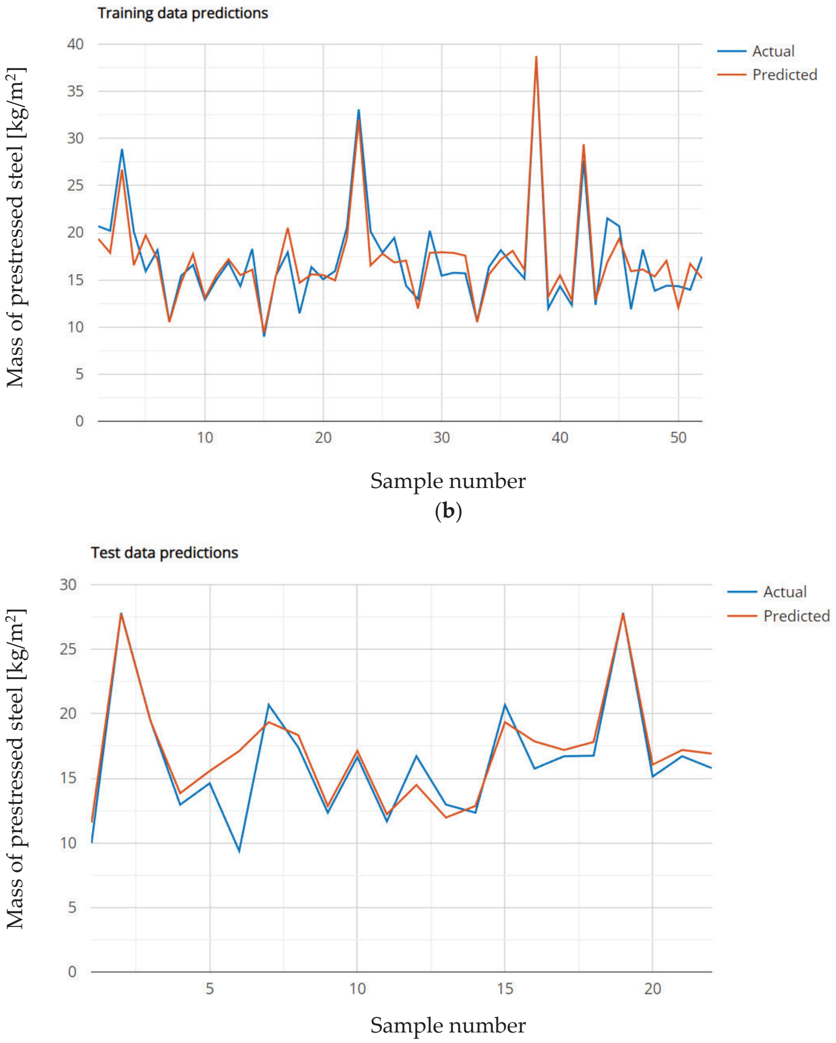
Figure A4. Pareto front of models in terms of model performance and model complexity for a model with 4 genes and depth up to 4.



Model ID	Goodness of fit (R^2) ▲	Model complexity	Model
64	0.604	1	$0.567\ x_1 - 0.623$
13	0.689	2	$0.679\ x_1 - 0.853\ x_4 + 6.71$
402	0.721	3	$1.61e\text{-}4\ x_1^3 + 11.3$
1,624	0.752	4	$1.72e\text{-}4\ x_1^3 - 0.48\ x_4 + 17.0$
8,881	0.755	5	$1.78e\text{-}4\ x_1^3 - 0.456\ x_4 - 0.00248\ x_3 + 16.9$
6,379	0.805	6	$1.63\ x_1 - 1.1\ x_2 + 0.0723\ x_3 - 2.21\ x_3^{1/2} + 13.9$
1,656	0.841	7	$0.0577\ x_3 + 1.89e\text{-}4\ x_1^3 - 1.86\ x_3^{1/2} + 22.6$
1,032	0.85	10	$0.0541\ x_3 + 1.91e\text{-}4\ x_1^3 - 1.74\ x_3^{1/2} - 5.44e\text{-}4\ x_4^3 + 22.9$
8,909	0.85	8	$0.0219\ x_3 - 0.297\ x_4 - 5.1\ \log(x_3) + 1.91e\text{-}4\ x_1^3 + 34.6$
1,443	0.855	12	$(0.695\ x_3 + 16.6\ x_4 + 0.205\ x_1\ x_4 + 1.45e\text{-}4\ x_1^3\ x_4 - 1.69\ x_3^{1/2}\ x_4)/x_4$
1,481	0.858	19	$(0.652\ x_3)/x_4 - (248.0\ x_3)/x_1^3 + 1.71e\text{-}4\ x_1^3 - 1.42\ x_3^{1/2} + 20.7$
8,456	0.858	16	$(0.278\ x_3)/x_4 - (7.59\ x_4)/x_2 - 5.04\ \log(x_3) + 1.76e\text{-}4\ x_1^3 + 34.4$
8,719	0.858	18	$(2.17e\text{-}22\ (8.07e{+}17\ x_1^3\ x_2^3 + 1.1e{+}17\ x_2^3\ x_3^2 - 1.73e{+}22\ x_2^3\ \log(x_3) + 1.32e{+}23\ x_2^3 - 6.3e{+}22\ x_4^3))/x_2^3$
135	0.863	28	$1.99e\text{-}4\ x_1^3 - (488.0\ x_3)/x_2^3 - 0.671\ \log(x_3)^2 + (20.0\ x_3)/(x_1\ x_4) + 20.5$
524	0.863	36	$2.02e\text{-}4\ x_1^3 - (493.0\ x_3)/x_2^3 - 2.02e\text{-}4\ x_1^2 - 0.668\ \log(x_3)^2 + (20.0\ x_3)/(x_1\ x_4) + 20.6$
615	0.863	33	$1.99e\text{-}4\ x_1^3 - 0.671\ \log(x_3)^2 - (488.0\ x_3)/x_2^3 - 1.99e\text{-}4\ x_1 + (20.0\ x_3)/(x_1\ x_4) + 20.5$
1,031	0.863	26	$(0.67\ x_3)/x_4 - (3.54\ x_1^3)/\exp(x_2)^{1/2} + 1.82e\text{-}4\ x_1^3 - 1.6\ x_3^{1/2} + 21.2$
1,976	0.863	23	$(0.659\ x_3)/x_4 - (259.0\ x_3)/\exp(x_2)^{1/2} + 1.83e\text{-}4\ x_1^3 - 1.57\ x_3^{1/2} + 20.9$
5,951	0.865	54	$4.81\ x_1 - 49.8\ \log(\exp(x_1^{1/2})) - 4.81\ \log(x_3) - (1.42e\text{-}14\ (3.35e{+}15\ x_2 - 3.35e{+}15\ x_3))/x_4^3 - (7.22e{+}4\ x_1)/x_2^4 + 167.0$
6,951	0.865	40	$0.0184\ \exp(x_1^{1/2}) - (3960.0\ x_4^2)/x_2^4 - (2.22e\text{-}16\ (1.96e{+}15\ x_1 - 1.96e{+}15\ x_3))/x_4 - 7.82\ x_3^{1/4} + 34.0$

Figure A5. Original output from the GPTIPS 2.0 software with analytical expressions of the models that make up the Pareto front (models with 4 genes and a maximum depth of generated trees of up to 4).

(**a**)



(**b**)

Figure A6. Graphic representation of modeled (model gene = 4, depth = 4) and actual values of prestressed steel consumption: (**a**) training set and (**b**) testing set.

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buildings

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Article

Definition of Compliance Criterion Weights for Bridge Construction Method Selection and Their Application in Real Projects [†]

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Abstract: The main research purpose of the present paper is the establishment of certain compliance criteria, applied for the selection of the most appropriate, per case, bridge construction method, as well as the definition of the weights of these criteria. The five basic concrete bridge construction methods considered in this study are: Cast-in-place, Precast I-Girder, Incremental Launching, Advanced Shoring, and Balanced Cantilever. In this context, the choice of construction method in a concrete road bridge project is proposed based on seven compliance criteria which are: safety, economy, durability, construction speed, serviceability, aesthetics, and environmental harmonization. The inclusion of all these criteria is achieved via the decision-making tool of multi-criteria analysis. A notable innovation of the current study is that road bridges are divided into three categories (bridges for highways, national roads, and provincial roads), in accordance with the importance of the road that contains them. Thus, three different sets of weights of criteria are calculated, corresponding to each bridge category. The research method used for this purpose was a structured questionnaire that was distributed to a large number of selected experts in the field of bridges, who come either from academia or the construction industry. The research results showed that the criteria of safety and economy are the most significant according to the experts, while aspects such as the correlations between experts' profile and their weights were also considered. Finally, the derived criterion weights were applied to two case studies of real bridge projects in Greece.

Keywords: bridge construction methods; compliance criteria; multi-criteria analysis; criterion weights; questionnaire; experts; correlation analysis; case studies

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1. Introduction

Road bridges are structures that provide passage over a barrier or gap. Bridges also constitute one of the three categories of construction projects, the other two being buildings and special structures. Compared to the other two types of construction projects, bridges are ranked second in terms of investment volumes, but first in terms of construction difficulty. As road bridges can be categorized according to the materials used to build the structure, the focus of the current study is on concrete road bridges.

The subject of the construction or the maintenance of road bridges has been addressed extensively in the international literature. This becomes evident from a plethora of studies that examine various issues such as the most economical design of certain structural members of the bridge as well as the improvement of the bridge design in relation to their earthquake resistance or their capacity under traffic loading. In fact, most of these studies concern technical issues of the design of bridge structures. Conversely, the current study deals with decision-making regarding concrete road bridges and specifically with the selection of the most suitable bridge construction method in cases where there is a need for the construction of a concrete road bridge. In the specific paper, this is achieved with the aid of the decision-making tool of multi-criteria analysis.

1.1. Relevant Research on Multi-Criteria Analysis Applications in Bridges

Multi-criteria analysis methods have been widely used at an international level for various decision-making issues related to road bridges. Some indicative studies on this topic are described below. Initially, according to Patel et al. [1], the resilience of infrastructure considers four attributes, which include rapidity, resourcefulness, resilience robustness, and finally redundancy (4Rs), which are related to technical, organizational, social, and economic (TOSE) dimensions. Current practice evaluates bridge resilience using the factors associated only with the 4Rs, but the current research additionally considers the TOSE dimensions. This paper proposes a Bridge Resilience Index, thus facilitating a roadmap for managing, maintaining, and enhancing the resilience of bridges. To accomplish this, certain multi-criteria decision-making techniques are used, such as the Analytical Hierarchy Process (AHP), to obtain relative weights of the 4Rs and their associated TOSE factors; the TOPSIS method to determine the 4Rs; and the Weighted Sum Method (WSM) to assess the Bridge Resilience Index.

Descamps et al. in 2011 [2] investigated an improvement method based on multiple criteria for lightweight bridges. The approach encompasses a constrained force density method. The latter was developed in order to enforce geometric restrictions. Then, the approach was extended to investigate identification of optimized forms via simultaneous consideration of the force density method and multi-objective genetic algorithms. It was proposed that the approach be implemented in larger scale applications.

Balali et al. in 2014 [3] presented the use of the multi-criteria method PROMETHEE for the selection of appropriate materials and appropriate construction methods, as well as the structural system of a bridge, with the aid of a case study. Furthermore, in 2013 Chaphalkar and Shirke [4] proposed the fuzzy AHP multi-criteria method in conjunction with a second multicriteria method, fuzzy TOPSIS, for selecting the type of structural system of a bridge, afterwards comparing the results of the two multi-criteria methods.

Stefanidou and Kappos [5] proposed in 2021 a methodology for bridge fragility curves of actual bridges, which was extended to bridges with various retrofit schemes. The approach for the choice of bridge retrofit scheme is based on a number of identified performance criteria.

According to Zeng et al. [6], bridge structures across active faults are vulnerable to large surface deformation and velocity pulses. The specific research proposes the adoption of a multi-criteria optimizing methodology and examines the damping effect of the optimized damper system on a cable-stayed bridge across a strike–slip fault. Within this research initiative, the mainstream multiple-criteria decision analysis theory is optimized by incorporating new function forms and a control parameter to evaluate the optimum fault-crossing angles of the case bridge. The optimum multi-criteria approach is accompanied by the beetle antennae search algorithm to improve the damper system of the case bridge.

Zhu et al. [7] presented in 2023 a multi-criteria optimization approach regarding reliable adaptation strategies of coastal bridges. The introduced methodology could produce adaptation strategies focusing on the main superstructure unseating failure. This can be accomplished by implementing a pragmatic bridge vulnerability analysis, applying multi-criteria optimization towards the performance of different adaptations and finally investigating strategy reliability against the unknown occurrence of imminent climate futures. A number of exogenous uncertainties are also examined. These include future economics and climate scenarios, which are also evaluated via sensitivity analysis.

Tegos and Aretoulis in 2019 [8] focused on the pre-selection of the most suitable bridge type. The approach considered not only cost-effectiveness but also the satisfaction of a number of conflicting compliance criteria. The development of a reliable decision support system regarding that kind of selection is a significant research objective. Moreover, certain evaluation criteria governing bridge design are established. The specific criteria are then weighted and incorporated within two multi-criteria analysis methods. The application of these methods can lead to the respective optimal selection of the bridge type, among a number of potentially appropriate alternatives [8].

Bana e Costa et al. [9] introduced in 2008 a multiple criteria approach which evaluates and hierarchizes bridges and tunnels based on specific parameters and criteria. These include their structural vulnerability and strategic significance towards the creation and application of civil protection strategies. The latter involve both retrofitting and emergency response, in the case of seismic occurrences.

Pan [10] also in 2008 emphasized that the identification of an appropriate bridge construction method is critical for the success of bridge construction projects. The AHP methodology has been broadly applied for providing solutions in multiple criteria decision analysis problems. However, it has been reported that the standard AHP approach is not capable of managing unknown parameters associated with the consideration of one's preference to an exact number or ratio. The current research introduces a fuzzy AHP model to overcome this difficulty. The suggested methodological method incorporates fuzzy numbers and the α-cut concept to respond to the imprecision inherent to the process of subjective judgment. Finally, a case study that assesses bridge construction methods is shown in order to highlight the application of the model.

The following research paper by Jaafaru and Agbelie [11] combines machine learning, multi-criteria analysis and evolutionary optimization models for bridge maintenance planning. This paper provides a bridge maintenance planning framework considering financial and performance parameters. The specific study managed to analyze 95 bridges in a network with an 84% accuracy machine learning model prediction. The decision-makers' preferences were utilized to hierarchize all bridges via multi-attribute utility theory.

Bakhtin [12] in 2022 introduced the results of the creation of a complex algorithm for multi-criteria optimization of biocrossings (landscape bridges) on high speed roads. The research focus is on accidents with wildlife. The emphasis was based on the issue of multi-criteria optimization of landscape bridges, with a very large number of criteria and parameters, and indeed in two directions. These directions considered a classical road overpass over migration routes and a landscape bridge over a motorway.

Antoniou et al. [13] in 2016 introduced an approach for cost pre-estimation and material quantity formulation for overpass bridges. This model is based on data from fifty-seven existing bridges. The aim is to assist stakeholders in the bridge construction industry when selecting the most cost-effective design solution, towards the reduction of the risk of failure and the loss of funding [13].

Pouraminian and Pourbakhshian [14] in 2019 dealt with the study of the shape of a concrete arched bridge, involving a particle swarm optimization algorithm. According to the results appearing in this study, the Pareto front is generated, which enables the decision-maker or designer to pick the compromise solution. This is achieved within twenty optimum designs. Furthermore, in order to facilitate the tasks of the decision-maker, two multiple objective decision-making methods were applied to identify the optimum solution.

Božanić et al. [15] in 2019 focused their research effort on the introduction of a model for the allocation of a single-span bailey bridge. To that end, the authors applied multi-criteria decision analysis. Based on relevant studies, the seven key criteria which have the greatest influence on the selection were identified in earlier work by Kočić: (1) access roads, (2) scope of work on site arrangement, (3) properties of banks, (4) width of water barrier, (5) masking conditions, (6) scope of works on joining access roads with the crossing point, (7) protection of units.

In 2021 Upadhya et al. [16] focused their research interest on a very critical topic. Their emphasis is placed on a multi-criteria decision-making approach for the choice of a bridge superstructure construction method. Based on AHP and questionnaire surveys, they managed to come up with a decision support system. The AHP method identified the most appropriate method of bridge superstructure construction.

Finally, the study by Keshavarz-Ghorabaee et al. [17] aims at the bridge design and mainly at the multi-criteria problem, applying the TOPSIS method to clarify and assess the conceptual design process under uncertainty. In the presentation of the proposed approach, an example of multi-criteria assessment of bridge design, with quantitative and qualitative criteria, is applied. Summarizing most of the research papers focus on bridge design issues. A limited number of papers deal with decision-making specifically on selecting the construction method.

1.2. Introduction to the Proposed Approach

Currently, five dominant bridge construction methods exist: Cast-in-place, Precast I-Girder, Incremental Launching, Advanced Shoring, and Balanced Cantilever. When a road bridge project is to be constructed, the choice of the corresponding method is not an easy one, since the methods present significant differences in terms of their principles, technical characteristics and requirements. At the same time, there are a number of parameters that must be considered, namely: the topographic features of the area, as well as the requirements for safety, economy, durability, aesthetics of the project, etc. As a result, the construction method should be aligned with these parameters, which are usually antagonistic. Therefore, a compromise is required in order to satisfy all the above parameters or criteria.

Despite the existence of the aforementioned factors in bridge design, in practice, until recently the choice of construction method was based almost exclusively on the economic criterion, or in other cases, the decision relied on the subjective opinion of the involved engineers, based only on their own bridge design experience. In contrast, the present study attempts to contribute to the development of an approach for a justified selection of the best ranking bridge construction method on a case-by-case basis among the five dominant ones. The main novelty of this research is that the selection will be based on the performance of the alternative construction methods against seven criteria that are established within the present study, which are: safety, economy, durability, construction speed, serviceability, aesthetics, and environmental harmonization. The inclusion of the set of criteria and the management of such a complex problem are achieved in the current research via the use of multi-criteria analysis.

The overarching goal of the present paper is the definition of the weights of the compliance criteria, which is crucial for the application of multi-criteria analysis. The research approach that was chosen for the evaluation of the criterion weights is the questionnaire survey. Thus, a structured questionnaire was distributed to a substantial number of Greek bridge experts. One of the challenges of this research was the appropriate selection of a representative sample of experts. More specifically, the 19 experts to whom the survey was addressed come from academia and the construction industry. A number of these selected experts belong to the private sector, and a corresponding number belong to the public sector.

Moreover, a noteworthy novelty of the current study is that the concrete road bridges have been categorized into three classes, namely bridges for highways, national roads, and provincial roads, taking into consideration that each bridge category has different importance and requirements. Consequently, the questionnaire survey does not produce universal criterion weights applicable to all road bridges. Instead, the survey succeeds in defining three specialized sets of criterion weights, assigned to each road bridge category.

Additionally, an important objective of this paper was to investigate if the evaluated weights of the experts are affected by their field of activity and experience, and to draw useful conclusions. Furthermore, the research investigated any possible correlations among the criterion weights themselves.

As far as the structure of the paper is concerned, in Section 2 the proposed compliance criteria for the selection of bridge construction method are presented analytically. In the

Section 3, the methods that were used in this study are described. In particular, the decision-making tool of multi-criteria analysis is presented in Section 3.1, while the questionnaire survey is analyzed in Section 3.2. Subsequently, the Section 4 contains the findings of the questionnaire survey, namely the exported sets of the criterion weights, as well as the description of the participating experts. Section 5 includes the application of correlation analysis among the criterion weights, as well as the examined correlation between the experts' field of activity and the proposed weights. Section 6 contains the discussion of the results. Section 7 includes the two case studies of the research, where the set of weights, corresponding to the bridge categories of highways and national roads, are applied in two real bridge projects in Greece, aiming at the selection of the most suitable construction method per case. Finally, Section 8 includes the conclusions and future research.

2. Compliance Criteria for the Selection of Bridge Construction Method

The choice of the most appropriate per-case construction method in a road bridge project, as already mentioned, must be aligned with a pool of defined criteria. However, for years the selection of bridge construction method in practice was mostly based on the criterion of economy. In the current research in contrast, a more integrated approach is considered.

In particular, seven compliance criteria are introduced to this end, which include: safety, economy, durability, construction speed, serviceability, aesthetics, and environmental harmonization. A brief definition of the concept of each compliance criterion, according to a previous study of Tegos and Markogiannaki [18] in 2019, is presented below:

- Safety

This criterion corresponds not only to the level of safety according to current codes (Eurocodes) for bridges, but moreover to the additional level of safety resulting from the response of statically indeterminate structures. In countries with high seismicity, the term safety mainly corresponds to seismic safety.

- Economy

The criterion is related to the intended reduction of the cost of the project, yet without devaluation of the rest of criteria. In the context of this study, the criterion of Economy is related only to the construction cost of the project, while the maintenance cost is taken into account in the criterion of Durability. It is noted that in recent years, there have been continuous research efforts regarding the limitation of bridge construction cost.

- Durability

The term Durability refers to the minimization of maintenance needs during the lifetime of the project. In the case of bridges, maintenance needs are associated with the use of bearings, joints, and seismic dampers. As mentioned above, the maintenance cost of a bridge is reflected in the performance of the criterion of Durability, and not in Economy. It is noteworthy that sometimes maintenance cost could even reach the construction cost level.

- Construction Speed

The criterion of Construction Speed is directly related to the expected completion time of the project, which is intended to be minimized. The (average) construction speed is defined here as the ratio of the length of the bridge deck to the total construction time of the bridge (namely the deck, the abutments, the piers, and their foundations). The aforementioned total construction time includes also the assembling, disassembling and transfer times of the necessary mechanical equipment used in the construction.

- Serviceability

The usual concept of serviceability is linked to the quality of traffic service; however, in this study, the term "Serviceability" means the development of an adequate structural response to the imposed deformations (namely the expansion and contraction of the deck) during the operation phase of the bridge. It is notable that the use of bearings is the best solution to the problem of serviceability.

- Aesthetics

The concept of Aesthetics in the field of bridges includes certain established rules related to the choice of geometric dimensions, which attempt to reconcile safety and geometric proportions that contribute to an aesthetic effect. Some indicative aesthetic rules are the following: all piers should have the same width; the variability of height of the deck cross-sections (arc shape) is positively evaluated; etc.

- Environmental Harmonization

The criterion of Environmental Harmonization is related to the existing architectural tradition of the area, as well as to the surrounding landscape of the bridge. The selection of the deck type and the geometric dimensions of the bridge should be affected by these two factors and be in harmony with them. In addition, the concept of this criterion includes the desirable minimization of landscape alteration and environmental impact in the area affected by the bridge project.

3. Methods

The methods that were used in this study mainly consist of the questionnaire survey, as well as the use of multi-criteria analysis (MCA), in order to build on the results of the questionnaire.

More specifically, two MCA methods were used. Initially the Analytic Hierarchy Process (AHP) was used for the core of the research, namely the calculation of the compliance criterion weights, and secondly, the PROMETHEE method was used specifically to calculate the performance of the bridge construction methods in the two case studies. The algorithm of the AHP method was applied manually with the aid of Microsoft Excel, whereas the PROMETHEE method was applied using the relevant software Visual PROMETHEE (Version 1.4.0.0.). Moreover, the program IBM SPSS Statistics was used for a more thorough analysis of the research results, namely for the implementation of correlation analysis.

In the following section, first, the multi-criteria analysis methods are presented, followed by the analytical presentation of the content of the questionnaire.

3.1. Multi-Criteria Analysis Methods of AHP and PROMETHEE

3.1.1. Definition

The tool of multi-criteria analysis (MCA) is a dominant application of operations research in the field of decision-making. The method constitutes a systematic and mathematically standardized procedure, suitable for dealing with complex decision-making problems, in which many competing alternatives (projects, actions, or scenarios) exist and a number of conflicting compliance criteria are taken into account. In the case of the present study, the competing alternatives include the five aforementioned bridge construction methods. The ultimate goal of the method of multi-criteria analysis is to achieve a rational compromise among the considered criteria, and thus to lead to the optimal choice [18]. In the current study, two specific multi-criteria methods are used, and they are presented below.

3.1.2. The AHP Multi-Criteria Method

The method of multi-criteria analysis that is used primarily in this paper (for the computation of weights of the compliance criteria) is the Analytic Hierarchy Process (AHP). The AHP method was developed by T.L. Saaty in the USA in 1977 and is one of the most widespread MCA approaches. AHP aims to quantify relative priorities for a given set of alternatives on a ratio scale, based on the judgment of the decision-maker [19]. The alternatives are evaluated against several quantitative and/or qualitative criteria, depending on how they contribute in achieving the overall goal that has been set.

More specifically, in the first step of the analytic hierarchy process, the decision-making problem is structured according to a hierarchy, where the top element is the overall goal of the decision. The second level of the hierarchy represents the criteria, while the lowest level represents the alternatives [20].

The second step of the method includes the calculation of the priorities (scores), which is performed based on the pairwise comparisons provided by the decision-makers. Each lower level of the hierarchy is prioritized according to its immediate upper level [20]. These pairwise comparisons are carried out using Saaty's fundamental 1–9 scale [19]. This scale enables the decision-maker to integrate his knowledge and experience in an intuitive way, in order to express the intensity of his preference between two elements of the same level.

Thus, the criteria are prioritized in terms of their importance with respect to the overall goal via the performance of successive pairwise comparisons among them. The result of this procedure is the definition of the priorities (relative weights) of the criteria. Subsequently, the alternatives are prioritized, via pairwise comparisons among them, in terms of their importance with respect to each specific criterion. This procedure leads to the determination of the local priorities of the alternatives. Ultimately, the two aforementioned types of priorities lead to the calculation of the global priorities of the alternatives and, by extension, to their final ranking. However, the current study focuses only on the initial stage of this process, namely on the definition of the criterion weights, which is achieved with the aid of the questionnaire survey.

In general, the strength of AHP is that it provides a structured yet relatively simple solution to the decision-making problem, as it organizes tangible and intangible factors in a systematic way [21]. In the context of the present study, this property of the method is very important, as the research contains certain quantitative criteria, such as Economy and Construction Speed, but also many qualitative ones such as Serviceability, Aesthetics or Environmental Harmonization.

3.1.3. The PROMETHEE Multi-Criteria Method

The second multi-criteria analysis method used in the study (for the evaluation of the construction methods in the two case studies) is PROMETHEE. The acronym stands for "Preference Ranking Organization METHod for Enrichment Evaluations". PROMETHEE is a widely known and used outranking method that was developed by J.P. Brans in 1982 and further extended by Brans and Vincke in 1985 [22], Brans et al. in 1986 [23]. Its characterization as an outranking method means that the method is based on pairwise comparisons of the alternatives, while the ultimate goal of PROMETHEE is to provide the decision-maker with a ranking of the existing alternatives.

Before the application of the method, the decision-maker needs at first to define the criteria taken into account for the decision. Then, all the alternatives to be ranked need to be evaluated according to those criteria [20]. The implementation of PROMETHEE requires two additional types of information, which are: (1) the weights of the criteria under study, and (2) the preference function used by the decision-maker when comparing the contribution of the alternatives in terms of each separate criterion. Therefore, the PROMETHEE method is based on the computation of preference degrees. A preference degree is a score which expresses how an alternative is preferred over another alternative, based on the criterion considered, from the decision-maker's point of view. A preference degree of 1 thus means a total preference for one of the alternatives and a preference degree of 0 means that there is no preference at all, while if there is some preference, but it is not total, then the intensity will be between 0 and 1 [20].

More specifically, according to Ishizaka and Nemery [20], the method includes three main steps:

1. Computation of preference degrees for every ordered pair of actions (alternatives) on each criterion;
2. Computation of uni-criterion flows (which are an aggregation of the criterion preference degrees, globally for an action);

3. Computation of global flows (which are an aggregation of the uni-criterion flows, by taking into account the weights of the criteria).

Thus, the global positive, negative, and net flows are computed. Eventually, PROMETHEE II (the most basic version of the method), which is used in the current paper, provides a complete ranking of the alternatives from the best to the worst one based on their global net flows [24].

3.2. Presentation of the Questionnaire

The questionnaire developed in this research had a title quite similar to the title of the current paper, namely: "Determination of compliance criterion weights for the selection of bridge construction method". The number of experts, to whom the questionnaire was addressed, is nineteen, and they come from either the construction industry or the academic/research field, and they are among the most experienced engineers in the field of bridges in Greece. The content of the questionnaire is analytically presented below and divided into discrete subsections, which are, specifically: the questions about the profile of the participants, the necessary information for the experts, the explanation for the three versions of the questionnaire, and finally a presentation of the main part of the questionnaire [25].

3.2.1. Profile of the Participants

In the initial part of the questionnaire, there are three questions about the profile of the experts (engineers) that participate in the survey: In the first one, the experts are asked about their main field of activity in relation to bridges. Four possible answers are provided, namely: Private Sector, Public Sector, Academia, Research Field. In the second one, they are asked about the type of their employment in relation to bridges, where the possible answers include: Project Manager, Designer, Job in Construction Company, Supervising Engineer, Bridge Design Reviewer, Academic, Researcher. Finally, the third question concerns the years of their experience in the field of Bridges (up to 5 years, 5–10 years, 10–20 years, or more than 20 years).

3.2.2. Necessary Information Provided to the Experts

Afterwards, the experts are provided with some necessary information or explanations for completing the questionnaire, such as: the subject of the doctoral research, part of which is the current survey, as well as the goal of the questionnaire, a concise definition of multi-criteria analysis, the names of the alternative construction methods, and the compliance criteria that are used in the research. Subsequently, the participants are provided with a brief definition of the concept of each compliance criterion, which is similar to the corresponding part of Section 2.

3.2.3. The Three Versions of the Questionnaire

In the current study, concrete road bridges are divided into three categories, depending on their importance, namely: bridges of highways, of national roads, and of provincial roads. Consequently, three different sets of weights of the compliance criteria need to be calculated, one for each different bridge category. That means that the experts are asked to complete the questionnaire in its three versions; specifically, they have to complete three similar sub-questionnaires, essentially with the same questions each, but from a different point of view.

The above-mentioned categorization is essential, as it is obvious that the priority (weight) of many criteria varies depending on the importance of the road containing the bridge in question. It is reasonable that regarding the bridges for provincial roads, the criterion of Economy is usually predominant, while regarding the bridges for highways in particular, other criteria, such as durability or aesthetics, could have a significant weight. An additional noteworthy difference is that the highways are usually built in a new environment, while the national and provincial roads are built near residential areas or existing road networks, presenting more legislative restrictions on construction. All the above explanations are also provided to the experts in the questionnaire.

3.2.4. The Main Part of the Questionnaire

What follows is the main part of the questionnaire. This includes the three similar sub-questionnaires, of which one is dedicated to questions about bridges for highways, one to questions about bridges of national roads and one to questions about bridges for provincial roads. As already mentioned, the questions in each sub-questionnaire are exactly the same; however, the experts are asked to respond to each sub-questionnaire from a different perspective each time, keeping in mind the different needs of each bridge category.

Each sub-questionnaire contains 22 questions, in which:

1. The first one asks the experts to make a preliminary prioritization of the seven compliance criteria, depending on their importance in the process of selecting a bridge construction method. The goal of this question is for the experts to form an initial opinion on the subject, before the main questions.
2. The questions 2–22 contain the successive pairwise comparisons of all the compliance criteria. This means that each criterion is compared to every other criterion. These questions have all the same pattern and consist of 2 parts:
    (1) In the first sub-question, the experts are asked which criterion of the two of the respective pair (e.g., safety or durability) is more important, while they also have the choice of answering that the two criteria are equivalent in importance.
    (2) In the second sub-question, they are asked to rate the degree of predominance of the criterion they have chosen over the other. Here, the possible answers are 5 adverbs that express a gradual increase, stating that the criterion predominates: imperceptibly/slightly/appreciably/significantly/catalytically. Each adverb corresponds to a value on a scale from 1 to 5, which is used afterwards for the application of the multi-criteria analysis method of AHP.

4. Findings of the Questionnaire Survey

4.1. Presentation of the Calculated Weights of the Criteria

The responses of the nineteen experts to the questionnaire were converted into suitable values for the algorithm of the multi-criteria analysis method of AHP, which was applied successively 19 times, for each one of the three bridge categories (i.e., 57 times in total). This process led to the calculation of the criterion weights of each expert, and eventually, to the final weights of compliance criteria (the averages of the 19 experts' weights per criterion), concerning the bridges of highways (Tables 1 and 2), the bridges for national roads (Tables 3 and 4) and the bridges for provincial roads (Tables 5 and 6).

Table 1. Experts' weights of compliance criteria for bridges for highways (part 1).

Experts / **Criteria**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Safety	0.248	0.266	0.290	0.279	0.269	0.260	0.246	0.279	0.288	0.302
Durability	0.212	0.253	0.258	0.186	0.265	0.175	0.151	0.219	0.192	0.168
Economy	0.171	0.136	0.136	0.186	0.164	0.192	0.302	0.153	0.184	0.133
Aesthetics	0.107	0.099	0.073	0.100	0.049	0.116	0.041	0.052	0.082	0.043
Constr. Speed	0.100	0.096	0.106	0.099	0.112	0.127	0.096	0.104	0.114	0.092
Serviceability	0.092	0.075	0.075	0.088	0.089	0.065	0.125	0.143	0.087	0.216
Environ. Harmon.	0.070	0.075	0.062	0.062	0.052	0.065	0.039	0.050	0.053	0.046

Main field of activity of experts: Exp. 1: Academic, Exp. 2: Research, Exp. 3: Research, Exp. 4: Private Sector, Exp. 5: Private Sector, Exp. 6: Private Sector, Exp. 7: Public Sector, Exp. 8: Private Sector, Exp. 9: Public Sector, Exp. 10: Public Sector.

Table 2. Experts' weights of compliance criteria for bridges for highways (part 2).

Experts Criteria	11	12	13	14	15	16	17	18	19	Average
Safety	0.255	0.274	0.339	0.263	0.225	0.254	0.253	0.069	0.299	0.261
Durability	0.193	0.219	0.171	0.207	0.209	0.216	0.228	0.106	0.229	0.203
Economy	0.126	0.154	0.108	0.161	0.159	0.082	0.157	0.369	0.148	0.169
Aesthetics	0.083	0.064	0.060	0.120	0.056	0.126	0.105	0.049	0.051	0.078
Constr. Speed	0.121	0.093	0.069	0.090	0.085	0.051	0.110	0.240	0.087	0.105
Serviceability	0.129	0.128	0.206	0.091	0.216	0.158	0.084	0.133	0.140	0.123
Environ. Harmon.	0.092	0.067	0.046	0.068	0.050	0.114	0.062	0.033	0.046	0.061

Main field of activity of experts: Exp. 11: Private Sector, Exp. 12: Public Sector, Exp. 13: Private Sector, Exp. 14: Public Sector, Exp. 15: Academic, Exp. 16: Private Sector, Exp. 17: Private Sector, Exp. 18: Academic, Exp. 19: Private Sector.

Table 3. Experts' weights of compliance criteria for bridges for national roads (part 1).

Experts Criteria	1	2	3	4	5	6	7	8	9	10
Safety	0.203	0.228	0.226	0.224	0.308	0.234	0.278	0.254	0.253	0.253
Durability	0.130	0.144	0.123	0.135	0.200	0.117	0.178	0.173	0.117	0.151
Economy	0.222	0.207	0.245	0.220	0.173	0.234	0.098	0.191	0.214	0.218
Aesthetics	0.071	0.073	0.057	0.070	0.066	0.070	0.057	0.045	0.064	0.057
Constr. Speed	0.195	0.159	0.199	0.177	0.145	0.159	0.229	0.143	0.180	0.151
Serviceability	0.116	0.119	0.095	0.115	0.044	0.117	0.109	0.131	0.119	0.113
Environ. Harmon.	0.063	0.070	0.055	0.059	0.064	0.069	0.051	0.063	0.053	0.057

Table 4. Experts' weights of compliance criteria for bridges for national roads (part 2).

Experts Criteria	11	12	13	14	15	16	17	18	19	Average
Safety	0.250	0.250	0.322	0.223	0.259	0.300	0.221	0.069	0.307	0.245
Durability	0.206	0.150	0.161	0.158	0.225	0.203	0.160	0.106	0.169	0.158
Economy	0.132	0.191	0.110	0.195	0.127	0.067	0.200	0.369	0.219	0.191
Aesthetics	0.101	0.065	0.076	0.075	0.051	0.115	0.066	0.049	0.052	0.067
Constr. Speed	0.095	0.174	0.046	0.163	0.092	0.062	0.182	0.240	0.124	0.153
Serviceability	0.140	0.109	0.224	0.120	0.198	0.138	0.115	0.133	0.093	0.124
Environ. Harmon.	0.076	0.061	0.059	0.066	0.048	0.115	0.056	0.033	0.037	0.061

4.2. Description of the Participating Experts

Concerning the profile of the 19 experts that participated in the survey, there is a variety regarding the main field of activity related to bridges that was stated by the experts, as shown in the footnotes under Tables 1 and 2. Thus, there are 5 experts from the public sector (and, more specifically, from the state-owned company Egnatia Odos S.A.), 9 experts from the private sector, 3 experts from academia and 2 experts from the research field. Moreover, in Table 7, the additional characteristics of the experts are presented.

Table 5. Experts' weights of compliance criteria for bridges for provincial roads (part 1).

Experts **Criteria**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Safety	0.174	0.144	0.138	0.191	0.154	0.176	0.241	0.217	0.208	0.278
Durability	0.114	0.160	0.114	0.113	0.128	0.115	0.160	0.184	0.113	0.231
Economy	0.237	0.236	0.261	0.226	0.284	0.232	0.228	0.225	0.233	0.135
Aesthetics	0.062	0.067	0.074	0.059	0.040	0.065	0.052	0.041	0.057	0.045
Constr. Speed	0.211	0.196	0.241	0.208	0.210	0.232	0.115	0.188	0.208	0.178
Serviceability	0.136	0.130	0.111	0.131	0.117	0.115	0.151	0.094	0.120	0.088
Environ. Harmon.	0.066	0.067	0.061	0.072	0.067	0.065	0.053	0.051	0.061	0.045

Table 6. Experts' weights of compliance criteria for bridges for provincial roads (part 2).

Experts **Criteria**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**Average**
Safety	0.272	0.238	0.321	0.176	0.203	0.284	0.159	0.069	0.324	0.209
Durability	0.187	0.166	0.159	0.119	0.130	0.198	0.117	0.106	0.150	0.146
Economy	0.147	0.193	0.080	0.205	0.222	0.116	0.234	0.369	0.210	0.214
Aesthetics	0.072	0.062	0.060	0.067	0.070	0.096	0.069	0.049	0.040	0.060
Constr. Speed	0.153	0.166	0.044	0.195	0.195	0.061	0.234	0.240	0.142	0.180
Serviceability	0.103	0.106	0.233	0.170	0.116	0.162	0.117	0.133	0.081	0.127
Environ. Harmon.	0.066	0.069	0.102	0.068	0.063	0.084	0.069	0.033	0.053	0.064

Table 7. Experts' experience and types of their employment in relation to bridges.

Expert	**Years of Experience**	**Project Manager**	**Designer**	**Construction Company**	**Supervising Engineer**	**Bridge Design Reviewer**	**Academic**	**Researcher**
1	>20		√		√	√	√	√
2	10–20		√			√		√
3	5–10							√
4	10–20			√	√			√
5	up to 5		√			√		
6	up to 5	√	√			√		
7	>20	√						
8	>20		√					
9	>20		√		√	√		
10	>20		√		√	√		
11	10–20		√					
12	>20		√		√	√		
13	>20		√			√		

Table 7. *Cont.*

Expert	Years of Experience	Project Manager	Designer	Construction Company	Supervising Engineer	Bridge Design Reviewer	Academic	Researcher
14	>20	√	√	√	√	√		√
15	10–20	√		√			√	√
16	>20		√			√		
17	5–10		√	√				√
18	>20					√	√	
19	10–20		√			√		

5. Correlation Analysis

To achieve a further analysis of the results of the criterion weights, the tool of correlation analysis was also applied, with the aid of IBM SPSS Statistics, in two ways: (1) among the variables regarding the profile of the experts and the weights assigned to the compliance criteria by the experts, and (2) among the derived criterion weights themselves. In the software platform IBM SPSS Statistics, concerning the first application, no correlations were identified, but on the other hand, significant correlations were identified regarding the second application among the criterion weights.

5.1. Implementation of Correlation Analysis among the Criterion Weights

It is noteworthy that, according to Field [26], the Pearson's correlation coefficient and the significance value are the indicating factors for the assessment of the correlation analysis' results. More specifically, the Pearson's correlation coefficient is a measure of the linear relationship between two variables. It takes on values close to 1 for strong relationships and -1 for adverse strong relationships. Moreover, significance values less than 0.05 reveal strong correlation, while those values that range between 0.05 and 0.06 demonstrate the tendency to correlate.

In this study, the values of the calculated criterion weights from the 19 experts were used to identify the correlations among the criterion weights. That means that the weights of each criterion were associated with the weights of each one of the rest of criteria, in order to identify the degree of correlation among them. This correlation analysis was conducted separately for all 3 bridge categories (bridges for highways, for national roads, and for provincial roads), for which individual criterion weights were calculated.

The specific part of the study can reveal interesting aspects about the way the criteria are weighted by the most of the experts. For instance, it can reveal if there is any pattern according to which some criteria usually receive directly proportional weight or some others receive inversely proportional weight.

Tables 8–10 present the results of the correlation analysis regarding the criterion weights for highway bridges, national road bridges and provincial road bridges, respectively. In particular, each one of these three tables depicts the results with the values of Pearson's correlation coefficient, but only for the cases where the two-tailed significance was below 0.05, i.e., where there was strong correlation between two criterion weights. It is also notable that in the three tables, certain symbols have been used to represent the different levels of significance of the correlations. Specifically, beyond the cases with significance (p) below 0.05, there is a special interest for those ones where the significance value is less than 0.01, and even more for the cases where it is less than 0.001 (presenting the strongest possible correlation).

Table 8. Results from correlation analysis for highways.

Criteria	Safety	Durability	Economy	Aesthetics	Constr. Speed	Serviceability	Environ. Harmoniz.
Safety	1	0.491 *	−0.758 ***		−0.815 ***		
Durability		1	−0.660 **		−0.510 *		
Economy			1		0.781 ***		−0.584 **
Aesthetics				1		−0.513 *	0.741 ***
Constr. speed					1		
Serviceability						1	
Environ. harmoniz.							1

Note: N = 19, blank cells: not significant ($p > 0.05$), * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, two-tailed significance.

Table 9. Results from correlation analysis for national roads.

Criteria	Safety	Durability	Economy	Aesthetics	Constr. Speed	Serviceability	Environ. Harmoniz.
Safety	1	0.599 **	−0.795 ***		−0.664 **		
Durability		1	−0.775 ***		−0.642 **		
Economy			1	−0.527 *	0.662 **		−0.573 *
Aesthetics				1	−0.517 *		0.859 ***
Constr. speed					1	−0.547 *	−0.497 *
Serviceability						1	
Environ. harmoniz.							1

Note: N = 19, blank cells: not significant ($p > 0.05$), * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, two-tailed significance.

Table 10. Results from correlation analysis for provincial roads.

Criteria	Safety	Durability	Economy	Aesthetics	Constr. Speed	Serviceability	Environ. Harmoniz.
Safety	1	0.670 **	−0.855 ***		−0.815 ***		
Durability		1	−0.675 **		−0.600 **		
Economy			1		0.776 ***		−0.639 **
Aesthetics				1			0.530 *
Constr. speed					1	−0.545 *	−0.546 *
Serviceability						1	0.670 **
Environ. harmoniz.							1

Note: N = 19, blank cells: not significant ($p > 0.05$), * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, two-tailed significance.

An examination of the results of correlation analyses conducted for the three bridge categories, and specifically of the values of Pearson's correlation coefficient (r), led to the following conclusions:

Concerning the criterion weights for the highway bridges, the most significant positive correlations were those between Economy and Construction Speed (where the value of the correlation coefficient r is equal to 0.781), and between Aesthetics and Environmental Harmonization (where r is equal to 0.741). On the other hand, the most significant negative correlations were those between Safety and Construction Speed (r = –0.815) and those between Safety and Economy (r = –0.758). As is shown in Table 8, in all these cases, the significance (*p*) value is less than 0.001; that is, the correlation is of the highest possible degree. It should be noted that a strong positive correlation of two variables means that, as one variable increases, the other increases by a proportionate amount. Conversely, in a negative correlation, if one variable increases, the other decreases by a proportionate amount [26].

Regarding the criterion weights for the bridges of national roads (Table 9), the most significant correlations, with a value of p below 0.001, were the positive one between Aesthetics and Environmental Harmonization (r = 0.859) and the negative correlations between Safety and Economy (r = −0.795), and between Durability and Economy (r = −0.775). Moreover, it is noteworthy that Construction Speed was significantly correlated, on the one hand negatively with Safety (r = −0.664) and Durability (r = −0.642), and on the other hand positively with Economy (r = 0.662), with $p < 0.01$ in all cases.

Finally, as far as the bridges for provincial roads are concerned (Table 10), the strongest correlations (with $p < 0.001$) were the following: Economy was significantly and positively correlated with Construction Speed (r = 0.776), and it was negatively correlated with Safety (r = −0.855), while Safety was also negatively correlated with Construction Speed (r = −0.815). Also noteworthy (but with $p < 0.01$) are the significant correlations between Durability and Safety, positively (r = 0.670), and between Durability and Economy, negatively (r = −0.675).

5.2. Correlations between Experts' Field of Activity and Their Weights

In the present study, an attempt was also made to investigate any possible correlation of the experts' field of activity with their weights, in order to draw useful conclusions concerning the priorities of each field that deals with bridges in Greece. Despite the fact that initially the use of the platform IBM SPSS Statistics did not show significant correlations regarding this kind of variable, the specific issue was examined in this study via a different methodology, with the aid of Microsoft Excel.

More specifically, the experts who come from the Academic and the Research fields, namely the experts No. 1, 2, 3, 15 and 18, were grouped together, considered "theoreticians". On the other side are the experts who come from the "field of applications" (the rest of the experts), who are divided into two separate sub-categories: the experts from the public sector and the experts from the private sector. Consequently, there are a total of three subgroups of experts that were examined in this section.

Afterwards, for each bridge category and for each criterion separately, the data from Tables 1–6 were used via the following procedure: the weights of the experts belonging to each one of the above subgroups were separated from the rest of the weights, and the average of them was calculated. The averages calculated in this way constitute the special weights of criteria that correspond to each one of the above three subgroups of experts and are presented in the below three Tables 11–13, per bridge category.

Table 11. Weights per subgroup of experts for the bridges for highways.

Criteria / Subgroups	Safety	Durability	Economy	Aesthetics	Constr. Speed	Serviceability	Environ. Harmoniz.
"Theoreticians"	0.220	0.208	0.194	0.077	0.125	0.118	0.058
Experts from Public Sector	0.275	0.187	0.187	0.070	0.097	0.129	0.055
Experts from Private Sector	0.276	0.209	0.146	0.082	0.098	0.123	0.066

Table 12. Weights per subgroup of experts for the bridges for national roads.

Subgroups \ Criteria	Safety	Durability	Economy	Aesthetics	Constr. Speed	Serviceability	Environ. Harmoniz.
"Theoreticians"	0.197	0.145	0.234	0.060	0.177	0.132	0.054
Experts from Public Sector	0.251	0.151	0.183	0.064	0.179	0.114	0.058
Experts from Private Sector	0.269	0.169	0.172	0.073	0.126	0.124	0.066

Table 13. Weights per subgroup of experts for the bridges for provincial roads.

Subgroups \ Criteria	Safety	Durability	Economy	Aesthetics	Constr. Speed	Serviceability	Environ. Harmoniz.
"Theoreticians"	0.146	0.125	0.265	0.065	0.217	0.125	0.058
Experts from Public Sector	0.228	0.158	0.199	0.057	0.172	0.127	0.059
Experts from Private Sector	0.233	0.150	0.195	0.060	0.164	0.128	0.070

6. Discussion

In the current section, the main findings of the questionnaire survey regarding the weights of the compliance criteria are discussed. Moreover, the findings from the application of correlation analysis among the criterion weights, as well as the ones regarding the correlations between experts' profile and their weights, are discussed too.

6.1. Discussion of the Findings of the Questionnaire Survey

The results regarding the final weights of compliance criteria per bridge category, namely the averages of the 19 experts, presented in Table 2, Table 4, and Table 6, provide the following rankings among the criteria:

Bridges of Highways:

(1) Safety, (2) Durability, (3) Economy, (4) Serviceability, (5) Construction Speed, (6) Aesthetics, (7) Environmental Harmonization

Bridges of National Roads:

(1) Safety, (2) Economy, (3) Durability, (4) Construction Speed, (5) Serviceability, (6) Aesthetics, (7) Environmental Harmonization

Bridges of Provincial Roads:

(1) Economy, (2) Safety, (3) Construction Speed, (4) Durability, (5) Serviceability, (6) Environmental Harmonization, (7) Aesthetics

In general, the results show clear differences among the three final groups of weights of the criteria, which correspond to the three bridge categories. These differences include substantial increases or decreases in the weight of some criteria, by around 5–6%, or even over 7% in the case of Construction Speed, as well as significant changes in the final ranking for certain criteria, among the three bridge categories.

It is interesting to note that the criterion of Economy is ranked third in the bridges for highways, then second in the bridges for national roads, and finally first in the bridges for provincial roads. Also notable are the changes in the weight and the ranking of Durability, but presenting an opposite trend, as it is ranked second in the case of highways, then third in national roads, while it is ranked fourth in the provincial roads.

Moreover, in all three bridge categories, the criteria of Safety and Economy are always in the first three places in the final rankings, and one of them always occupies first place. On the other hand, the criteria of Aesthetics and Environmental Harmonization in all bridge categories are ranked in the last two places, while especially in the cases of national and provincial roads, there is a significant difference between their weights and the weights of the rest of criteria.

6.2. Discussion of the Correlation Analysis among the Criterion Weights

Regarding the results of correlation analysis applied among the criterion weights, it is worth mentioning that there are certain criteria which, in all three bridge categories, appear significantly and positively correlated with each other, as regards their weighting by the 19 experts. This means that, as one criterion weight increases, the other increases by a proportionate amount. These pairs of criteria are in particular:

(1) Economy with Construction Speed,
(2) Aesthetics with Environmental Harmonization,
(3) Safety with Durability (mainly in national road and provincial road bridges)

On the other hand, there are more pairs of criteria which always appear significantly and negatively correlated with each other. As mentioned above, in a significant negative correlation, if one criterion weight increases, the other decreases by a proportionate amount. The most notable among these pairs of criteria with negative correlations are the following:

(1) Safety with Economy (probably the most significant correlation of all, with a value of p always below 0.001),
(2) Safety with Construction Speed,
(3) Durability with Economy,
(4) Durability with Construction Speed (mainly in national road and provincial road bridges)

6.3. Discussion of the Correlations between Experts' Profile and Their Weights

An initial finding that emerges from the correlation of the experts' field of activity with their weights, and more specifically from Tables 11–13 above, is that the experts from the public sector show great similarities with those from the private sector, both in their weight rankings and in the weight values themselves. The only exceptions are: (1) their weights for the criterion of Economy in the highway bridges, which is evaluated as much more important by the experts of the public sector, as they rank it second (along with Durability) with a weight of 0.187, while those of the private sector rank it third, with a significant difference behind Durability, and (2) the criterion of Construction Speed in national road bridges, which is valued much more by public sector experts (who rank it third, with a very high weight of 0.179, while the private sector experts rank it fourth, with a not so great weight of 0.126. In general, the experts who come from the field of applications seem to evaluate the criterion of Safety as the most important in any case, since they rank it first by far in all three bridge categories.

On the other hand, the experts whose weights differ greatly from the other two categories are the "theoreticians", namely these from the Academic and the Research fields. These experts tend to rate Economy very high in all bridge categories, and always higher than the other two subgroups, ranking it third but very close to Durability and Safety in highway bridges, first in national road bridges, and first by an overwhelming margin of almost 12% in provincial road bridges. Moreover, they tend to rate Construction Speed higher than the other groups of experts, giving to the criterion in all bridge categories a higher ranking compared to the total of 19 experts of the survey (fourth instead of fifth in Highway bridges, third instead of fourth in national road bridges and second instead of third in provincial road bridges).

7. Case Studies

The problem of selecting the most suitable construction method is examined for two case studies, namely two real bridge projects in Greece, by using multi-criteria analysis and, by extension, the relative weights of the compliance criteria that were calculated in the present study. The use of two case studies that belong to different bridge categories was deemed necessary, so that there would be an opportunity to apply two of the three different sets of weights of the criteria that were calculated in the present study, corresponding to the three bridge categories.

The two selected bridge projects are very similar, both in their length and their height from the ground, but as mentioned above, the first one belongs to the national road network, while the second one to the highway network of Greece. For each case study, detailed information on its data, as well as figures, are presented below, while in each one of them multi-criteria analysis is applied in order to select the most suitable bridge construction method per case.

7.1. Case Study 1

The project that was examined in the first case study is the G1 River Bridge of the Sminthi—Echinos Section (70.1.5) of the Vertical Axis 70 of Egnatia Motorway, located near Xanthi, in the Eastern Macedonia Prefecture of Greece. The final study was submitted and approved in 2017, but the bridge is not yet constructed. In practice, it is designed to be constructed with the Cast-in-place method, span by span, and has the following data.

It is a river bridge located very close to Sminthi Village; it is part of a national road and has a total length of 336 m. This, according to the design of the bridge, is distributed in 10 spans as follows: 24.00 m + 8 × 36.00 m + 24.00 m. The bridge has a maximum height of 18 m above ground, while its longitudinal slope ranges from 1.9 to 7.0%. The deck of the bridge has a width of 10.20 m, which, together with the sidewalks, is 14.20 m. The bridge is in seismic zone I and is shown in Figure 1. Based on the geometric data (total bridge length and maximum height of bridge above ground), it can be easily understood that, among the five existing construction methods, only the four of them are feasible, namely Cast-in-place, Precast I-Girder, Incremental Launching, and the Advanced Shoring method. Apparently, the method that was rejected is the Balanced Cantilever, due to the low height of the bridge above ground.

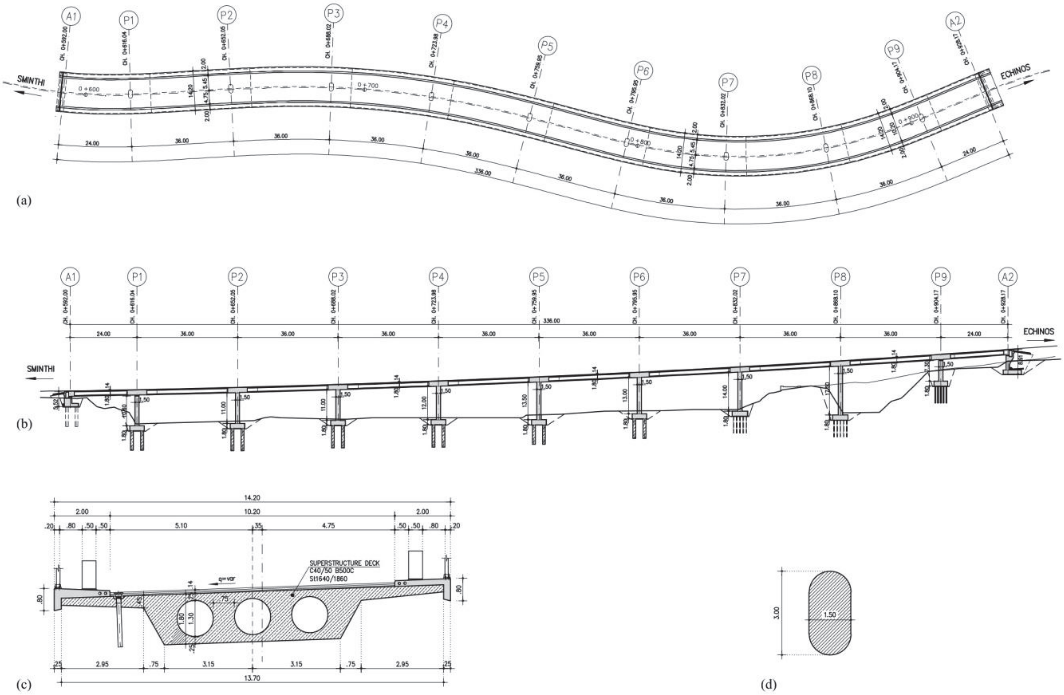

Figure 1. Bridge of case study 1, designed by the Cast-in-place method: (**a**) Plan. (**b**) Longitudinal section. (**c**) Cross-section. (**d**) Pier cross-section.

7.1.1. Additional Technical Data of the Real Bridge

The one branched river bridge is configured by a continuous superstructure with ten spans (total length 336.0 m on the bridge axis) made of prestressed concrete, which was cast in situ. The bridge is to be constructed in nine stages, starting from the southern abutment (A1) with construction joints at 20% of every span. In plan, the bridge horizontal alignment is on three successive circular arcs with radii of 150, 300, and 160 m, respectively, as well as the corresponding transition curves, located very close to Sminthi Village and at a great length within the river bed, close to the banks of two streams (Miroi and Magdi). The red line is also on a vertical concave arc with a radius of 6000 m, at a height ranging between 3.0 and 18.0 m from the natural terrain.

The piers, which have clear heights ranging between 7.3 and 17.5 m, have a single-column configuration and a rectangular cross-section (1.5 × 3.0 m) with semicircular edges (r = 0.75 m) and are founded on pile caps. The superstructure is monolithically connected to the seven central piers P2 to P8, resting on bearings at the outermost piers P1 and P9, as well as at the abutments, forming a case of semi-integral bridge with satisfactory behavior for both vertical as well as horizontal loads, with expansion joints only at the abutments and with reasonable displacements.

The cross-section of the girder is voided slab beam with a height of 1.8 m, a total width of 14.20 m (upper flange including 10.2 m deck and 2.0 m sidewalks at both edges) with a variable transverse inclination (max = 7%), carrying two-way traffic. Safety barriers, street lighting poles, insulation of the deck with a special membrane, and drainage of the deck with longitudinal and vertical drainage pipes are also provided.

7.1.2. Application of Multi-Criteria Analysis for the Selection

The multi-criteria analysis method of PROMETHEE II is applied, using the four feasible construction methods which were mentioned above, as alternatives. For the needs of its application, the software Visual PROMETHEE was used.

The seven compliance criteria were applied with a nine-point scale, while all criteria need to be maximized. The weights of the criteria were derived from the weights of compliance criteria from the 19 experts for the bridges for national roads (please see Table 4: last column). In addition, the Preference function selected was the V-shape, with a preference threshold (P) equal to 3, as it was considered the most appropriate function for the needs of this selection problem.

The performance of each construction method against each criterion is presented in Table 14 as follows. It is noted that the evaluations of the four alternatives were obtained via a special questionnaire addressed to an expert in bridge design (one of the 19 who participated in the main survey), who brings together the qualities of a bridge designer, a bridge design reviewer, and a researcher in this field. However, the most important fact is that he was directly involved in the real design of the specific bridge (as well as in the design of the bridge of the second case study).

Table 14. Evaluations of the construction methods for case study 1.

Criteria / C. Methods	Safety	Durability	Economy	Aesthetics	Constr. Speed	Serviceability	Environ. Harmoniz.
Cast-in-place	7	8	6	7	5	6	7
Precast I-Girder	5	5	8	5	9	9	5
Incremental Launching	6	6	4	8	4	5	8
Advanced Shoring method	6	6	3	7	5	5	7

As follows in Table 15, the resulting positive, negative, and net preference flows of the alternatives are presented, as they emerged from Visual PROMETHEE:

Table 15. Flows (scores) of the four alternatives for case study 1.

Constr. Methods/Flows	Phi+	Phi−	Phi
Cast-in-place	0.4113	0.1491	0.2622
Precast I-Girder	0.4472	0.2965	0.1507
Incremental Launching	0.1372	0.3089	−0.1716
Advanced Shoring	0.0903	0.3316	−0.2412

Therefore, based on the net preference flows (the last column "Phi"), the ranking of the four feasible construction methods, from best to worst is the following:

1. Cast-in-place
2. Precast I-Girder
3. Incremental Launching
4. Advanced Shoring

Eventually, according to the application of multi-criteria analysis, the chosen bridge construction method in the first case study is Cast-in-place, verifying the actual design of the bridge. Precast I-Girder was ranked second, not by a very large margin.

7.2. Case Study 2

The project that is examined in the second case study is the T4 Valley Bridge of the New Kostarazi—Argos Orestiko Section (45.1.4) of the Vertical Axis 45 of Egnatia Motorway, located between Siatista and Krystallopigi in the Western Macedonia Prefecture of Greece. The final study was submitted and approved in 2003; the bridge was then constructed and was opened to traffic in 2005. In practice, it was designed and constructed with the Precast I-Girder method and possesses the following data.

It is a valley bridge with two independent branches, one for each traffic direction; it is part of the Egnatia vertical motorway network, so it is considered part of the highway network, and it has a total length of 309.4 m. This, according to the design of the bridge, is distributed in 10 spans as follows: 30.45 m + 6 × 31.00 + 2 × 31.25 m + 30.45 m. The bridge has a maximum height of 15 m above ground, while its longitudinal slope ranges from −2.0 to 2.5%. Each branch of the bridge carries one-way traffic, with two traffic and one emergency lane, a sidewalk on the external edge, and a safety barrier on the internal edge between the branches, which are 20 cm apart. Each branch has a deck with a width of 11.00 m, which together with the sidewalk and the safety barrier is 12.65 m. Thus, the total width of the bridge is 25.50 m.

The bridge is in seismic zone I and is shown in Figure 2. Based on the geometric data (total bridge length and maximum height of bridge above ground), it can be easily understood that, among the five existing construction methods, only the four of them are feasible, as in case study 1, namely Cast-in-place, Precast I-Girder, Incremental Launching, and Advanced Shoring. Apparently, the method that was rejected is the Balanced Cantilever, due to the low height of the bridge above ground.

7.2.1. Additional Technical Data of the Real Bridge

The two-branched valley bridge is configured by a series of simply supported prestressed precast girders (total length 309.45 m on the bridge axis) forming a 10 span T-beam grid superstructure. Each branch span consists of five double T precast beams, with a height of 1.74 m at an axial distance of 2.70 m. A 10 cm-thick precast slab is placed between the beams to support the additional 16 cm-thick slab, which was cast in situ during construction. The total thickness of the deck slab (flange) is thus 26 cm, and the total height of the slab beam is 2.0 m. The five beams are laterally connected with the flange and two cross girders at the pier supports (no intermediate connection). In order to avoid the expense of installing and maintaining/replacing joints, a continuous slab arrangement is provided in the longitudinal direction. Thus, the deck slab is continuous over five spans and only three expansion/contraction joints are needed (abutments A1, A2, and pier P5).

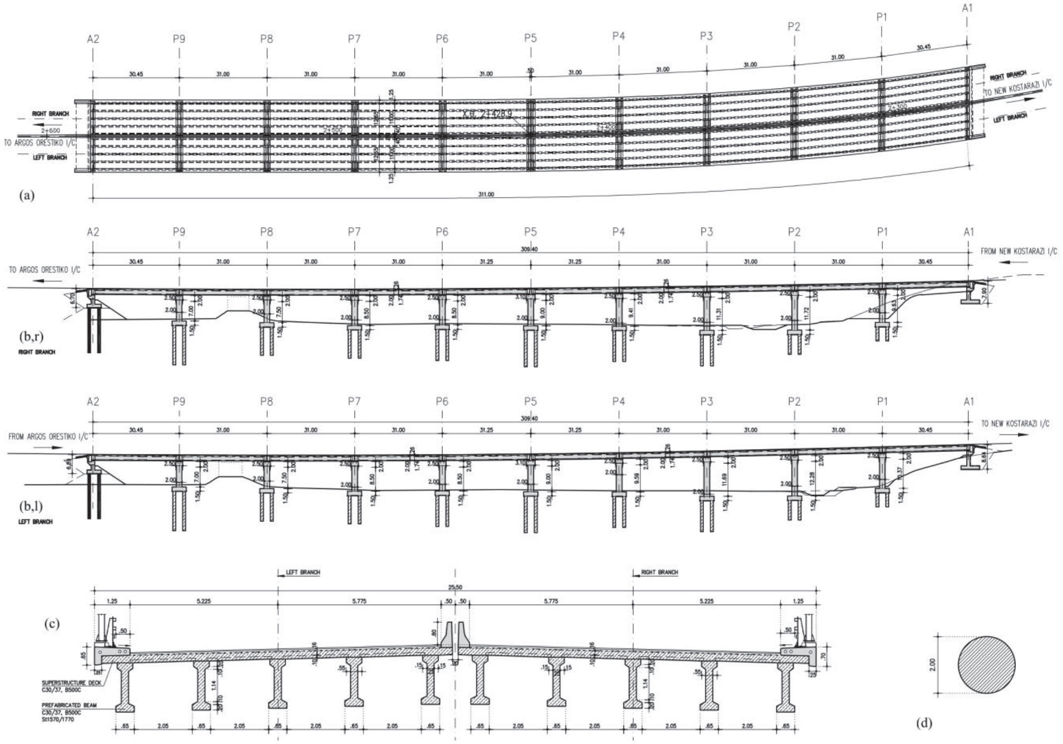

Figure 2. Bridge of case study 2, constructed by the Precast I-Girder method: (**a**) Plan. (**b**) Longitudinal section. (**c**) Cross section. (**d**) Pier cross-section.

The beams rest on circular elastometallic bearings above the pier cap beams, forming a floating seismic isolation system with low damping. The piers of each branch are independent, stithy-shaped, and founded on pile caps. The piers, which have clear heights ranging between 7.0 and 12.3 m, have a single-column configuration and a circular cross-section with a 2.0 m diameter. The cap beam has a width of 2.5 m (except M5 where b = 3.1 m) and a height which varies from 0.8 to 2.0 m. Antiseismic stoppers are provided at an appropriate distance so as to remain inactive during the seismic design action.

In plan, the bridge horizontal alignment is on the transition to a curve with 800 m radius for almost half of the length and on a straight line for the rest of the length. The red line is also on a vertical concave arc with a radius of 9000 m, at a height ranging between 8.0 and 15.0 m from the natural terrain.

The transverse inclination of each branch is variable (max = 7%), carrying one-way traffic. Safety barriers, street lighting poles, insulation of the deck with a special membrane and drainage of the deck with longitudinal and vertical drainage pipes are also provided.

7.2.2. Application of Multi-Criteria Analysis for the Selection

The multi-criteria method of PROMETHEE II is applied also in case study 2, using the four feasible construction methods as Alternatives, again with the aid of the software Visual PROMETHEE.

The exact same settings as in case study 1 are used in the program, concerning the scale of the criteria and the Preference function, but here the criterion weights used are different, as they were derived from the weights of compliance criteria extracted by the 19 experts for the bridges of highways (please see Table 2: last column).

As follows in Table 16, the performance of the construction methods against each criterion is presented. The evaluations of the four alternatives were obtained from the same expert as in case study 1, via the same special questionnaire.

Table 16. Evaluations of the construction methods for case study 2.

Criteria **C. Methods**	**Safety**	**Durability**	**Economy**	**Aesthetics**	**Constr. Speed**	**Serviceability**	**Environ. Harmoniz.**
Cast-in-place	7	7	6	6	5	5	6
Precast I-Girder	5	5	9	5	9	9	5
Incremental Launching	6	6	5	7	4	5	7
Advanced Shoring method	6	6	5	6	5	5	6

In Table 17 below, the positive, negative, and net preference flows of the alternatives, which were derived from the program of Visual PROMETHEE, are presented:

Table 17. Flows (scores) of the four Alternatives for case study 2.

Constr. Methods/Flows	**Phi+**	**Phi−**	**Phi**
Cast-in-place	0.2709	0.1478	0.1231
Precast I-Girder	0.3970	0.2680	0.1290
Incremental Launching	0.1133	0.2260	−0.1127
Advanced Shoring method	0.0787	0.2181	−0.1394

Consequently, based on the above net preference flows, the final ranking of the four participating construction methods, from best to worst, is the following:

1. Precast I-Girder
2. Cast-in-place
3. Incremental Launching
4. Advanced Shoring

In conclusion, the application of multi-criteria analysis indicated that the selectable construction method in the second case study is the Precast I-Girder, thus verifying the selection of the construction method that was made in practice. It is noteworthy that the Cast-in-place method was ranked second by only a very marginal difference from Precast I-Girder, indicating that in fact it could also be a suitable construction method for the current bridge project.

7.3. Discussion of Results of the Two Case Studies

According to the results extracted from the multi-criteria analysis, in two bridge projects in Greece that are quite similar in terms of their geometric data, but differ regarding their bridge category, two different distributions of weights of the compliance criteria were applied and ultimately, different results were obtained in terms of the selected construction method.

Moreover, it is notable that the methods of Incremental Launching and Advanced Shoring, which were ranked third and fourth in both final rankings, had particularly low scores with a very large distance from the first two methods in the bridge of case study 1, which is part of a national road. However, in the bridge of case study 2, which is part of a highway, the distances of the two aforementioned methods from the others have been noticeably reduced. This could be explained by the fact that the specific two methods are usually not particularly suitable for national (or provincial) roads due to their technical requirements.

8. Conclusions

The main research purpose of the present study was the proposal of seven compliance criteria for the selection of the most appropriate per-case bridge construction method, as well as the definition of the weights of these criteria, in order for them to be used in the decision-making tool of multi-criteria analysis. An important novelty of this research is exactly the use of these seven compliance criteria, instead of the use of only the criterion of economy, which was dominant in practice for years regarding the selection of bridge construction method. Another remarkable innovation of the study is that three different sets of criterion weights are calculated, corresponding to the three different categories of road bridges that are defined in the study, namely the bridges of highways, of national roads and of provincial roads. Thus, the proposed weights of compliance criteria are adjusted to the different importance of each bridge project.

The practical significance of the research lies in the fact that the compliance criteria and their weights extracted from the present study could be possibly utilized by awarding authorities for the evaluation and the assignment of the optimal design approach for bridge projects. In this way, the essential matter of the selection of bridge construction method could be addressed in a rational and systematized way, via multi-criteria analysis, instead of a possibly subjective choice of the method by individual designers, based only on their own experience from previous bridge projects. In addition, there will be no need to calculate new weights of criteria for each individual bridge project, since the three proposed sets of criterion weights can cover all the range of the usual concrete road bridges, in terms of their importance and requirements.

Regarding the weights of compliance criteria extracted from the research, it is worth mentioning that the criteria of Safety and Economy appear to be the two most popular criteria among the 19 bridge experts who participated in the present survey, considering all three categories of bridges. In fact, in all of the categories, these two criteria always occupy the first two or three places. In addition, the criterion of Durability is also evaluated as particularly important, as it maintains generally high positions in the experts' rankings, and especially in the most important category, namely highway bridges, it occupies second place. Conversely, it is notable that the criteria of Aesthetics and Environmental Harmonization are clearly underestimated in the preferences of experts, having been ranked in the last two places in all bridge categories.

The general preference of the experts towards the criterion of Safety could be possibly explained by the fact that this term mainly corresponds to seismic safety, and Greece is the most seismically active region in Europe, due to some unique geological characteristics that it presents. On the other hand, their preference towards the criterion of Economy most probably indicates the limited budgeting of public works, such as bridges in Greece, which could sometimes present constraints that are taken into account by the decision-makers in selecting the bridge construction method.

In addition, an important finding of the research is that there are obvious differences among the three final sets of weights of the compliance criteria, corresponding to the three bridge categories, of highways, national roads and provincial roads. These differences concern both the final ranking and the weight values of certain criteria, and thus, they justify the choice made in the research to treat the three bridge categories separately, depending on their importance.

Concerning the profile of the bridge experts that participated in the survey, it is noteworthy that the opinions of the experts coming from the public sector, regarding the relative importance of the compliance criteria, generally resemble to a large extent the opinions of the experts from the private sector. Compared to these groups of experts who come from the field of applications, the views of the experts from the Academic and the Research fields differ greatly, especially regarding the criteria of Economy and Construction

Speed, which they tend to rate much higher in any bridge category. Moreover, the fact that the 19 experts participating in the research come from all fields related to bridges, namely from both academia and construction industry (that is represented from the private and public sector), is considered that has led to certain weights of compliance criteria that present a significant degree of mutual acceptance by all parties who expertise in bridge design.

Regarding the results of the correlation analysis among the criterion weights, it is noteworthy that in all three bridge categories, the pair of the criteria Economy—Construction Speed, as well as the pair of Safety—Durability present strong positive correlation. On the other hand, the pairs of the criteria Safety—Economy, Safety—Construction Speed, and Durability—Economy present strong negative correlation.

Finally, it is worth mentioning that, when applying multi-criteria analysis for the selection of the most suitable construction method in a bridge project, the weights of the compliance criteria that are used can play a very important role in the final decision, but not always the decisive one, as the choice is also based on other essential factors such as the geometric data of the bridge or the data of the project area, which may affect the performance of the methods against the criteria. The current research considered seven compliance criteria and implemented two multi-criteria analysis methods. As part of the future research, it is proposed that more criteria could be considered and additional methods of multi-criteria analysis could be implemented in the context of the selection of bridge construction method.

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Assessing the Delay, Cost, and Quality Risks of Claims on Construction Contract Performance

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Abstract: Conflicts are frequent within the complex professional environment of the construction industry. If claims cannot be overcome amicably, they result in disputes that lead to litigation. Identification of the causes of these claims and their impact on the duration, cost, and quality of the final project is expected to facilitate the prevention of unsuccessful performance of construction contracts. The novelty of this study is that after codifying the most common causes of construction contract claims derived from the extant literature, they are further investigated in terms of their probability of occurrence and the perceived impact they have on the project completion time, its total cost, and quality. Based on calculated relative importance indices from expert opinion, this paper proposes probability and severity of impact values for 39 common causes of claims in the construction industry. These can be applied to calculate their risk values for stakeholders in public construction contracts to plan mitigation measures for contractual claims. The findings show that the top five highest risk causes of contractual claims in the Greek construction industry are changes in quantities, work, or scope, design quality deficiencies or errors, payment delays, delays in work progress, and the financial failure of the contractor.

Keywords: claim management; causes of claims; construction industry; contract management; relative importance index; risk management; construction contract performance; disputes; conflicts

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1. Introduction

The construction sector in Greece experienced a substantial decline after the fiscal crisis of 2008, following the downward trend in GDP and the subsequent financial and banking crisis. However, in recent years, it has managed to recover, especially after 2017, when growth rates were observed in the country [1]. Since then, the number of public works construction contracts has been increasing, and copious amounts of money have been allocated by the country's public entities operating in the construction sector. As with all construction industries, the Greek construction industry is plagued with delays and cost overruns that inevitably lead to claims and disputes that, in many cases, end up in litigation, which inevitably cost additional money to both disputing parties.

Within this complex professional environment, where different objectives and benefits compete, according to each involved stakeholder's perspective, conflicts are sure to arise [2]. If these differences cannot be overcome with common courtesy or the use of management skills, they may result in the submission of a claim, i.e., a request for compensation for damages incurred by any party to the contract [3] that if rejected by the other party, result in disputes [4], which are slow to be resolved, especially if they end up in court. Therefore, the submission and rejection of a claim define the start of dispute evolution [5] which may or may not have significant impacts on contract performance. Therefore, identification of the causes of these claims and their impact on the duration, cost, and quality of the final project is expected to facilitate the successful performance of the construction project.

Initially, a literature review was conducted regarding research on claims in the construction industry since 1990. The search was implemented through the Google Scholar platform and through databases such as www.scopus.com and www.researchgate.com, where hundreds of scientific articles which included the keywords "construction claims" or "construction disputes" were identified. Following this, 50 research papers were chosen to undergo complete content analysis. The selection criteria were those articles available for free access that included a list of construction contract causes of claims. As seen in Table 1, the research scope for eighteen of these was related to determining and evaluating the causes of construction claims, and eight were regarding dispute resolution methodologies, while two examined both. Also, fourteen studies were dedicated to claim management issues, and four proposed specific claim negotiation processes. Three articles discussed the dispute development process [6], investment risks associated with claims [7], and stakeholders' perceptions of organizational justice and cooperative behavior related to claims management [8], respectively. Finally, Olalekan et al. [9] conducted a bibliometric study of construction disputes. Their results showed that research in this area has focused on managing already existing disputes by litigation, arbitration, and Alternative Dispute Resolution (ADR), while a gap remains around dispute prevention methods.

Furthermore, the content analysis of the 50 examined articles revealed that four types of data sources were used. Data were obtained from the literature, questionnaire surveys, interviews, case studies, or a combination of these. Their geographical spread is noteworthy as they referred to construction claim research in 19 different countries. This is to be expected as the legal, social, and political environments of construction industries around the world are highly diverse. As a result, the findings of one country cannot necessarily be applied to other countries. As a result, research work on construction contract claims in the Greek construction industry was not found.

During the content analysis, it was discovered that regardless of the scope of the research paper, most provided a list of common causes of claims that were investigated from their point of view. Researchers like Ali et al. [10], Arditi and Pattanakitchamroon [11], and Yusuwan and Adnan [12] focused on one specific cause, i.e., extension of time (EOT) claims, while Ballesteros-Pérez et al. [13] through analyzing severe weather conditions leading to work stoppages and productivity loss leading to project delays created a model that offers advantages for predicting weather-related productivity losses at the design stage.

On the other hand, other researchers examined a significantly greater number of causes of claims (Table 1). For example, Yousefi et al. [14] included sixty risks leading to claims, which they classified into nine categories, i.e., integration, scope, time, procurement, communication, risk, human resource cost, cost, and quality management categories. Using this classification, they developed a model based on the probability impact matrix and used the analytical hierarchy process (AHP) and artificial neural networks (ANNs) to predict the frequency of claims in construction projects. Similarly, Chau [15] created ANN models as a prediction tool prior to litigation for estimating the resolution of a claim. Cakmak and Cakmak [16] used the analytical network process and showed that contractor-related causes of contractual claims and their subcategories are the most common in the Turkish construction industry.

Both Iskandar et al. [17] and Mishmish et al. [3] examined how the ranking of the importance of claims in construction vary between different categories of stakeholders. Their research differed in terms of data sources as Iskandar et al. [17] relied on questionnaires, while Mishmish et al. [3] relied on case studies as well as questionnaires.

The quest of numerous researchers was to determine the most common causes of claims for a particular type of project. For example, Nabi and El-Adaway [18] examined the associations between 40 causes of claims for a specific type of construction, that of modular construction in the United States of America (USA). They found that modular construction disputes are prompted by multiple causes rather than just one cause at a time. Similarly, Bakhary et al. [19] examined the causes of contractual claims in cases of public and private projects in Malaysia's transport, oil, and gas sectors. They found that lack of awareness among on-site staff to proactively identify contractual claims, lack of access to or unavailability of relevant documents, and conflicts that arise during negotiation between the contracting authority (CA) and the contractor are the main problems associated with the contractual claim management process. Furthermore, Kisi et al. [20] examined transport construction projects in Nepal with data collected from a questionnaire-based investigation. They found that contractual claims related to variations, location, conditions, and delays were the most common.

Finally, Shen et al. [21] examined how contractual claims are managed for diverse types of projects worldwide. They considered external risks (social, political, physical, and financial), the organizational behavior of clients (untimely payments, change orders, inefficient processing), and the definition of the project in the contract (unclear technical specifications, unclear scope of work) as causes of contractual claims. Their study findings suggest that external risk, client organizational behavior, and project definition in the contract can directly influence contractual claims.

One example of research work aiming to bring claim management techniques up to date with the use of digital tools is that of Ibraheem and Mahjoob [22], who showed the potential of building information modelling (BIM) in the prevention of causes of claims related to inaccurate quantity estimates, excessive change orders, errors and design changes, drawing and specification defects, as well as lack of communication between various design disciplines. This was achieved by taking advantage of specific BIM functions such as 3D visualization, clash detection, coordination, and quantity measurement take-off. Before their research, no system was being implemented in Iraq to manage contractual claims, indicating the benefits to be achieved in terms of claim reduction by applying innovative technologies in construction contract management.

For green building projects in Turkey, Mohammadi and Birgonul [7] evaluated the relative importance index (RII) for factors leading to (a) professional liability risks, (b) third-party certification risks, (c) financial risks, and (d) legal contractual risks based on expert opinion and found that legal risks are the ones that cause the contractual claims between the parties involved in sustainable construction projects indicating the significance of being able to identify and assess potential contractual claims in advance through appropriate risk management techniques.

Based on the existing literature described in the previous paragraphs, there is abundant research interest in the causes of contractual claims and the prediction of the probability of their occurrence. However, no relevant recent research examines this issue in the construction industry in Greece. Moreover, even though each study examines similar causes, comparisons of their results are obstructed due to a lack of standard coding. Therefore, after the content analysis of the selected studies, this paper defines a cause of claims breakdown structure (CCBS) that includes the 39 most common causes of claims that are encountered in real projects internationally as found in the literature.

The novelty of this study is that these common causes of claims, as defined by the literature review and content analysis, are further investigated in terms of their probability of occurrence and the perceived impact they have on the project completion time, its total cost, and quality. As a result, a risk assessment tool for claim prevention can be provided for use by practitioners to fill the gap determined by Olalekan et al. [9] in their recent bibliometric review.

Therefore, the research questions (RQ) are:

1. What is the frequency of occurrence of each cause of contractual claim?
2. What is the perceived impact of each cause of claims on the project's duration?
3. What is the perceived impact of each cause of claims on the project's final cost?
4. What is the perceived impact of each cause of claims on the quality of the project?
5. What are the top five highest risk causes of claims on the overall performance of construction contracts?

Table 1. Literature review content analysis.

Authors	Year	Data Source [1]	Research Scope	Causes	Country
Abdul-Malak et al. [23]	2002	LR	Claims management	0	
Aibinu et al. [8]	2011	Q/CS	Stakeholder perception	0	Singapore
Ali et al. [10]	2020	Q/I/CS	Claims management	1	Pakistan
Al-Sabah et al. [24]	2003	LR	Causes of claims	7	Kuwait
Arditi and Pattanakitchamroon [11]	2006	LR	Claims management	1	N/A
Bakhary et al. [19]	2015	Q	Causes of claims	8	Malaysia
Ballesteros-Pérez [13]	2017	LR	Dispute resolution	1	Spain
Barman and Charoenngam [25]	2017	CS	Claims management	6	UK
Cakmak and Cakmak [16]	2014	Q/CS	Causes of claims	28	Turkey
Chan and Suen [26]	2005	Q	Causes of claims and dispute resolution	16	China
Chan et al. [27]	2006	I	Dispute resolution	2	Hong Kong
Chaphalkar et al. [4]	2015	CS	Causes of claims	10	India
Chau [15]	2007	LR	Dispute resolution	24	Hong Kong
Cheung and Pang [28]	2013	LR	Causes of claims and dispute resolution	8	Hong Kong
Cheung and Suen [29]	2002	LR/I	Dispute resolution	0	Hong Kong
Cheung et al. [30]	2019	Q	Dispute resolution	56	Hong Kong
Diekmann and Girard [31]	1995	Q/CS	Claims management	0	USA
Gardiner and Simmons [32]	1998	I/CS	Causes of claims	3	UK
Gould [33]	1998	Q	Dispute resolution	0	UK
Ho and Liu [34]	2004	LR	Claims management	0	
Ibraheem and Mahjoob [22]	2021	Q/CS	Causes of claims	16	Iraq
Ilter and Bakioglu [35]	2018	CS	Claims management	19	Turkey
Iskandar [17]	2021	Q	Causes of claims	43	Indonesia
Jahren and Dammeier [36]	1990	I	Claims management	7	USA
Kartam [37]	1999	LR	Claims management	0	
Kilian et al. [38]	2005	CS	Causes of claims	7	USA
Kisi et al. [20]	2020	Q	Dispute resolution	7	International
Kululanga et al. [39]	2001	Q/CS	Claims management	0	Malawi
Kumaraswamy [40]	1998	LR/Q/ CS	Causes of claims	29	Hong Kong
Mishmish and El-Sauegh [3]	2018	Q/CS	Causes of claims	16	UAE
Mitropoulos and Howell [6]	2001	LR	Dispute Development Process	14	USA
Mohammadi and Birgonu [7]	2016	Q	Investment Risks	4	Turkey
Nabi and El-Adaway [18]	2022	CS	Causes of claims	40	USA
Olalekan et al. [9]	2021	LR	Bibliometric Review of Construction Claim Research	0	International
Ren and Anumba [41]	2002	LR	Claims Negotiation	0	
Ren et al. [42]	2003	CS	Claims Negotiation	2	
Ren et al. [43]	2002	LR	Claims Negotiation	4	
Scott and Harris [44]	2004	Q/I	Claims management	4	UK
Semple et al. [45]	1994	CS	Causes of claims	4	Canada
Shen et al. [21]	2017	Q	Claims management	10	International
Stamatiou et al. [46]	2019	LR	Claims management	19	Greece/UK
Treacy [47]	1995	LR	Dispute resolution	0	USA
Vidogah and Ndekugri [48]	1997	Q/I/CS	Claims management	4	UK
Viswanathan et al. [49]	2020	LR/Q	Causes of claims	14	India
Wong and Maric [50]	2016	CS	Causes of claims	7	Australia
Yogeswaran et al. [51]	1998	CS	Causes of claims	11	Hong Kong
Yousefi et al. [14]	2016	LR/CS	Causes of claims	60	Iran
Yuan and Ma [52]	2012	LR	Claims Negotiation	0	
Yusuwan and Adnan [12]	2013	Q	Causes of claims	1	Malaysia
Zaneldin [53]	2006	Q/CS	Causes of claims	26	UAE

[1] LR = Literature Review; CS = Case Studies; I = Interviews; Q = Questionnaire.

The present study follows a mixed-methods research approach using a questionnaire addressed to 22 professional engineers who have been active in Greece for the last few years and engage in public procurement for construction projects from different workplaces. Data from 50 articles examining the causes of contractual claims in different countries for construction projects in public and private sectors were used to create the questionnaire. Data analysis included descriptive statistical analysis, reliability testing, use of relative importance index, and risk analysis.

The rest of this paper includes Section 2, which presents the methods for development of the cause of claims breakdown structure (CCBS), data collection, and analysis. The results are presented and discussed in Section 3. Finally, Section 4 presents the conclusions and limitations of the research, plus recommendations for future research.

2. Research Methods

2.1. Cause of Claims Breakdown Structure (CCBS)

The studies in Table 1 defined a series of causes of claims obtained from the literature reviews, questionnaire surveys, and/or case studies and then proceeded to categorize and rank them in various ways. The number of causes each researcher utilizes and analyzes also differs. Developing a unified classification of causes of claims in construction contracts and creating a common codification can provide a basis for comparing the results of international research. Eight studies examined over twenty causes, while twenty studies considered less than ten causes (Table 1).

After the initial collection and production of a study versus causes table with 539 causes (rows) and the 50 studies (columns) and following the removal of causes with the same name or grouping of others with similar meanings, they were consolidated to obtain a final list of 39 causes each appearing at least once and up to 23 times in the selected studies.

Causes of claims, like all risk sources, can be structured and codified to provide a standard representation to help understand, manage, and communicate on a project and industry level while allowing easy comparison between scientific research endeavors. A risk breakdown structure (RBS) is the categorization of risk sources in a hierarchical structure [54]. As a result, 39 factors were coded and classified in the CCBS, as shown in Figure 1. It provides a comprehensive yet detailed view of the hierarchy of the predominant causes of claims examined in the selected studies. Based on Cakmak and Cakmak's [16] categorization, the 39 factors were classified into the following 7 categories relating to the CA, the contractor, the design, the contract, human behavior, the project itself, and external factors.

2.2. Data Collection

The questionnaire examined the opinions of experts on 39 common causes of contractual claims in public construction contracts according to: (a) the frequency of their occurrence, (b) the perceived impact they have on the time to complete the project, (c) the perceived impact on the total cost of the project, and (d) the perceived impact on the quality of the final project.

A mixed-methods research approach [55] was applied that integrated qualitative data (opinions of experts) in quantitative form (based on closed-ended responses to a relevant survey) with quantitative research analysis methods (Likert scale ratings, relative importance index, and risk value). It was designed to quantitatively describe a population's trends, attitudes, or opinions [55] based on the qualitative views of the expert participants instead of actual data from claims made in real projects. This survey research method can be called the 'knowledge mining' method that has been used in construction management research by the authors and others to determine expert opinion and practitioners' insights on delay factors [56], cost escalation [57], contract types [58], project procurement systems [59,60], project managers' attributes [61], barriers to energy upgrading of buildings [62], safety control [63], as well as for claim management problems [19].

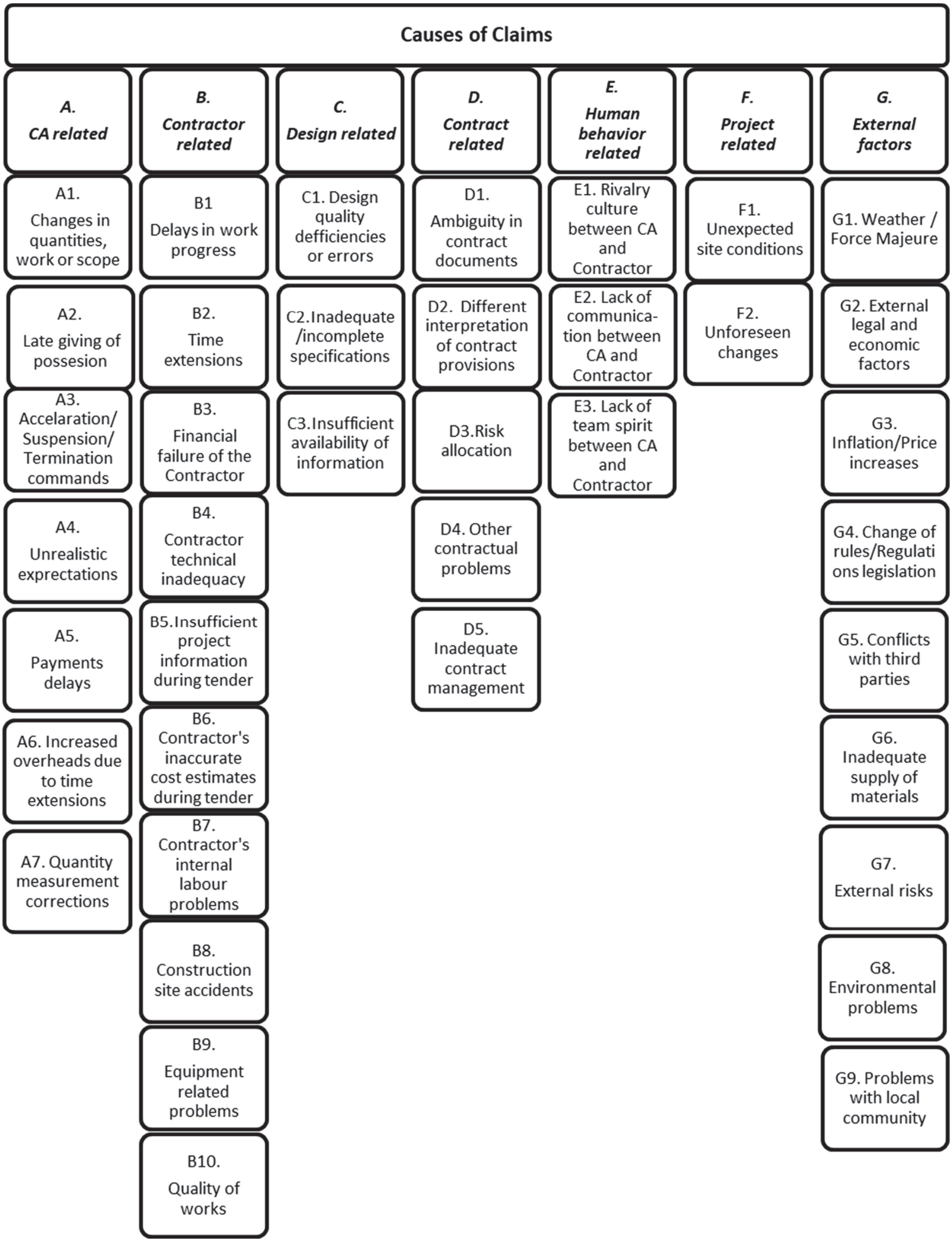

Figure 1. Cause of Claims Breakdown Structure (CCBS).

The questions were mostly multiple-choice, closed-ended questions. The first part of the questionnaire consisted of 11 questions that relate to the demographic and personal data of the survey participants, who are active engineers of different specializations. The second part included an assessment of the cause of contractual claims in public works' contracts in terms of the four variables (frequency of occurrence, impact on project completion time, total project cost, and quality of the final project). This section uses the five-point Likert scale, with the assessment being made using two ways of scoring:

- 1—Never, 2—Rarely, 3—Often, 4—Many times and 5—Always (RQ1).
- 1—Not at all, 2—Very little, 3—A little, 4—A lot, and 5—Very much (RQ2–4).

Participants expressed their opinions on the level of agreement for each variable using the above scales, which were later transformed into numerical scores with values from 1 to 5 in SPSS. In addition, the questionnaire included an open-ended question on ways to address or reduce the incidence of claims in the management of public construction contracts, which was not compulsory and was answered by 11 out of 22 sample participants.

From the outset, the questionnaire was chosen to be addressed to experts rather than the general population because of the nature and scope of the subject matter, which requires knowledge and experience in public works' contracting. Professionals with knowledge of public construction project management have also faced contractual claims and disputes and can objectively capture the root causes of construction contractual claims. It should be noted that the corresponding author, who has decades of personal experience in claim management for highway construction contracts, retained numerous experienced contacts in the industry to whom a private direct message was sent to inform them of the purpose of the survey. Thus, this convenience sampling method [64] collected 22 responses by posting on the LinkedIn social media platform and by sending 36 personal invitations through Meta Messenger and Viber. The questionnaires were distributed via Google Forms and were completed and submitted anonymously from January to February 2023.

2.3. Data Analysis Methodology

The data from the questionnaire survey were analyzed using the IBM SPSS statistical tool. For the Likert scale questions, it was found that the mean and standard deviation of the variables were not sufficient, as most of the results were near the neutral answer. Thus, it was chosen to perform the subsequent data analysis by calculating each variable's relative importance index (RII) and to use the results to carry out a risk analysis by calculating the resulting risk value (RV) to measure the risk of each cause of contractual claim on the duration, time, quality, and overall performance of the final project.

The RII has been used in construction management research to assess the severity of identified delay factors on project duration and cost escalation [65–68], to rank the significance of contributing factors to accidents [63], and to conduct meta-analyses of data from multiple studies [69].

In this study, the RII was calculated using Microsoft Excel according to Equation (1), adapted from Holt [70], for each of the 156 variables (39 causes × 4 research questions) rated on a five-point Likert scale.

$$\mathrm{RII} = \sum\nolimits_{a=1}^{m} \frac{\mathrm{P_i U_i}}{\mathrm{nN}} \tag{1}$$

where

m = number of integers on the response scale (in this case 5);
P_i = takes values 1 to 5 in increasing frequency/severity;
U_i = number of respondents that selected P_i;
N = Total number of respondents (N = 22);
n = maximum value of maximum rating (in this case 5).

It should be clarified that all questions were compulsory (except the open-ended question), and thus, there were no blank answers. As a result, the RII can take values from 0 to 1 and is therefore taken as a measure of the probability of occurrence of a particular cause of claims. In this case, the lowest possible value is 0.2 since in the worst-case scenario of all respondents choosing Never or Not at all, the formula produces an RII value of 0.2.

The risk analysis complements the RII analysis, as the RII method, although effective in ranking the various causes of claims in terms of their perceived frequency of occurrence, does not take into account the magnitude of their impact or the vulnerability that a particular construction project may have for each cause of claim and thus does not provide all the knowledge required to conduct contractual claim risk analysis for a new project [68].

Risks on the successful outcome of a construction contract correspond to uncertain events or situations which, if they manifest, may have a positive or negative impact on the objectives of the construction project [54]. In this case, the causes of claims are risks that, if they occur, will have a negative impact on the objective of completing the project within the planned schedule, budgeted cost, and expected quality. In this context, the risk is considered a multidimensional quantity approximated by a point estimate as the expected value resulting from multiplying the probability of the cause of the claim occurring (P) by its consequence, impact, or severity (S), given that it has taken place. Thus, the risk value (RV) of the cause of a claim can be calculated using Equation (2) [54]:

$$\mathrm{RV} = \mathrm{P_i} \times \mathrm{S_i}, \tag{2}$$

3. Results and Discussion

3.1. Demographic and Personal Characteristics

Tables 2 and 3 present the demographic data and experience of the 22 survey participants. All participants have experience in public contract management either as engineers of the construction contractor or as engineers of the CA or both. Furthermore, 17 participants responded that they have experience in construction contract management as engineers employed by the contractor, and 16 people responded that they have experience in construction contract management as supervising engineers for the CA (72.73%), and 50% had experience in both. Overall, it was judged that the sample was quite experienced in managing public construction contracts in the capacity of construction contractor engineer and the capacity of CA engineer.

Table 2. Demographic data of the sample.

Sex:	Men (68.2%), Women (31.8%)
Age:	26–34 (4.5%), 35–44 (9.1%), 45–54 (45.5%), 55–64 (31.8%), 65 and over (9.1%)
Highest Academic Degree:	First University Degree (45.5%), Postgraduate Degree (45.5%), PhD (9.1%)
Profession:	Civil Engineer (72.7%), Architect (4.5%), Electrical Engineer (4.5%), Other (18.2%)

Table 3. No of participants experienced in different types of construction projects.

Construction Type	No. of Experienced Participants	Construction Type	No. of Experienced Participants
Buildings	15 (68.18%)	Ports	5 (22.73%)
Roads	19 (86.36%)	Airports	4 (18.18%)
Water networks	17 (77.27%)	Railway	4 (18.18%)
Sewage networks	13 (59.09%)	Metro	3 (13.64%)

3.2. Relative Importance Indices (RII)

Cronbach's alpha reliability index was calculated for each of the four research questions by including the thirty-nine tested causes derived from the literature in each of them. A high internal consistency for the data set was observed (Table 4) as the Cronbach's alpha index takes values greater than 0.7 in each case [71].

Table 4. Cronbach's alpha reliability index.

Research Question	Degree of Reliability (Cronbach's Alpha)	Research Question	Degree of Reliability (Cronbach's Alpha)
RQ1 Frequency of occurrence	0.949	RQ3 Severity of impact on cost	0.985
RQ2 Severity of impact on duration	0.977	RQ4 Severity of impact on quality	0.984

The evaluation of the resulting RII was made by considering the following transformation scheme adapted from Chen et al. [72] to suit the rating scale employed in the questionnaire.

- High for values greater than 0.8;
- High-medium for values between 0.6 and 0.8;
- Medium for values between 0.4 and 0.6;
- Low for values between 0.2 and 0.4.

Table 5 presents the mean, standard deviation, and RII index of the respondents' answers to RQ1–RQ4 as well as the number of times each cause appeared in the 50 studies. First, regarding the frequency of occurrence of the examined causes of claims as they have experienced them during their professional career, we observed that in the Greek construction industry, the most frequently occurring cause is "Changes in quantities, work, or scope (A1)" with an RII = 0.75. Next, the results relating to RQ2 showed the most significant impact on the project duration is caused by "Financial failure of the contractor (B3)" with an RII = 0.78. Furthermore, regarding the perceived severity of the impact of the various causes of claims on the total project cost (RQ3), we observed that the cause with the most significant impact on the total project cost (RII = 0.79) is "Inflation/Price Rises (G3)". Finally, from the responses to RQ4, it is observed that in the Greek construction sector, the cause of contractual claims with the greatest impact on the quality of the final project is "Time extensions (B2)" (RII = 0.81). Table 6 depicts the causes ranked in the top ten for each research question, i.e., the most frequent causes and the ten causes with the most severe perceived impact on the final duration, cost, and quality. It is interesting to note that while "Changes in quantities, work or scope (A1)" is the most probable cause, it is perceived to have a significant impact (>0.6) on cost (RII_C = 0.75), duration (RII_D = 0.78), and not on quality. On the other hand, the cause perceived to have the greatest impact on the quality of the project "Time extensions (B2)" is not in the top 10 frequent causes at all. Finally, the three causes of claims rated in the top ten in all four categories are "Payment delays (A5)", "Design quality deficiencies or errors (C1)", and "Inflation/price increases (G3)". Therefore, as these three causes are perceived by the experts as having a significant impact on time, cost, and quality, while also considered to have a high frequency of occurrence, it is expected that they will emerge in the top 10 highest risk causes of claims that should be avoided by public work clients. The next section describes the results of the risk analysis on all 39 causes.

Table 5. Statistical results of research questions 1 to 4.

CCBS Code	No. of Occurrences in Literature	RQ1 Frequency of Occurrence			RQ2 Severity of Impact on Duration			RQ3 Severity of Impact on Cost			RQ 4 Severity of Impact on Quality		
		Mean	**Sd.**	**RII$_{i}$**	**Mean**	**Sd.**	**RII$_{id}$**	**Mean**	**Sd.**	**RII$_{ic}$**	**Mean**	**Sd.**	**RII$_{ip}$**
A1	23	3.73	1.03	0.75	3.77	0.61	0.75	3.91	0.87	0.78	2.82	0.80	0.56
A2	9	3.05	1.13	0.61	3.82	1.10	0.76	3.23	0.97	0.65	2.45	0.67	0.49
A3	18	2.41	0.85	0.48	3.05	0.95	0.61	3.00	0.98	0.60	2.55	0.91	0.51
A4	6	2.68	0.89	0.54	2.91	1.02	0.58	3.00	1.07	0.60	2.64	0.95	0.53
A5	12	3.23	0.81	0.65	3.86	1.04	0.77	3.59	1.05	0.72	3.23	0.87	0.65
A6	7	3.23	1.02	0.65	3.36	1.05	0.67	3.50	1.01	0.70	2.91	1.07	0.58
A7	3	3.14	0.83	0.63	3.23	0.81	0.65	3.23	0.92	0.65	2.64	0.49	0.53
B1	19	3.32	0.72	0.66	3.82	0.85	0.76	3.41	0.96	0.68	2.86	0.94	0.57
B2	17	3.41	0.96	0.51	3.91	0.87	0.61	3.18	0.91	0.65	2.73	1.03	0.81
B3	6	2.82	0.73	0.68	3.82	0.91	0.78	3.27	1.03	0.64	3.45	1.14	0.55
B4	12	2.18	0.66	0.56	3.68	0.84	0.76	3.36	1.09	0.65	3.55	1.14	0.69
B5	5	2.27	0.70	0.44	3.18	1.05	0.74	3.05	1.09	0.45	3.09	1.11	0.71
B6	8	3.73	1.03	0.45	3.77	0.61	0.64	3.91	0.87	0.61	2.82	0.80	0.62
B7	8	3.05	1.13	0.51	3.82	1.10	0.64	3.23	0.97	0.69	2.45	0.67	0.61
B8	4	2.41	0.85	0.50	3.05	0.95	0.63	3.00	0.98	0.60	2.55	0.91	0.59
B9	3	2.68	0.89	0.36	2.91	1.02	0.55	3.00	1.07	0.56	2.64	0.95	0.52
B10	16	3.23	0.81	0.45	3.86	1.04	0.60	3.59	1.05	0.61	3.23	0.87	0.61
C1	13	3.23	1.02	0.65	3.36	1.05	0.75	3.50	1.01	0.76	2.91	1.07	0.74
C2	11	3.14	0.83	0.52	3.23	0.81	0.66	3.23	0.92	0.64	2.64	0.49	0.67
C3	3	3.32	0.72	0.51	3.82	0.85	0.65	3.41	0.96	0.60	2.86	0.94	0.65
D1	12	3.41	0.96	0.49	3.91	0.87	0.63	3.18	0.91	0.61	2.73	1.03	0.60
D2	8	2.82	0.73	0.53	3.82	0.91	0.67	3.27	1.03	0.63	3.45	1.14	0.60
D3	8	2.18	0.66	0.44	3.68	0.84	0.58	3.36	1.09	0.55	3.55	1.14	0.53
D4	4	2.27	0.70	0.45	3.18	1.05	0.61	3.05	1.09	0.55	3.09	1.11	0.52
D5	11	2.55	0.80	0.43	3.18	0.91	0.63	3.45	1.14	0.61	3.05	1.05	0.57
E1	6	2.50	0.86	0.45	3.14	1.04	0.61	3.00	1.16	0.63	2.95	1.13	0.56
E2	16	1.82	0.73	0.45	2.73	1.03	0.63	2.82	1.01	0.63	2.59	1.10	0.57
E3	6	2.23	0.69	0.44	3.00	1.02	0.62	3.05	1.13	0.62	3.05	1.09	0.56
F1	13	2.55	0.86	0.51	3.05	0.79	0.67	3.23	0.97	0.62	4.05	1.17	0.61
F2	5	3.23	0.75	0.56	3.77	0.97	0.70	3.82	1.01	0.69	3.68	1.25	0.60

Table 5. *Cont.*

CCBS Code	No. of Occurrences in Literature	RQ1 Frequency of Occurrence			RQ2 Severity of Impact on Duration			RQ3 Severity of Impact on Cost			RQ 4 Severity of Impact on Quality		
		Mean	**Sd.**	**RII_i**	**Mean**	**Sd.**	**RII_{id}**	**Mean**	**Sd.**	**RII_{ic}**	**Mean**	**Sd.**	**RII_{ip}**
G1	11	2.59	0.91	0.56	3.32	1.00	0.62	3.18	1.05	0.66	3.64	1.29	0.60
G2	9	2.55	0.80	0.47	3.23	1.19	0.61	3.00	1.07	0.63	3.27	1.32	0.53
G3	6	2.45	1.06	0.56	3.14	1.13	0.71	3.05	1.05	0.79	3.00	1.16	0.66
G4	6	2.64	0.90	0.48	3.36	1.22	0.62	3.14	1.08	0.66	3.00	1.31	0.57
G5	7	2.18	0.96	0.49	2.91	0.97	0.58	2.77	1.07	0.59	2.64	1.05	0.55
G6	6	2.23	0.87	0.49	3.05	0.90	0.70	2.77	0.81	0.72	2.59	0.91	0.61
G7	3	2.14	0.83	0.42	3.14	1.17	0.55	3.05	1.05	0.55	2.86	1.17	0.53
G8	2	2.23	0.87	0.45	3.05	1.21	0.62	3.14	1.17	0.62	2.82	1.01	0.54
G9	2	2.27	0.83	0.47	3.14	1.21	0.62	3.14	1.21	0.58	2.86	0.99	0.51

Table 6. Top ten causes of claims in terms of frequency and severity of impact on duration, cost, and quality.

Freq.	RII_i	Rank	Duration	RII_{id}	Rank	Cost	RII_{ic}	Rank	Quality	RII_{iq}	Rank
A1	0.75	1	**B3**	0.78	1	**G3**	0.79	1	**B2**	0.81	1
B3	0.68	2	**A5**	0.77	2	**A1**	0.78	2	**C1**	0.74	2
B1	0.66	3	**B1**	0.76	3	**C1**	0.76	3	**B5**	0.71	3
A5	0.65	4	**A2**	0.76	3	**A5**	0.72	4	**B4**	0.69	4
A6	0.65	4	**B4**	0.76	3	**G6**	0.72	4	**C2**	0.67	5
C1	0.65	4	**A1**	0.75	6	**A6**	0.7	6	**G3**	0.66	6
A7	0.63	7	**C1**	0.75	6	**F2**	0.69	7	**A5**	0.65	7
A2	0.61	8	**B5**	0.74	8	**B7**	0.69	7	**C3**	0.65	7
B4	0.56	9	**G3**	0.71	9	**B1**	0.68	9	**B6**	0.62	9
F2	0.56	9	**F2**	0.7	10	**G1**	0.66	10	**G6**	0.61	10
G1	0.56	9	**G6**	0.7	10	**G4**	0.66	10	**B7**	0.61	10
G3	0.56	9							**F1**	0.61	10
									B10	0.61	10

3.3. Risk Analysis

The degree of risk refers not only to the probability of something happening but also to the impact of the risk in question. The RII index calculated for the frequency of occurrence of the causes as rated by the respondents (Table 6) was used to determine the (P) probability values. The severity (S) value is subjective and varies according to the risk aversion of the decision maker and the actual conditions for each project [68]. However, in the case of this research, the RII indicators obtained by processing the respondents' answers on the extent to which they believe that each cause impacts the duration (RII_{id}), cost (RII_{ic}), and quality of the final project (RII_{iq}) were calculated (Table 6).

The degree of risk in terms of time (RV_t), cost (RV_c), and quality (RV_q) of the final project was then calculated as follows:

$$RV_D = P_i \times S_{id} = RII_i \times RII_{id}, \tag{3}$$

$$RV_C = P_i \times S_{ic} = RII_i \times RII_{ic}, \tag{4}$$

$$RV_Q = P_i \times S_{iq} = RII_i \times RII_{iq} \tag{5}$$

Table 7 presents the risk values (RV_D, RV_C, RV_Q) and their ranking according to the calculated risks on project duration (Rank RV_D), total project cost (Rank RV_C), and project quality (Rank RV_Q). The three causes with the highest risk value in terms of project duration are "Changes in the quantities, work, or scope (A1), "Financial failure of the contractor (B3)", and "Delays in work progress (B1)". Of the three, only "Financial failure of the contractor (B3)" was perceived as having the greatest impact on duration while "Changes in quantities, work or scope (A1)" ranked sixth with a significant RII_D value of 0, 75, and "Delays in work progress (B1)" ranked third with an $RII_D = 0.76$ but with medium to high probability of occurrence $RII_i = 0.66$. Obviously, changes in scope take time to take effect and if design changes are required, in cases of increased quantities will also require additional time to be completed. Similarly, financial problems endured by the contractor will lead them to adjust their resource planning which will inevitably take their toll on project progress. Finally, it goes without saying that any delays on the progress of work will have detrimental effects on project completion.

The riskiest causes of claims regarding the increase in project costs are, again, "Changes in quantities, work, or scope (A1)". Notably, instead of "Inflation/Price Increases (G3)" emerging as the second riskiest cause on cost increase which was perceived with the highest impact on cost, this time, in second place is "Design quality deficiencies or errors (C1), and in third place is "Payment delays (A5)" in terms of risk value on cost increases. It is found that change orders and design deficiencies are risks with a greater potential to lead to project cost overruns than causes related directly to payment delays. Finally, to prevent significant impacts on the quality of projects, mitigation measures to prevent claims arising from "Design quality deficiencies or errors (C1), "Payment delays (A5)", and "Changes in quantities, work or scope (A1)" should be implemented.

Table 7. Ranking by RV on project time, cost, and quality.

CCBS Code	RV_D	Rank RV_D	RV_C	Rank RV_C	RV_Q	Rank RV_Q	TRV1	Rank TRV1	TRV2	Rank TRV2
A1	0.56	1	0.59	1	0.42	3	0.54	1	0.52	1
A2	0.46	6	0.40	9	0.30	19	0.43	7	0.39	9
A3	0.29	25	0.29	26	0.24	33	0.28	25	0.28	28
A4	0.31	21	0.32	18	0.29	23	0.31	20	0.31	20
A5	0.50	4	0.47	3	0.42	2	0.48	4	0.46	3
A6	0.44	7	0.46	4	0.38	6	0.43	6	0.42	6
A7	0.41	9	0.41	8	0.33	13	0.40	10	0.38	10
B1	0.50	3	0.45	5	0.38	7	0.47	5	0.44	5
B2	0.31	22	0.33	17	0.41	4	0.33	17	0.35	12
B3	0.53	2	0.44	7	0.37	8	0.49	2	0.45	4
B4	0.43	8	0.36	12	0.39	5	0.41	8	0.39	8
B5	0.33	19	0.20	39	0.31	16	0.30	23	0.28	26
B6	0.29	27	0.27	30	0.28	24	0.28	26	0.28	25
B7	0.33	18	0.35	14	0.31	17	0.33	18	0.33	17
B8	0.32	20	0.30	22	0.30	21	0.31	21	0.30	21
B9	0.20	39	0.20	38	0.19	39	0.20	39	0.20	39
B10	0.27	36	0.27	30	0.27	25	0.27	33	0.27	30
C1	0.49	5	0.49	2	0.48	1	0.49	3	0.49	2
C2	0.34	14	0.33	16	0.35	10	0.34	14	0.34	14
C3	0.33	17	0.31	21	0.33	14	0.33	19	0.32	18
D1	0.31	23	0.30	23	0.29	22	0.31	22	0.30	22
D2	0.36	12	0.33	15	0.32	15	0.35	13	0.34	15
D3	0.26	37	0.24	36	0.23	37	0.25	37	0.24	37
D4	0.27	32	0.25	35	0.23	36	0.26	36	0.25	36
D5	0.27	35	0.26	34	0.25	32	0.27	35	0.26	35
E1	0.27	32	0.28	27	0.25	29	0.27	32	0.27	31
E2	0.28	30	0.28	27	0.26	28	0.28	30	0.27	29
E3	0.27	34	0.27	32	0.25	31	0.27	34	0.26	34
F1	0.34	16	0.32	20	0.31	17	0.33	16	0.32	18
F2	0.39	11	0.39	10	0.34	11	0.38	11	0.37	11
G1	0.35	13	0.37	11	0.34	11	0.35	12	0.35	13
G2	0.29	28	0.30	24	0.25	30	0.28	28	0.28	27
G3	0.40	10	0.44	6	0.37	9	0.40	9	0.40	7
G4	0.30	24	0.32	19	0.27	26	0.30	24	0.30	23
G5	0.28	29	0.29	25	0.27	27	0.28	27	0.28	24
G6	0.34	15	0.35	13	0.30	19	0.34	15	0.33	16
G7	0.23	38	0.23	37	0.22	38	0.23	38	0.23	38
G8	0.28	31	0.28	29	0.24	34	0.27	31	0.27	33
G9	0.29	26	0.27	33	0.24	35	0.28	29	0.27	32

An attempt is then made to synthesize the results to determine which causes have the highest overall risk level considering all three risk values (RV_D, RV_C, RV_Q). Based on the results of the individual RVs for the three variables considered, weight is given to each risk level by considering two scenarios. The first probability scenario (Scenario 1) assumes a weighting factor of 70% for the project duration (w_d), 15% for the impact on the total cost (w_c), and another 15% for the effect on the quality of the final project (w_q). That is, the decision maker, in this case, considers the impact on duration more important than the impact on cost and time. The results differ in the case of the second scenario (Scenario 2), in which the weighting factor for the impacts on duration, cost, and quality of the final project are considered equal and thus calculated at 33.3% for each variable. Table 7 presents the results of Scenario 1 and Scenario 2 with the ranking of each cause according to the resulting total risk value (TRV) as follows:

$$TRV_i = w_d \times RV_{Di} + w_c \times RV_{Ci} + w_q \times RV_{Qi,} \quad (6)$$

We observe that both scenarios agree on the top five most dangerous causes of contractual claims that affect overall project performance although in a slightly different order. These are once again "Changes in quantities, work, or scope (A1)", followed by "Design quality deficiencies or errors (C1), "Payment delays (A5)", "Delays in work progress (B1)", and the "Financial failure of the contractor (B3)".

3.4. Expert Proposals for Mitigation Measures

The questionnaire included an open-ended question on the participants' views on how claims can be addressed or reduced in the management of public construction contracts. Participant P3 believes that one way is "*to better inform potential contractors about the project and the site conditions during the formulation of the financial offer, and another is to promote a team spirit between the contractor and the contracting authority*".

According to Participant P7, one way is to "*draw up detailed rules, specifications and studies*". Similarly, participant P11 considers that the solution is "*better designs and more elaborate contract documents*". The twelfth participant, P12, suggests more "*professionalism and proper training*". Participants P14 and P16 mention as a way of resolution "*the most comprehensive designs possible, timely giving possession of the land, ensuring financial flow throughout the project, timely response by the CA to problems*" and "*better designs with supervision by the designer during construction*", respectively.

There is another view expressed by the thirteenth participant (P13) that "*better preparation of the pre-contractual stage for all kinds of licensing and anything related*" is needed. Participant P18 suggests "*tendering with a design-build system*". In contrast, participant P20, based on their experience in the execution of public works, considers that "*the Amicable Settlement Committee or as it is now called Arbitration can help all stakeholders*" and believes "*the activation of article 176 of Law 4412/16 is necessary for a wider range of projects and not only for projects above 10.000.000€*". This stipulation refers to the procedures for applying arbitration as a dispute resolution method instead of the administrative and judicial procedures that can be used in all cases of public works' contracts in Greece.

The above suggestions provided by the respondents on how claims can be addressed or reduced in the management of public construction contracts were given without knowledge of the results of the risk assessment conducted based on their individual ratings of frequency of occurrence and severity of impact. Of all the suggestions made, only four participants indicated mitigation measures related to four of the five highest risk causes identified in this study. Suggestions were made by P7, P11, P14, and P16 to prevent claims due to "Changes in quantities, work or scope (A1)" and "Design quality deficiencies (C1)" by "*drawing up detailed rules, specifications and studies*", providing "*better designs and more elaborate contract documents,*" or "*the most comprehensive designs possible*", and ensuring "*better designs with supervision by the designer during construction*". Also, P14 considered it necessary to *"ensure financial flow throughout the project"* as a mitigation measure for "Payment delays (A5) " that will inevitably facilitate prevention of "Financial failure of the contractor (B3)". No suggestions were made to prevent "Delays in work progress (B1)" directly by any of the participants.

4. Conclusions

Based on the calculated RII values from the opinions of experts in the field, this paper proposes probability and severity of impact values for 39 common causes of claims in the public construction industry in Greece. These can be applied for the calculation of their RVs to guide Greek stakeholders in public construction contracts to plan mitigation measures for the consequences of contractual claims on construction contract performance. From the ranking of the causes based on the TRV, the causes of contractual claims that most affect the performance of construction projects in Greece are highlighted. In response to RQ 5, it is shown that the top five highest risk causes of contractual claims in the Greek construction industry that affect overall project performance are "Changes in quantities, work, or scope (A1)", followed by "Design quality deficiencies or errors (C1), "Payment delays (A5)", "Delays in work progress (B1)", and the "Financial failure of the contractor (B3)".

This research article contributes to the international literature on the causes of contractual claims in construction projects as it pioneers through its simultaneous examination of the views of experts on the frequency of occurrence of causes of contractual claims and their perceived impact on the time, total cost, and quality of the final project, for which there is a research gap in the literature. In addition, it defines a cause of claims breakdown structure (CCBS) that includes the most common causes of claims that are encountered in real projects internationally, as found in the literature, which international researchers can use to facilitate comparison of results to provide global conclusions. The limitations of this study are that it needs to be more focused on specific construction types and that it is based only on expert opinion. It should, therefore, be verified based on existing project claims data and with a questionnaire survey directed to a greater number of stakeholders in the construction industry. The results could then be further analyzed using factor analysis and analysis of variance to evaluate the independence or not of the individual causes of claims as well as differences in opinions between groups of respondents (CA, contractor, designer). In addition, this study could be further expanded to include expert opinion and data from private projects and private clients to see if significant differences occur between public and private construction projects.

Nevertheless, the results of this study can be used as a springboard for the development of an optimal streamlined dispute prevention method for which a gap in the literature remains [9]. The research team envisages that this can be achieved by the adoption of advanced technologies to address the above-flagged issues. By combining BIM, Blockchain, and smart contracts, progress payments can be automated [73–76] and delays in work progress and associated EOT claims can be better managed [10]. Additionally, the utilization of specific BIM functions, such as 3D visualization, clash detection, coordination, and quantity measurement take-off, can ensure minimization of changes in quantities, work, or scope and design quality deficiencies or errors [22]. Finally, provisions in the tender procedures to prevent the selection of a contractor with indications of financial difficulties can be implemented to avoid claims caused by the financial failure of the contractor.

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Synergies and Challenges: Exploring Organizational Perspectives on Digital Transformation and Sustainable Development in the Context of Skills and Education

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Abstract: The discourse surrounding digital transformation (DT) and sustainable development (SD) is pervasive in contemporary business and organizational operations, with both processes considered indispensable for sustainability. The success or failure of these endeavors hinges significantly on factors such as the behavior and skill sets of individuals within organizations. Thus, the purpose of the paper is twofold: to investigate the perceptions of organizations on digital transformation and sustainable development with regards to skills and education, and, secondly, to use the insights from these perceptions as a starting point for the use of systems thinking as a tool that could assist in achieving these states. To achieve the objective, a research effort was conducted that included desktop research, interviews with experts, and the development of a survey that was disseminated across Europe with questions on digital transformation and sustainable development. Finally, a general causal loop diagram was designed, illustrating the processes of digital transformation and sustainable development within organizations from a top-down view. The study reveals commonalities between DT and SD, recognizing both processes as advantageous with shared deficiencies in specific skill sets. It highlights a synergistic relationship between initiating DT and fostering SD activities. Furthermore, the research underscores the temporal aspects of these processes, acknowledging delayed positive effects and immediate implementation costs that challenge decision-makers to balance long-term benefits with short-term viability. In conclusion, the exploration emphasizes the dynamic nature of DT and SD, urging continual attention to the evolving landscape and the imperative for a shared understanding within organizational contexts.

Keywords: digital transformation; sustainable development; survey; perceptions; systems thinking; causal loop diagram

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1. Introduction

Digital transformation (DT) and sustainable development (SD) are two terms that dominate the discussion in the operations of businesses and organizations. Digital transformation is the application of automation and digitization to all aspects of an organization while sustainable development has been defined as the ability to satisfy needs without a detriment to future generations' ability to do the same [1,2].

These processes are not only considered fundamental for businesses and organization, but they appear indispensable in their effort for longevity and sustainability [3]. This is not limited to large corporations but includes Small and Medium Enterprises (SMEs), and public and private organizations in all economic areas. For example, in the construction industry, a driving economic force for every country, digital transformation is seen as a disruptive force [4], one, however, that its increasing adoption affects and improves productivity and efficiency [5].

Similarly, sustainable development, despite the vague nature of its definition, is constantly codified in national legislations as a necessary modus operandi of organizations. Pressure from the law, clients, and international treaties like the Sustainable Development Goals is making businesses consider the environmental and societal impacts of their operations [6].

Despite their complexity, both digital transformation and sustainable development are considered as vehicles for tremendous opportunities for success [7], but they are accompanied by great challenges and risks as well [8]. Among those are the lack of innovation and expertise, technical barriers and, most importantly, the lack of the necessary skills [9].

Furthermore, enterprises often perceive digital transformation as a risky endeavor. The World Economic Forum [3] identifies technological risks, such as cyber-attacks and data fraud, among the top global concerns, alongside environmental risks. These risks pose the potential for financial losses and significant damage to reputation. Therefore, it is crucial to enhance the digital and Information and Communication Technologies (ICT) literacy of both employees and managers.

Merely possessing the digital/computer infrastructure necessary for achieving digital transformation is insufficient. It is equally important to cultivate the ability to manage, integrate, and generate information. This, in turn, elevates ICT literacy. ICT literacy involves utilizing digital technology, communication tools, and/or networks to access, manage, integrate, evaluate, and create information, enabling effective functioning in a knowledge society [10].

In summary, while digital transformation holds the potential for success and sustainability, its achievement requires an organization to evolve into a learning entity. Becoming a learning organization is paramount, as it is the only organizational model positioned to thrive in the midst of digital transformation.

In a similar manner, the author of [11] in his research identified the risks associated with sustainable development. The managers interviewed expressed resistance to the notion of sustainable development and accompanying standards, citing a belief that the advantages of sustainability did not outweigh associated costs. Additionally, they argued that their in-house environmental systems fulfilled the same objectives. This hesitance can be linked to the broader challenge of sustainable development. This societal issue poses a dilemma for many firms, as they grapple with uncertainty regarding how to effectively respond.

To bridge this gap, there is a need for the institutionalization of sustainable development within the regulatory frameworks, societal norms, and prevailing mindsets of managers and employees. This can be achieved by translating the fundamental principles of sustainable development into tangible business practices, establishing more robust metrics for measuring sustainable development, and empowering and engaging employees. Through these initiatives, firms are more likely to adopt sustainable development as an integral aspect of their organizational activities.

Consequently, managers of businesses and organizations need to adopt a different mindset in order to achieve the desired digital transformation and sustainable development. This mindset needs not to rely solely on notions of linearity and equilibria, but to account for people's behavior. Finally, it should look not only in the future but also account for short-term gains and losses [12].

Systems thinking is a natural candidate for such an effort. It is a way of investigating the behavior of systems over time [13] using a top-down approach to represent them and reveal insights into how potential strategies could drive their functions. For that reason, it has been applied to industries and organizations to investigate how digital transformation and sustainable development can be achieved.

Sanchez [14] utilized systems thinking to explain managerial decisions for digital transformation; Von Kutzeschenback and Brønn [7] developed a framework to represent the process at Uber, while Moellers et al. [15] worked similarly within the BMW industry. The focus in the literature has not solely been on case studies, but there were efforts to use systems thinking as an instructional tool to facilitate the process of digital transformation [16,17].

In a similar manner, Bagheri and Hjorth [18,19] used systems thinking to showcase that sustainable development is a never-ending process and not a final destination, while de Oliveira Musse et al. [20] used the methodology to support complex decision-making processes with multiple stakeholders in planning for sustainable development in Brazil. Finally, Williams et al. [21], through a comprehensive literature review, identified education as one of the most important drivers for sustainable development.

Hence, the success or failure of digital transformation and sustainable development hinges significantly on various factors, with the behavior of individuals within organizations and their skill sets playing a crucial role. Numerous studies have sought to explore the perspectives of both employees and managers concerning these processes. However, it remains imperative to continually gather the most recent updates and opinions, recognizing the potential for shifts in viewpoints, especially in light of external events that may impact these dynamics. Hence, it is essential to highlight the ongoing nature of this exploration, underscoring the need for up-to-date insights into the evolving landscape of digital transformation and sustainable development within organizational contexts.

The definitions of digital transformation and sustainable development often lack precision, emphasizing the need for a shared understanding or representation of how these concepts might materialize within organizational contexts and impact their processes. This representation need not be exhaustive but should serve as a catalyst for dialogue and establish a common language accessible to all involved parties. Causal Loop Diagrams (CLDs) and systems thinking represent ideal tools for this purpose for several reasons. Firstly, they enable the depiction of an organization's system from a top-down perspective. Additionally, a diagram can serve both as the starting point and the culmination of this process, functioning as a powerful communication tool. Moreover, these diagrams possess the flexibility to be expanded and transformed into quantitative models, offering a more nuanced understanding of complex interactions. Lastly, their simplicity belies their ability to depict causal relationships, exposing hidden dynamics within the system.

Thus, the purpose of the current paper is twofold: to investigate what are the perceptions of organizations with regards to digital transformation and sustainable development and especially with regards to skills and education, and, secondly, to use the insights from these perceptions as a starting point for the use of systems thinking as a tool that could assist in achieving these two states.

The rest of the paper is organized as follows: Section 2 is focused on explaining the methodologies that were used to achieve the paper's objectives, while results are explained in Section 3. Conclusions and future research efforts are discussed in the last section of the paper.

2. Materials and Methods

To achieve the objective of the paper, a multi-pronged research effort was conducted. This effort was in the context of the SYSTEMA project (E+ KA2, 2020-1-IT02-KA204-080082), whose purpose was to increase the skills of employees in organizations by teaching systems thinking with a focus on how these skills could be applied to digital transformation and sustainable development.

The research started with a literature review using scientific databases on how systems thinking has been applied to digital transformation and sustainable development. In addition, desktop research of educational and research programs was conducted in order to identify potential gaps in the market. Once this part was finalized, interviews with the project partners (European organizations from academia, the business sector, and associations) and market experts indicated the kind of questions that they would like to see answered with regards to digital transformation and sustainable development.

A survey was designed and disseminated across Europe for 4 moths (in an online form) with questions on digital transformation and sustainable development [22]. The questionnaire was divided into three sections: the first focused on digital transformation, the second on sustainable development, while the last attempted to capture the perceptions of people on the interaction between the two.

Once the responses were gathered, a process for data cleaning was initiated. Entries that were left unanswered were replaced with the notation N/A. Moreover, data entries with more than 50% of the questions not answered were completely removed from the database. The final database included 285 responses, which were analyzed with Excel.

The responses originated from 16 countries across Europe and the world, while the majority was in the 25–34 age cohort. Moreover, there were more answers from males than females. Finally, the respondents worked across a variety of sectors, including construction, engineering, information and communication, and education (Figure 1). It is essential to note that no sample calculation was executed as part of this project. The primary goal was to construct a dynamic and comprehensive understanding of organizations' perceptions regarding various aspects of digital transformation and sustainable development. This research, being a component of an EU-funded initiative governed by stringent timelines, faced constraints in terms of the population size due to the necessity of acquiring responses from a diverse array of backgrounds. Consequently, assumptions about the population size cannot be made, and it is crucial to underscore that the sample size is considered small. The emphasis on diversity within the respondent pool aimed to capture a broad spectrum of perspectives despite the logistical constraints imposed by the project's timeline and funding parameters. Finally, the results that are illustrated in the current paper are part of the overall research and more details can be found in [22].

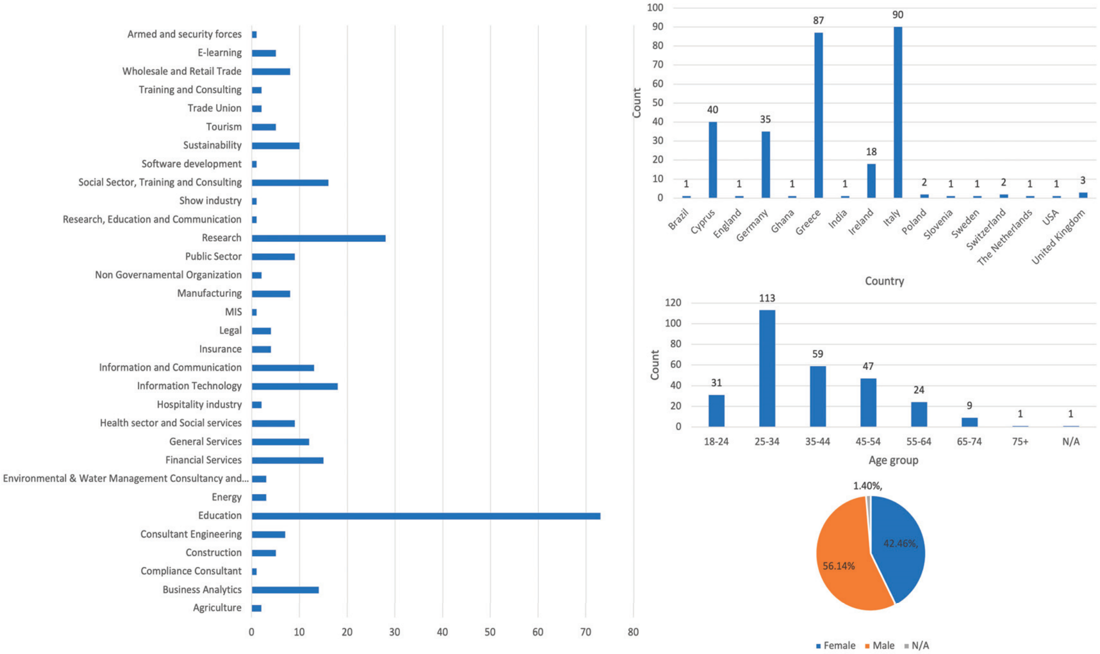

Figure 1. Demographics (the numbers along the x axis of the figure on the left represent the number of responses) [22].

After the analysis of the results and in accordance with a review of the literature, a general causal loop diagram was designed illustrating the processes of digital transformation and sustainable development within organizations from a top-down view. The whole research process is depicted in Figure 2 below.

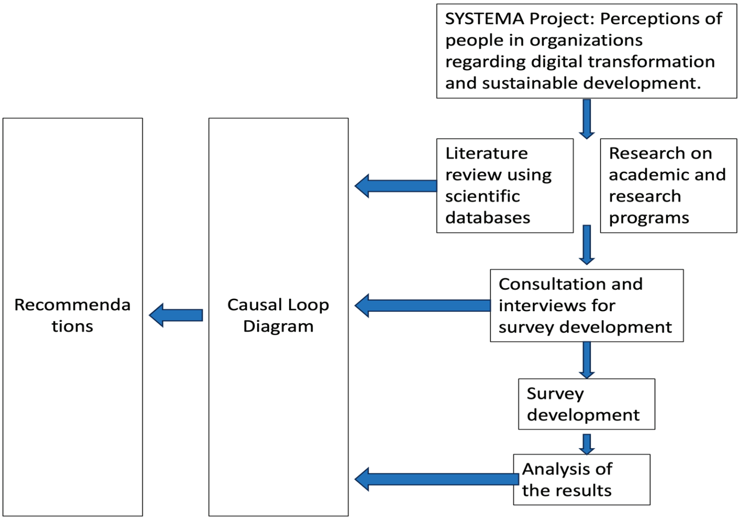

Figure 2. Flowchart of the research process.

Insights and results are discussed in detail in the following section.

3. Results and Discussion

3.1. Results on Digital Transformation

In the question whether the respondent believes that digital transformation can offer opportunities and competitive advantages, the vast majority either agreed or strongly agreed and only around 8% of the answers indicated that digital transformation is neutral to the organization (Figure 3). Thus, people agree with the general conclusions from the literature on the merits of digital transformation.

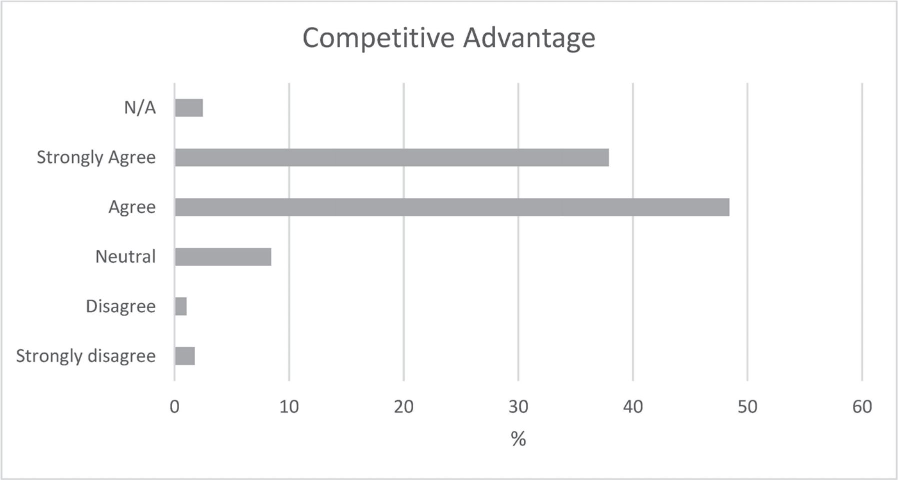

Figure 3. Opinions on whether digital transformation can offer a competitive advantage to the organization [22].

In addition, it was investigated whether there is a relation between the sector or role that a respondent has in the organization and whether digital transformation is seen as a competitive advantage. For that reason two chi-squared tests [23] were performed. The null hypotheses are stated as follows:

H0_1: *The perception that digital transformation can offer a competitive advantage to their organization is independent of their sector.*

H0_2: *The perception that digital transformation can offer a competitive advantage to their organization is independent of their role in the same organization.*

The results of the tests are summarized in Table 1 and show that both null hypotheses cannot be rejected. As a result, all types of employees, employers, teachers, etc., in all sectors recognize that digital transformation could be beneficial for their organization.

Table 1. Results of the chi-squared tests. H0_1: The perception that DT can offer a competitive advantage to their organization is independent of their sector. H0_2: The perception that DT can offer a competitive advantage to their organization is independent of their role in the same organization.

	χ^2	Degrees of Freedom	Critical Value for 5%	p Value
H0_1	193.22	198	231.8	0.58
H0_2	45.88	35	49.802	0.1

Moreover, a series of questions was asked about the status of Digital Transformation within each respondent's organization and more particularly:

1. If they believe that their organization has encountered difficulties in finding people with the appropriate skills;
2. If they believe that they are suitably prepared;
3. If their organization has started its digital transformation.

The results are illustrated in Figure 4 below.

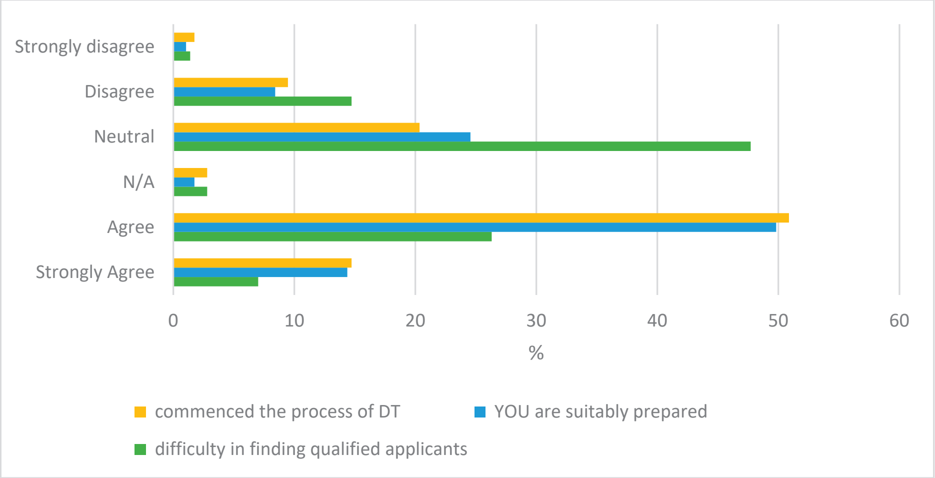

Figure 4. Answers on the process of digital transformation [22].

Notably, a significant portion of the responses regarding the challenges in locating suitable individuals was categorized as "Neutral". However, it is worth acknowledging that a notable proportion of respondents chose the "Agree" option, indicating some level of difficulty. Simultaneously, the majority of respondents expressed confidence in their organization's initiation of the digital transformation process and their readiness for it.

In order to explore the potential relationship between the difficulty in finding appropriate individuals and the organization's progress in digital transformation, a chi-squared test was conducted. The null hypothesis is defined as follows:

H0: *The difficulty of finding suitable applicants within the organization is independent of the progress of digital transformation in the same organization*.

The summarized results are presented in Table 2 below.

Table 2. Results of the chi-square test. H0: The difficulty of finding suitable applicants within the organization is independent of the progress of digital transformation in the same organization.

	χ^2	**Degrees of Freedom**	**Critical Value for 5%**	***p* Value**
H0	244.92	36	50.998	6.67242×10^{-33}

As evident from the results, the calculated value exceeds the critical value, leading to the rejection of the null hypothesis. Consequently, it becomes apparent that a relationship exists between the two inquiries, and this outcome is in line with expectations. When an organization struggles to identify suitable individuals, it is evident that the digital transformation process is likely to encounter significant challenges.

Finally, to assess the current skills gap, a question about which competencies are missing was asked and the respondents were given the following options (the list of competencies was designed after interviews with the project partners, attempting to capture a variety of upper level competencies that could be delineated to specific skills) and are presented on Table 3 below:

Table 3. Skills and their explanations.

Skill	**Explanation**
Literacy Competency	The ability to identify, express, understand, create, and interpret concepts, facts, and opinions; it implies the ability to communicate and connect effectively with others
Multilingual Competency	The ability to use different languages appropriately and effectively
Critical Thinking and Problem Solving Competencies	The ability to develop and apply critical thinking and insight in order to solve a range of problems in everyday situations
Competencies in Science, Technology, and Engineering	Competency in science refers to the ability and willingness to explain the natural world. Competencies in technology and engineering are the application of knowledge of science in response to human wants and needs.
Digital Competency	It involves the confident, critical, and responsible use of and engagement with digital technologies for learning at work and participation in society.
Personal, Social, and Learning to Learn competencies	The ability to reflect upon oneself, effectively manage time and information, work with others in a constructive way, remain resilient. and manage one's own learning and career
Citizenship Competency	The ability to act as responsible citizen and to fully participate in civic and social life based on an understanding of social, economic, legal, and political concepts and structures
Entrepreneurship Competency	The capacity to act upon opportunities and ideas and transform them into value
Cultural Awareness and Expression Competency	The ability to understand and respect how ideas and meaning are creatively expressed and communicated in different cultures
Business Management Competency	The ability to manage successful people and projects

The results are outlined in Figure 5 below. Notably, Digital Competencies, Competencies in Science, Technology, and Engineering, along with Learning to Learn Competencies, emerge as the most conspicuous areas lacking within organizations to facilitate successful digital transformation.

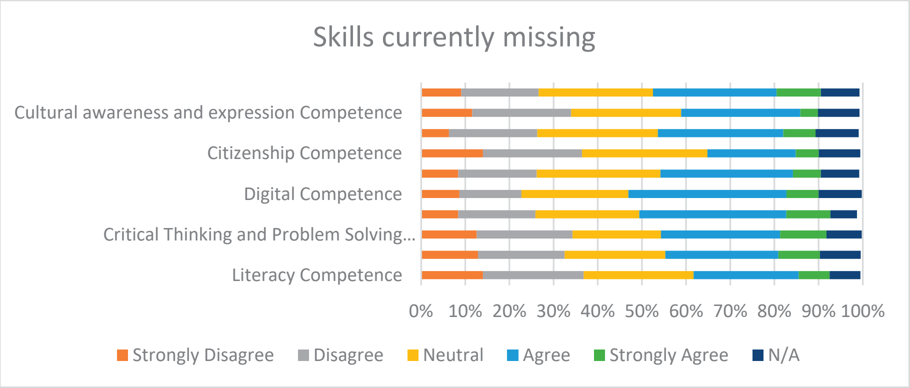

Figure 5. Results on missing skills for successful digital transformation [22].

In conclusion, several key lessons have emerged from the responses related to the issue of digital transformation within organizations. These lessons can be summarized as follows:

A significant majority of respondents either agree or strongly agree with the idea that digital transformation can provide a competitive advantage to their organizations. This reflects a widespread recognition of the potential benefits of embracing digital transformation.

Across various sectors and roles, including employees, employers, and educators, there is a shared understanding that digital transformation can be advantageous for their respective organizations. This consensus underscores the broad acknowledgment of the positive impact digital transformation can have.

The majority of respondents believe that their organizations have already initiated the process of digital transformation and concurrently feel adequately prepared for it. This points to a prevailing sense of readiness and commitment to this transformative journey.

It is noteworthy that the difficulty in finding suitable applicants for an organization is closely tied to whether the digital transformation (DT) process has commenced. This interdependency suggests that organizations struggling to locate the right talent may face significant challenges when embarking on their digital transformation journey.

Digital Competencies, Competencies in Science, Technology, and Engineering, as well as Learning to Learn Competencies, stand out as the most prominent areas lacking within organizations when aiming for successful digital transformation. These competencies are crucial components that need development and enhancement to support the successful execution of digital transformation initiatives.

3.2. Results on Sustainable Development

When examining the potential for sustainable development to provide a competitive edge to organizations, the majority of respondents express agreement, with 48% agreeing and an additional 31% strongly agreeing with this notion. This significant consensus highlights a prevailing belief in the capacity of sustainable development to confer a competitive advantage (Figure 6).

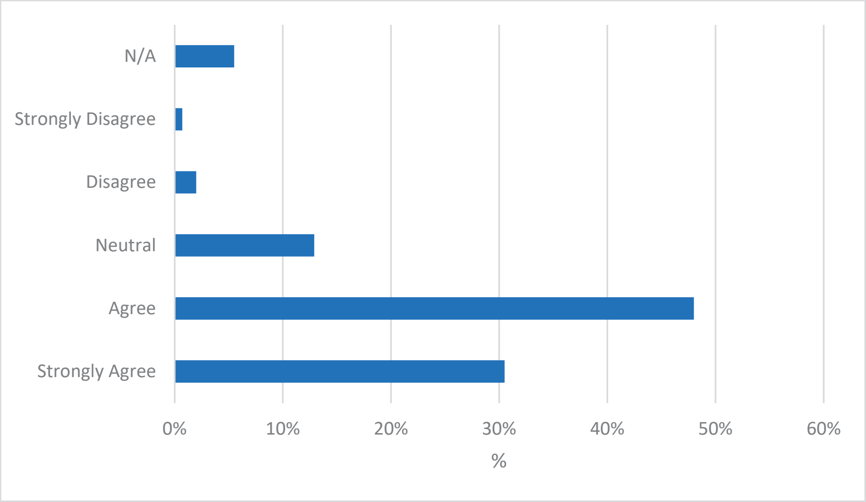

Figure 6. Opinions on whether sustainable development can offer a competitive advantage to the organization [22].

Furthermore, an analysis was carried out to determine whether there exists a correlation between a respondent's sector or role within an organization and their perception of sustainable development as a competitive advantage. The null hypotheses are as follows:

H0_1: *The perception that sustainable development can provide a competitive advantage to their organization is not influenced by their sector*.

H0_2: *The perception that sustainable development can provide a competitive advantage to their organization is not influenced by their role within the same organization*.

The results of the tests are summarized in Table 4, and they indicate that neither null hypothesis can be rejected. Consequently, it is evident that individuals across various sectors and roles, including employees, employers, and teachers, all share the perspective that sustainable development holds potential benefits for their organizations.

Table 4. Results of the chi-squared tests. H0_1: The perception that sustainable development can provide a competitive advantage to their organization is not influenced by their sector. H0_2: The perception that sustainable development can provide a competitive advantage to their organization is not influenced by their role within the same organization.

	χ^2	Degrees of Freedom	Critical Value for 5%	p Value
H0_1	153.82	198	231.82	0.99
H0_2	35.95	35	45.88	0.42

Moreover, a series of questions was asked about the status of Sustainable Development within each respondent's organization and more particularly:

1. If they believe that their organization has encountered difficulties in finding people with the appropriate skills;
2. If they believe that they are suitably prepared;
3. If their organization has started its digital transformation.

Figure 7 summarizes the results.

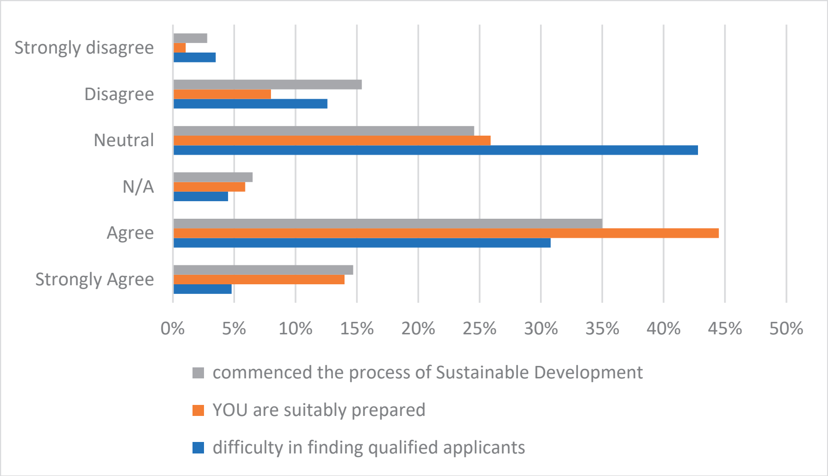

Figure 7. Answers on the process of sustainable development [22].

Notably, a significant portion of responses concerning the challenges in finding appropriate individuals leaned towards a "Neutral" stance. However, it is worth acknowledging the presence of difficulty, as the second-largest percentage of respondents expressed an "Agree" perspective. Simultaneously, the majority of respondents believe that their organizations have embarked on the sustainable development process and are adequately prepared for it.

In order to explore the potential relationship between the difficulty in finding suitable individuals and the initiation of sustainable development within organizations, a chi-squared test was conducted. The null hypothesis is articulated as follows:

H0: *The perception that the organization's struggles in finding appropriate applicants is unrelated to the organization's progress in commencing sustainable development*.

The summarized results can be found in Table 5 below.

Table 5. Results of the chi-squared tests. H0: The perception that the organization's struggles in finding appropriate applicants is unrelated to the organization's progress in commencing sustainable development.

	χ^2	Degrees of Freedom	Critical Value for 5%	*p* Value
H0	389.42	36	50.998	6.9977×10^{-61}

As evident from the data, the calculated value surpasses the critical value, signifying the rejection of the null hypothesis. Consequently, it becomes apparent that a relationship exists between the two variables, a result that aligns with expectations. When an organization encounters challenges in locating suitable individuals, it is evident that the initiation of sustainable development may encounter substantial obstacles.

Finally, concerning the skills that are perceived as lacking (Agree or Strongly Agree) within organizations to attain successful sustainable development, the most prominently identified areas include Business Management, Cultural Awareness, Entrepreneurship, Learning to Learn, Digital Competencies, and Competencies in Science. These competencies are viewed as being notably absent and essential for the achievement of sustainable development goals within organizations.

In summary, several valuable lessons have been gleaned from the responses concerning sustainable development within organizations. These lessons can be distilled as follows:

A significant majority of respondents either agreed or strongly agreed with the notion that sustainable development can confer a competitive advantage to their organizations, reflecting a widespread belief in its potential benefits.

Across various roles and sectors, including employees and employers, there is a unanimous acknowledgment that sustainable development can be advantageous for their respective organizations, underscoring a common understanding of its positive impact. The majority of respondents express a belief that their organizations have initiated the process of sustainable development and concurrently feel adequately prepared for this journey, emphasizing a strong sense of readiness and commitment.

Notably, the difficulty in finding suitable applicants for an organization is closely tied to whether the sustainable development process has commenced. This interdependency suggests that organizations struggling to locate the right talent may face significant challenges when embarking on their sustainable development endeavors.

Business Management, Cultural Awareness, Entrepreneurship, Learning to Learn, Digital Competencies, and Competencies in Science emerge as the competencies most conspicuously missing (Agree or Strongly Agree) within organizations, highlighting areas requiring attention and development to support successful sustainable development efforts.

Subsequently, the questionnaire allowed for an exploration of potential linkages between digital transformation and sustainable development. This involved scrutinizing whether responses to one issue were correlated with or influenced responses to the other. To accomplish this, a battery of statistical tests was conducted.

The primary null hypothesis inquires into whether the concepts of a competitive advantage in the context of digital transformation and sustainable development are interrelated, and it is articulated as follows:

H0_1: *The perception that digital transformation offers a competitive advantage to the organization is unrelated to the similar perception concerning sustainable development*.

Another pivotal question under examination involves the potential connection between the skills considered lacking for digital transformation and those lacking for sustainable development. The corresponding null hypothesis is expressed as follows:

H0_2: *The perception the organization has faced difficulties in finding suitable individuals for achieving digital transformation is unrelated to the similar perception regarding sustainable development*.

Moreover, a further investigation delved into whether responses to the question concerning the initiation of processes for digital transformation and sustainable development were interconnected. The null hypothesis guiding this analysis is framed as follows:

H0_3: *Whether the organization has initiated the process of digital transformation is unrelated to whether it has initiated the process of sustainable development.*

The responses are summarized in Table 6 below.

Table 6. Results of the chi-squared tests for H0_1, H0_2, and H0_3.

	χ^2	**Degrees of Freedom**	**Critical Value for 5%**	***p* Value**
H0_1	102.58	36	50.998	2.58959×10^{-8}
H0_2	114.81	36	50.998	3.69478×10^{-10}
H0_3	91.77	36	50.998	9.15089×10^{-7}

The χ^2 result for H0_1 surpasses the critical value, leading to the rejection of the null hypothesis. Consequently, it becomes apparent that a relationship exists between digital transformation and sustainable development. Those respondents who view digital transformation as beneficial for an organization are more inclined to regard sustainable development as similarly advantageous.

The χ^2 result for H0_2 exceeds the critical value, necessitating the rejection of the null hypothesis. Consequently, respondents who acknowledge difficulties in finding suitable individuals for digital transformation are more inclined to report facing similar challenges in the context of sustainable development. This overlap in the skills required for both domains suggests that training individuals could potentially confer a dual advantage to any organization.

The χ^2 result for H0_3 surpasses the critical value, leading to the rejection of the null hypothesis. Consequently, the results suggest that respondents who affirm their organization's initiation of the digital transformation process are more inclined to respond similarly regarding sustainable development.

In summary, the battery of tests conducted underscores the numerous commonalities between digital transformation and sustainable development within organizations. Individuals perceive both processes as advantageous, they both exhibit a shared deficiency in specific skill sets, and an organization's commencement of the digital transformation journey often aligns with activities fostering sustainable development.

3.3. Systems Thinking for Digital Transformation and Sustainable Development

The authors of [20] developed causal loop diagrams (CLD) to depict in a systemic way the findings from the literature, a review of several educational and research programs on digital transformation and sustainable development, and the answers from a comprehensive survey. These diagrams were simple illustrations of how the two processes could affect the sustainability and growth of an organization and at which points the improvement of employees' and employers' skills could hinder or facilitate the two processes.

Nonetheless, the CLDs in [20] are generic and do not delineate clearly how digital transformation (with its effect on the quality of the product or service that the organization is producing) is causally connected with the dimensions of sustainable development. For that reason, a new CLD was developed in the context of the current paper that more clearly illustrates the relationships among these elements.

Central assumptions for the development of the CLD are the following:

- Sustainable development consists of three dimensions—an environmental dimension (represented as savings in resources), an economic dimension (represented as the revenues and costs of the organization), and a social dimension (represented as the effect it could have on the lives and development of employees).
- Digital transformation and sustainable development have effects on the quality of the product or service that the organization is producing. Their relationship is such that any increase (decrease) in one of the two processes will increase (decrease) the quality.
- Skills can directly affect the process of digital transformation (if one increases so does the other) and indirectly the process of sustainable development.
- Digital transformation depends on the necessary infrastructure. This representation encapsulates all the changes in mindset AND infrastructure that are necessary so that the organization proceeds in a meaningful digital transformation and not merely digitization.
- Finally, all the necessary aspects that affect digital transformation and sustainable development have a cost.

As it was mentioned above, the new CLD is not a comprehensive diagram. It enriches the diagrams of [20] and it is meant to communicate how the most basic relationships among various elements could affect both digital transformation and sustainable development.

Figure 8, below, presents this diagram. It showcases the fundamental components of the system interconnected by arrows denoting their causal relationships. These relationships can take one of two forms:

1. Positive—indicating that the variables change in the same direction, meaning if one increases, the other also increases, and if one decreases, the other decreases.
2. Negative—signifying that the variables change in opposite directions, implying that if one increases, the other decreases, and vice versa.

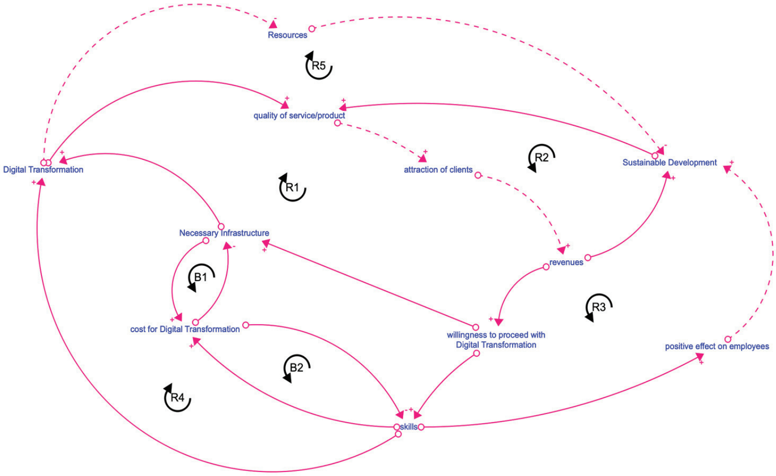

Figure 8. Causal loop diagram for the processes of digital transformation and sustainable development in an organization.

Additionally, the diagram features dotted arrows, which signify that the causal relationship between the connected elements includes a time delay. Furthermore, the connections within the diagram give rise to cycles or feedback loops, categorized into two types:

1. Positive loops (reinforcing loops)—these loops depict a scenario where an initial increase or decrease leads to a reinforcing increase or decrease after all the variables within the loop have been influenced. These are noted with the letter "R" in the CLD.
2. Negative loops (balancing loops)—in contrast, negative loops reveal that an initial increase or decrease in a variable leads to a decrease or increase after all the variables within the loop have been affected, sometimes even canceling out the initial change. These are marked with the letter "B" in the CLD.

As it can be observed, there are two negative feedback loops (B1 and B2) and 5 positive feedback loops (R1–R5).

The negative feedback loops establish connections between essential infrastructure, skills, and the cost incurred by the organization. As the required infrastructure for digital transformation expands, so does the associated cost of its development. However, an escalated cost implies a reduction in the development of additional infrastructure. A similar rationale applies to the enhancement of the skills possessed by the organization's personnel. Consequently, even at first glance, it becomes apparent that cost serves as a pivotal driving force and a balancing factor for both digital transformation and sustainable development.

On the other hand, the positive feedback loops serve to bolster both digital transformation and sustainable development. For instance, loop R1 originates from the premise that an increased emphasis on digital transformation enhances the quality of the products or services offered by the organization. This heightened quality, after a delay, attracts a larger client base, resulting in augmented revenues, again with a temporal lag. The increased revenues, in turn, act as a driving force for organizational management to continue with digital transformation efforts. This motivation, in a ripple effect, leads to the expansion of necessary infrastructure and ultimately culminates in improved levels of digital transformation.

Similarly, positive feedback loop R2 commences with the assertion that higher levels of sustainable development translate into an elevated quality of the services or products the organization provides. Following delays, the enhanced quality leads to the attraction of more clients and increased revenues, contributing to even higher levels of sustainable development.

It is crucial to note two key points. Firstly, the nature of positive loops implies that they reinforce a variable when it changes in the desired direction. However, the situation can swiftly turn negative if, for example, the level of digital transformation diminishes, resulting in lower quality, reduced client numbers, decreased revenues, and, ultimately, a decline in digital transformation levels.

Secondly, it can be observed that the positive effects of digital transformation and sustainable development may manifest at a later stage, while the costs associated with their implementation are nearly immediate. Striking a balance in this regard poses a formidable challenge for organizational decision-makers, as they must make choices that yield positive long-term impacts without jeopardizing the organization's short-term viability.

Finally, it should be noted that the CLD is an initial attempt to capture two complex processes. Hence, it is limited and may not capture the full scope or the elements that are necessary to better understand how to better achieve desired levels of digital transformation and sustainable development. Nonetheless, even in this simple representation, important insights are highlighted that could driver further processes.

One notable finding from our investigation is the close correlation between an organization's struggle to find suitable applicants and the initiation of the digital transformation (DT) process. This symbiotic relationship implies that organizations grappling with talent acquisition challenges may encounter significant hurdles when embarking on their digital transformation journey.

We also identified specific competencies pivotal for a successful digital transformation, with Digital Competencies, Competencies in Science, Technology, and Engineering, as well as Learning to Learn Competencies, emerging as the most prominent areas lacking within organizations. These competencies are indispensable components that necessitate development and enhancement to facilitate the seamless execution of digital transformation initiatives.

Furthermore, our research unveiled an apparent relationship between challenges in locating suitable individuals and the initiation of sustainable development. This underscores the substantial obstacles organizations may face when embarking on their sustainable development endeavors, especially in light of the identified skill deficits.

Our findings extend to the realm of sustainable development, where we identified skills perceived as lacking within organizations. Notably, areas such as Business Management, Cultural Awareness, Entrepreneurship, Learning to Learn, Digital Competencies, and Competencies in Science were highlighted as notably absent yet essential for the achievement of sustainable development objectives within organizations.

4. Conclusions

In this study, our primary objective was to delve into the perceptions of organizations regarding the interplay of digital transformation and sustainable development, particularly concerning skills and education. Furthermore, we aimed to employ systems thinking as a valuable tool to facilitate the realization of these two intertwined states.

The battery of tests we conducted reveals numerous commonalities between digital transformation and sustainable development within organizations. This alignment is manifested in the recognition of both processes as advantageous, shared deficiencies in specific skill sets, and a synergistic relationship between the initiation of digital transformation and activities fostering sustainable development.

Additionally, our study underscores the temporal aspects of these processes. Positive effects of digital transformation and sustainable development may materialize at a later stage, while the costs associated with their implementation typically demand immediate attention. Achieving a balance between long-term benefits and short-term organizational viability poses a formidable challenge for decision-makers.

The contributions of the research are as follows: This research paints a detailed portrait of how organizations perceive the intersections of digital transformation and sustainable development. A key emphasis lies in the identification of missing skills within the workforce and management, accompanied by an exploration into potential educational avenues to address these gaps. Spanning across diverse sectors, the study encompasses a broad spectrum of organizational landscapes. A notable feature is the inclusion of a causal loop diagram that elucidates the intricate interplay and causal relationships among various elements within an organization. This visual representation serves to illuminate the factors that either impede or facilitate the trajectories of digital transformation and sustainable development, offering a holistic understanding of the dynamics at play within organizational contexts.

Several key recommendations can be formulated for organizations navigating the intersection of talent acquisition, digital transformation, and sustainable development.

Recognizing the identified competencies crucial for successful Digital Transformation—Digital Competencies and Competencies in Science, Technology, Engineering, and Learning to Learn—it is imperative for organizations to institute comprehensive skill development programs. These initiatives should focus on enhancing these competencies among employees to ensure they are well-equipped for the evolving demands of the digital era.

Acknowledging the symbiotic relationship between talent acquisition struggles and the initiation of DT processes, organizations should develop integrated strategies that align talent acquisition efforts with the digital transformation journey. This entails not only seeking individuals with the required competencies but also fostering an internal culture of continuous learning and adaptability.

Given the apparent relationship between challenges in locating suitable individuals and the initiation of sustainable development, organizations should prioritize focused initiatives to address skills deficits. This involves targeted programs in Business Management, Cultural Awareness, Entrepreneurship, Learning to Learn, Digital Competencies, and Competencies in Science. Such initiatives will contribute to building a workforce capable of driving sustainable practices within the organization.

Organizations should conduct regular assessments to identify the existing skill sets of their workforce and conduct gap analyses against the competencies crucial for both digital transformation and sustainable development. This ongoing evaluation will provide insights into areas requiring further development and refinement.

Given the complexity of the challenges posed by the positive and negative loops in the context of digital transformation, organizations should adopt systems thinking. This involves understanding the interconnectedness of variables and recognizing that changes in one area can have cascading effects. It is crucial for decision-makers to anticipate potential negative repercussions and take proactive measures to mitigate them.

Recognizing the temporal disparity between the manifestation of positive effects and the immediate costs associated with digital transformation and sustainable development, organizational decision-makers must adopt a strategic perspective. Striking a balance requires choices that yield positive long-term impacts without compromising the short-term viability of the organization. This necessitates a careful evaluation of the timing and sequencing of initiatives.

In essence, these recommendations advocate for a proactive and integrated approach to talent management, skill development, and organizational strategy. By aligning these elements, organizations can better position themselves to navigate the challenges of the digital landscape and contribute meaningfully to sustainable development.

Lastly, it is essential to recognize that the causal loop diagram (CLD) presented in this study represents an initial attempt to capture two intricate processes. While it serves as a simplified representation, it may not encompass the entire scope of elements necessary for a comprehensive understanding of how to achieve desired levels of digital transformation and sustainable development. Nonetheless, this preliminary model highlights crucial insights that can propel further discussions and processes in these areas. All these gaps are avenues that we intend to explore in future efforts.

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Article

Integrating Combination Weighting of Game Theory and Fuzzy Comprehensive Evaluation for Selecting Deep Foundation Pit Support Scheme

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Abstract: Deep foundation pit support systems are important for reducing construction risks, to ensure the effectiveness and safety of support engineering, so the selection of a suitable support program is the inevitable requirement for the smooth construction of a foundation pit project. In order to improve the rationality of the support scheme, the analytic hierarchy process and the improved Entropy method are comprehensively used to determine the subjective and objective weights of the indexes, and the comprehensive weights are corrected based on the idea of game theory. Subsequently, fuzzy comprehensive evaluation is used for scheme selection, thereby constructing a model for optimizing deep foundation pit support schemes. The model is applied to a municipal pipe gallery project in Area A and the optimal support scheme is determined to be the soil nail wall and supporting piles and anchor ropes. The safety of the support scheme and the effectiveness of the selection model are verified through simulation and construction monitoring. Practice has proved the applicability and superiority of the model in dealing with construction projects characterized by ambiguity and insufficient data. In addition, the advantages and disadvantages of the mainstream evaluation methods of the current deep foundation pit support selection, applicable situations, and the influence mechanism of the geological environment are discussed in this paper, which helps to establish a more comprehensive framework for the selection of the support schemes.

Keywords: deep foundation pit engineering; decision making; deep foundation pit support schemes; combination weighting of game theory; improved entropy method; analytic hierarchy process (AHP)

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1. Introduction

Deep foundation pit engineering is a project closely related to high-rise buildings and complex underground projects in cities [1], which is highly comprehensive and complex, and attributed to high-risk engineering [2]. In the process of construction, it may cause deformation of the nearby soil and then damage the surrounding buildings and facilities, so a foundation pit support system is needed to protect the surrounding public facilities [3]. By selecting the appropriate support systems, such as retaining walls, bracing, and supporting structures, engineers can provide the adequate support to prevent the risk of structural damage or collapse during the construction and life of the structure. As a temporary supporting and strengthening structure, the main purpose of a foundation pit support system is to prevent the foundation pit from deformation and collapse under the action of earth pressure [4]. With the expansion of urban construction and the development and utilization of underground space, foundation pit engineering is also developing in the direction of larger areas and deeper depths, which puts forward higher requirements for the supporting effect of foundation pits [5]. An inappropriate foundation pit support system may lead to problems such as delays in the construction period, cost overrun, quality, safety, and so on [6]. Therefore, choosing a reasonable, safe, and economical support scheme is not only an important link to ensure the normal progress of the foundation pit project, but is also the foundation to ensuring the smooth completion of the construction project [7]. Deep foundation pit projects face multiple challenges in the selection of support systems, including different soil conditions, neighboring facilities, impacts on the environment, engineering limitations and spatial constraints, construction time pressure, technical feasibility, and economic viability.

Construction personnel and designers at home and abroad usually rely on previous experience and construction guidelines to select foundation pit support engineering schemes. However, in the context of increasingly complex urban renewal, relying on experience alone may not be able to fully address the multiple challenges faced in option selection [3]. In order to solve this problem, there is an urgent need to adopt scientific decision-making methods and comprehensively consider the key factors that may affect decision making, so as to provide an objective theoretical basis for scheme selection [8,9]. The multi-criteria decision-making (MCDM) method is widely used in different research fields and it can provide a logical framework, comprehensive evaluation, and comparison of various schemes, so that decision makers can choose more comprehensively and objectively [10]. Temiz and Calis [11] used AHP and the preference ordering organization method (PROMETHEE) to consider the fixed and quantitative indexes, rank the alternative schemes, and select the appropriate excavator for a construction site; Shahpari et al. [12] used Decision-making Trial and Evaluation Laboratory (DEMATEL) to determine the influence degree of each criterion, and then determine the index weight by the Analytic hierarchy process (AHP). Finally, the TOPSIS method was used to comprehensively evaluate the productivity level of residential construction. Branimir and Ana [13] applied te PROMETHEE II and AHP decision-making methods in a quarry and selected the best design model according to 22 different evaluation indexes. Palanikkumar et al. [14] applied the MCDM method of fuzzy logic to the selection of underground metal mining methods to determine the optimal mining methods. Weimin et al. [15] constructed a variable weight Fuzzy-AHP model to evaluate the safety of expansive soil slopes. Jin et al. [16] quantitatively analyzed the shadow response degree of factors related to the shear capacity of FRP-reinforced concrete deep flexural members by using the grey correlation method, and revealed the influence law of various factors on the shear capacity. At present, the general decision-making theory of engineering project schemes is relatively mature, but research on the decision making for foundation pit support schemes is relatively scarce, and foundation pit support involves the coupling of many complex factors, such as geology, soil, structure, construction, and so on. Its decision-making problem is more complex and special. Issa et al. [9] combined the fuzzy analytic hierarchy process with the TOPSIS method, and determined the optimal scheme of the project on the basis of considering the fuzziness of the evaluation index of the foundation pit scheme. Zhou Han and Cao Ping [17] established a hierarchical structure through the analytic hierarchy process, determined the index weight, then determined the relative superior degree matrix through expert investigation and theoretical analysis, established a fuzzy comprehensive evaluation model, and quantitatively evaluated the advantages and disadvantages of the alternative support scheme. Jing Wenqi et al. [18] determined the objective weight of the index through the CRITIC method and then used the TOPSIS-AISM clamping model to sort the spatial distances between the foundation pit support scheme and the ideal scheme, so as to determine the optimal support scheme. In the above studies, a single-decision method was used to determine the weight of evaluation index; however, the hybrid optimization decision method has a better efficiency and accuracy than the single-decision method [19,20]. In addition, in the safety and stability verification of the subsequent proposed scheme, key steps, such as scheme simulation calculation and construction monitoring, have not been carried out, which cannot fully prove the effectiveness and reliability of the foundation pit support scheme optimization model.

Deep foundation pit support structures play a crucial role in ensuring the safety of construction projects, especially in complex environments, such as comprehensive pipeline corridors, high-rise buildings, and other projects. The success of such projects depends largely on the effectiveness of the support scheme, so it becomes crucial to comprehensively assess the effectiveness and feasibility of the deep foundation pit support scheme, and the evaluation of the effectiveness of the support scheme is affected by both subjective and objective factors. In view of this, this paper comprehensively considers the influence of subjective and objective factors, uses the improved entropy value method and AHP method to determine the objective weights and subjective weights of the evaluation indexes, corrects the degree of contribution of subjective and objective weights to the comprehensive weights based on the game theory combination of weights, combines the fuzzy comprehensive evaluation theory to evaluate the merits of the program, and constructs a set of scientific and reasonable evaluation models of the deep foundation pit support program in order to support the decision makers of the construction project to select the most suitable deep foundation pit support program. The scientific validity and feasibility of the scheme selection model are substantiated through a detailed examination of a comprehensive pipeline corridor pit project, utilizing both simulation data and construction monitoring information.

2. Constructing the Decision Model for Deep Foundation Pit Support Scheme

2.1. Determination of Subjective Weight by Analytic Hierarchy Process (AHP)

The selection of the deep foundation pit support scheme is a complex decision-making problem containing multifaceted influencing factors, and the decision-making process involves multiple indicators such as the safety factor, technical level, and cost, etc. AHP is a method for multi-criteria analysis and decision making, which decomposes the complex decision-making problem into multiple indicators layer by layer and then establishes a judgment matrix of the relative importance degree to calculate the weight of each indicator [21], so it has been widely used in the evaluation of foundation pit support schemes, and the following are the steps used to calculate the weight:

Step 1: Construct the judgment matrix of each index through the experience of decision makers $X = (x_{ij})_{m\times m}$.

where x_{ij} represents the comparison result of the importance degree between element i and j, using a scale of 1–9 and $x_{ij} = \frac{1}{x_{ji}}$.

Step 2: Compute the nth root of the product of the elements of each row and normalize the vector to obtain the weights w_i and $W_1 = (w_1, w_2, \ldots, w_m)$.

$$\overline{w_i} = \sqrt[m]{\prod_{j=1}^{m} x_{ij}}, i = 1, 2, \ldots, m \tag{1}$$

$$w_i = \frac{\overline{w_i}}{\sum\limits_{i=1}^{m} \overline{w_i}} \tag{2}$$

where W_i is the subjective weight vector and $w_1, w_2, \ldots, w_m$ is the subjective weight of each index obtained by AHP.

Step 3: Calculate the maximum eigenvalue max coefficient of each index, and carry out a consistency test to ensure the accuracy and reliability of the data by using Equations (3)–(5). When the random consistency ratio CR < 0.10, it shows that the reliability of the judgment matrix is high, and the value of random consistency index is shown in Table 1.

$$\lambda_{\max} = \frac{1}{m}\sum_{i=1}^{m} \frac{(AW)_i}{w_i} \tag{3}$$

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{4}$$

$$CR = \frac{CI}{CR} \tag{5}$$

Table 1. Randomized consistency index (RI).

Matrix Order	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

2.2. Improved Entropy Method for Determining Objective Weights

The basic idea of the entropy method is to use the concept of information entropy to measure the amount of information of the index and its contribution to decision making, and to reflect the importance of the index through objective data, thus effectively weakening the influence of subjective factors [22,23]. However, because the evaluation index of the deep foundation pit support scheme is fuzzy and cannot be completely quantified, the traditional entropy method is used. There may be the problem of there being no way to obtain qualitative index data directly. In view of this, the algorithm is improved. For the evaluation index which cannot directly obtain the quantitative data, the set-value statistics method [24] is used to determine its state value, which is obtained by mapping qualitative indicators to quantitative data through Equation (6).

Step 1: Determine the initial matrix, in which the quantitative index can be obtained directly according to the actual project. For the qualitative index, the scoring interval is given by inviting a number of experts to take the percentile system as the scoring standard, and then the Formula (6) is used to determine its state value.

Assuming that there are q experts, the score range given by the k expert to the j evaluation index of the scheme is $\left[b_{1ij}^{k}, b_{2ij}^{k}\right](k = 1, 2, \ldots, q)$. Then, the state value of the jth evaluation index in the ith scheme are calculated using Equation (6):

$$b_{ij} = \frac{\sum\limits_{k=1}^{q} \left[\left(b_{2ij}^{k}\right)^2 - \left(b_{1ij}^{k}\right)^2\right]}{2\sum\limits_{k=1}^{q} \left(b_{2ij}^{k} - b_{1ij}^{k}\right)} \tag{6}$$

Step 2: Dimensionless processing of the data. If there are m sample objects in the evaluation, and each sample has n evaluation indicators, the initial matrix is expressed as $X = \left(x_{ij}\right)_{m \times m}$. Normalize the initial matrix as $A_{ij} = \left(a_{ij}\right)_{m \times n}$. Because different indicators have different dimensions, it is necessary to standardize the data ysing Formula (7) to eliminate the dimension of benefit-oriented indicators.

$$a_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \tag{7}$$

For cost-oriented indicators, let:

$$a_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \tag{8}$$

Step 3: Calculate the weighting of the *j*th evaluation indicator in the *i*th scheme.

$$P_{ij} = \frac{a_{ij}}{\sum\limits_{i=1}^{m} a_{ij}}, i = 1, 2, \ldots, m; j = 1, 2, \ldots, n \tag{9}$$

Step 4: Calculate the information entropy e_j. The greater the value of the information entropy, the higher the uncertainty of the data, the more the amount of information, and the smaller the weight of the index.

$$e_j = -\frac{1}{\ln m}\sum_{i=1}^{m}(P_{ij}\ln P_{ij}), i = 1,2,\ldots,m; j = 1,2,\ldots,n \tag{10}$$

Step 5: Calculate the coefficient of variation and objective weight of each index using Equations (11) and (12) to find the coefficient of variation and objective weight of each index, so obtain the objective weight vector $W_2 = (w_1, w_2, \ldots, w_n)$

$$g_j = 1 - e_j, j = 1,2,\ldots,n \tag{11}$$

$$w_j = \frac{g_j}{\sum\limits_{j=1}^{n} g_j}, j = 1,2,\ldots,n \tag{12}$$

2.3. Modifying the Comprehensive Weight Based on Combination Weighting of Game Theory

When using the analytic hierarchy process to determine the subjective weight, the consistency test can verify whether the expert judgment logic is consistent, but cannot eliminate the deviation caused by personal understanding; the entropy method obtains the objective weight of the index based on objective data, but the calculation results are extremely sensitive to extreme data, which may cause the calculation results to be contrary to reality. Therefore, the subjective weight obtained by the AHP method is combined with the objective weight obtained by the entropy method, and then the comprehensive weight of each index is calculated to overcome the limitations of using these two methods alone and ensure the accuracy of the decision-making results.

A reasonable allocation of the proportion of the weights obtained by different methods in the composite weights to ensure the scientific and reasonable nature of the composite weights is crucial to the calculation of the composite weights. Some scholars [25,26] have calculated the comprehensive weight by multiplicative addition, linear weighting, and average distribution, but they have not taken into account the mutual influence of different factors and the different influence range of the basic weight on the comprehensive weight. Therefore, this may produce a magnifying effect of the basic weight, which leads to a lack of reliability and accuracy of the evaluation results.

Drawing on the basic ideas of game theory, the subjective weights derived from AHP and the objective weights derived from the improved entropy method are used as the two game subjects in the non-cooperative game, and the deviation between the integrated weights and the subjective weights and objective weights is minimized by Equation (13) to correct the integrated weights, so as to make the results of the integrated weights more scientific and reliable. The specific calculation process is as follows [27]:

Step 1: Minimize the deviation between the comprehensive weight and the basic weights.

$$Min\left\|w - W_i^T\right\|, i = 1,2,\ldots,m \tag{13}$$

where the composite weight is calculated by $w = \sum\limits_{k=1}^{m} \alpha_k W_k^T$ and m is expressed as the number of base weights.

Then, Equation (13) is transformed into a system of linear equations equivalent to it by using the property of matrix differential.

$$\sum_{k=1}^{m} \alpha_k W_k W_k^T = W_i W_i^T, i = 1,2,\ldots,m \tag{14}$$

Step 2: By solving the linear equation group, obtaining the linear combination distribution coefficient $(\alpha_1, \alpha_2, \ldots, \alpha_m)$, and using Equation (15) to normalize it, the optimal linear combination coefficient can be obtained.

Step 3: Calculate the comprehensive weights of the indicators through Equation (15).

$$w^* = \sum_{k=1}^{m} \alpha_k^* W_k^T, k = 1, 2, \ldots, m \tag{15}$$

2.4. Scheme Optimization Based on Fuzzy Comprehensive Evaluation

Fuzzy comprehensive evaluation is an effective method for dealing with uncertainty in engineering decision-making problems. The application of fuzzy comprehensive evaluation in deep foundation pit engineering can effectively deal with the uncertainty problem by incorporating imprecise information and expert opinions, comprehensively considering multiple criteria such as safety, cost, and environmental impact, etc., and providing a flexible framework for program selection, so that the decision maker can objectively compare the satisfaction of the alternative programs and realize a quantitative analysis. Specifically, through expert discussion to determine the mapping relationship from indicator set $U = \{u_1, u_2, \ldots, u_n\}$ to evaluation set $V = \{v_1, v_2, \ldots, v_n\}$, so as to construct the affiliation matrix, transform the decision-making problem into a quantitative mathematical problem, and then use the weighted fuzzy algorithm to process the weighting information of each indicator to calculate the final evaluation results. The specific steps are as follows [28].

Step 1: Establish a quantitative evaluation set to express the pros and cons of each index, as shown in Table 2.

Table 2. Evaluation set.

Evaluation Grade	Very Poor	Poor	Ordinary	Good	Very Good
Point value (C)	1	2	3	4	5

Step 2: Evaluate the index through the experts and construct the membership matrix according to the evaluation results, which is expressed as:

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix}$$

where m is the number of experts and n is the number of assessment levels.

Step 3: Construct the fuzzy judgment matrix by Equation (16).

$$D = w^* R = (d_1, d_2, \ldots, d_n) \tag{16}$$

where w^* is the comprehensive weight of each index.

Step 4: Calculate the scheme evaluation value using Formula (17).

$$P = DC^T \tag{17}$$

3. Case Study and Model Application

3.1. General Situation of Project

The excavation depth of a municipal pipe corridor project in area is 14.6 m below the natural ground, and the construction period of the project is 9 months. There is a school under the construction site near the west side of the foundation pit and a main national highway running through the construction area on the north side. Therefore, the traffic cannot be interrupted during the construction period, and ground settlement around the foundation pit is highly required. In addition, there are two 120 kV high-voltage transmission lines over the construction area, which cannot be removed during the construction period, and the environment of the construction area is more complex, so it is necessary to comprehensively consider various factors to formulate the construction plan to ensure the safety and smooth progress of the construction. The soil layer involved in the excavation process of the foundation pit is mainly composed of miscellaneous fill, loess silt, silty clay, fine sand, medium coarse sand, and silt. The physical properties of each soil layer are shown in Table 3.

Table 3. Physical parameters of each soil layer.

Serial Number	Soil	Soil Thickness (m)	Bulk Density (kN/m^3)	Internal Friction Angle (°)	Adhesion (kPa)
1	Miscellaneous fillings	2.6	16.5	15.9	13.1
2	Loess	2.3	18.2	25.1	6.8
3	Powdery Clay	1.7	18.8	23.4	8.8
4	Fine sand	2.2	18.5	25	7
5	Medium coarse sand	1.3	18.9	25	30
6	Silt	4.5	16.1	5.6	5.2

According to the characteristics, geological conditions, and site characteristics of the foundation pit, three kinds of foundation pit support schemes are preliminarily determined, Scheme I: Soil nailing wall + supporting pile + steel support, Scheme II: soil nailing wall + supporting pile + anchor cable, and Scheme III: soil nailing wall + steel sheet pile.

3.2. Construction of Evaluation Index System

The deep foundation pit support scheme is a multi-level and multi-criteria complex decision-making problem, and its advantages and disadvantages are affected by many factors, so the construction of the evaluation index system of the deep foundation pit support scheme is the basis for scheme optimization. Combined with the actual characteristics of the project and on the basis of a large number of research papers [1,4,5,7], based on the principles of economy, safety, reliability, and science, starting from the four dimensions of technical index, economic index, environmental index, and safety index, the evaluation index system of the deep foundation pit support scheme is constructed, as shown in Figure 1. Among the secondary indexes, the construction period, foundation pit support cost, foundation pit support displacement, risk management cost, and support stability safety coefficient can be obtained directly according to the construction situation; the noise generated by the support project is expressed by the average daily noise decibel value during the construction period; and the air pollution caused by construction, the reliability of construction technology, the difficulty of construction, and the maturity of design theory are all qualitative indexes.

3.3. Determination of Deep Foundation Pit Support Scheme

A brainstorming session should be conducted in which the group, consisting of the construction manager, project manager, safety manager, and an experienced construction worker, discuss and arrive at a judgment matrix of the relative importance of each indicator. From Formulas (1) and (2), the subjective weight vector of the index is determined to be W_1 = (0.633, 0.106, 0.261, 0.667, 0.375, 0.25, 0.142, 0.525, 0.334), then the consistency test is carried out, and the CR < 0.1 is obtainted through the calculation of (3) to (5), so the consistency and credibility of the subjective weight are higher. According to the scoring range of each index of the three schemes by four experts, the set value of the qualitative index is calculated by Formula (6), as shown in Table 4, and the evaluation index parameters of each support scheme are shown in Table 5. Through Formulas (7)–(12), it is determined that the objective weight of each evaluation index is W_2 = (0.097, 0.094, 0.0101, 0.09, 0.151, 0.081, 0.081, 0.083, 0.134, 0.091, 0.0797). The subjective and objective weights are substituted into Equations (13) and (14) to find $\alpha_1^* = 0.822, \alpha_2^* = 0.177$. By using Formula (15), the comprehensive weight is w^* = (0.537, 0.104, 0.2364, 0.301, 0.631, 0.221, 0.141, 0.448, 0.284).

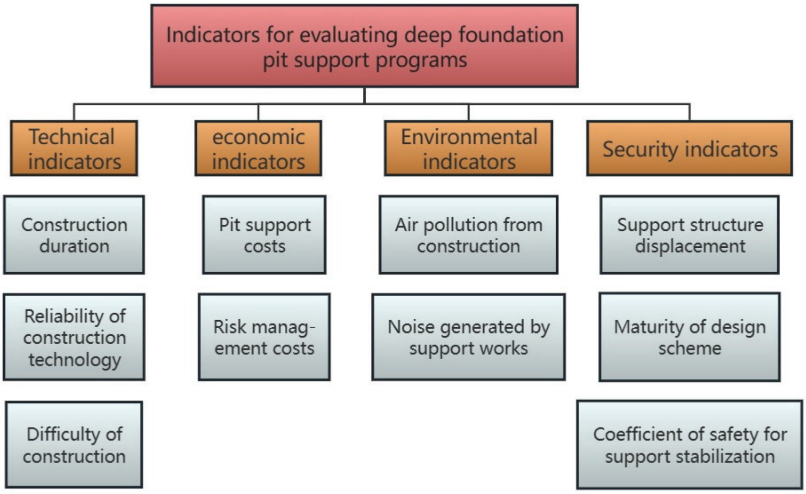

Figure 1. Evaluation index system of deep foundation pit support scheme.

Table 4. Qualitative indicator value.

Indicators	Scheme	Experts				Value	Unitization
		1	2	3	4		
Reliability of construction technology	I	[70, 80]	[70, 90]	[90, 100]	[70, 80]	81	0.81
	II	[70, 80]	[80, 90]	[90, 100]	[80, 90]	85	0.85
	III	[80, 90]	[80, 90]	[90, 100]	[90, 100]	90	0.9
Degree of construction difficulty	I	[80, 90]	[70, 90]	[70, 90]	[70, 80]	80.0	0.8
	II	[70, 80]	[70, 80]	[70, 80]	[60, 70]	72.5	0.725
	III	[60, 80]	[60, 80]	[50, 60]	[70, 80]	68.3	0.683
Air pollution from construction	I	[70, 80]	[80, 90]	[70, 80]	[80, 100]	85	0.85
	II	[80, 90]	[80, 90]	[80, 90]	[90, 100]	87	0.87
	III	[60, 70]	[70, 80]	[70, 80]	[70, 90]	81	0.81
Maturity of design scheme	I	[70, 80]	[70, 80]	[70, 80]	[60, 70]	72.5	0.725
	II	[80, 90]	[80, 90]	[90, 100]	[90, 100]	90	0.9
	III	[70, 80]	[70, 90]	[90, 100]	[70, 80]	81	0.81

Table 5. Evaluation indicator data for each support scheme.

Indicators	Guidelines	Scheme I	Scheme II	Scheme III
Technical indicators	Construction duration	70	55	45
	Reliability of construction technology	0.81	0.85	0.90
	Difficulty of construction	0.80	0.725	0.683
Economic indicators	Pit support costs	303.7	263.2	223.5
	Risk management costs	12.4	13.6	23.6
Environmental indicators	Noise generated by the support works	85	80	65
	Air pollution caused by construction	0.85	0.87	0.81
Safety indicators	Displacement of pit support	27	32	57
	Maturity of design scheme	0.725	0.90	0.81
	Coefficient of safety of support stabilization	1.95	1.90	1.68

Ten experts in related fields are invited to quantitatively evaluate the advantages and disadvantages of the evaluation indexes of each support scheme, and the evaluation results of Scheme I are shown in Table 6. The ratio of the frequency of occurrence of the evaluation grade to the total number of experts is taken as the affiliation degree of the index, so as to construct the affiliation degree matrix, and the affiliation degree matrix of Scheme I is:

$$R = \begin{bmatrix} 0.2 & 0.4 & 0.3 & 0.1 & 0 \\ 0.3 & 0.2 & 0.2 & 0.2 & 0.1 \\ 0.3 & 0.3 & 0.3 & 0.1 & 0 \\ 0.4 & 0.3 & 0.2 & 0.1 & 0 \\ 0.2 & 0.3 & 0.3 & 0.1 & 0.1 \\ 0.3 & 0.2 & 0.3 & 0.2 & 0 \\ 0.2 & 0.4 & 0.2 & 0.1 & 0.1 \\ 0 & 0.1 & 0.3 & 0.3 & 0.3 \\ 0.3 & 0.2 & 0.2 & 0.2 & 0 \\ 0 & 0 & 0.3 & 0.5 & 0.2 \end{bmatrix}$$

Table 6. Evaluation results of indicators for Scheme I.

Indicators	**Evaluation Results**				
	Very Poor	**Poor**	**Average**	**Good**	**Very Good**
Construction duration U_1	2	4	3	1	0
Reliability of construction technology U_2	3	2	2	2	1
Difficulty of construction U_3	3	3	3	1	0
Pit support costs U_4	4	3	2	1	0
Risk management costs U_5	2	3	3	1	1
Noise generated by support works U_6	3	2	3	2	0
Air pollution caused by construction U_7	2	4	2	1	1
Displacement of pit support U_8	0	1	3	3	3
Maturity of design scheme U_9	3	2	2	2	0
Coefficient of safety of support stabilization U_{10}	0	0	3	5	2

Combined with the comprehensive weight obtained by the combination weighting of game theory, the fuzzy judgment vector of the scheme is determined as $D = w^*R = (0.233, 0.233, 0.175, 0.243, 0.117)$, and the fuzzy comprehensive appraisal value of pit support Scheme I is calculated by Equation (17) as $P_1 = 2.776$. Similarly, the comprehensive appraisal value of Scheme II is calculated as $P_2 = 3.164$, $P_3 = 2.531$. The comprehensive appraisal value of the schemes: $P_2 > P_3 > P_1$, therefore, it is determined that Scheme II: soil nail wall + supporting piles + anchor cable is the optimal support scheme.

The excavation depth of the foundation pit is deep, and the setting of a soil nailing wall in the upper part can significantly improve the overall stability of the foundation pit and limit the displacement of the soil; according to the analysis of the characteristics and properties of the soil layer, the soil quality of the foundation pit is relatively soft, but in the face of a soft soil layer such as silty clay, the setting of an anchor cable can effectively resist the lateral thrust of the soil and effectively prevent the collapse of the foundation pit slope. In addition, there are schools, national trunk roads, and high-voltage transmission lines near the construction area, and the construction environment is complex. The construction area of the combined square plan of the soil nailing wall, supporting pile, and anchor cable is relatively small, and the construction process has less interference on the surrounding environment. Therefore, the results of the optimization model of the foundation pit support scheme based on the combination weighting of game theory and fuzzy comprehensive evaluation are consistent with the actual engineering situation, which shows that the model is feasible and effective in real engineering.

3.4. Verification of the Proposed Foundation Pit Support Scheme

Referring to the research idea of reference [29], this paper uses the combination of simulation calculation and construction monitoring to verify the safety, applicability, and reliability of the proposed deep foundation pit support scheme. The specific simulation calculation and construction monitoring results are as follows.

3.4.1. Simulation Calculation of the Proposed Scheme

The excavation depth of the upper part of the foundation pit is 5.4 m, the soil nailing is set to 4 rows, the length of the soil nailing is 6 m, and the slope inclination angle is assumed to be 45°. The Fellenius method of slices is used to calculate the overall stability of the upper part of the foundation pit. The pull-out load of each soil nail is within the standard value of 76–107 kN, the pull-out safety factor of soil nail is more than 6, and the maximum influence range of the foundation pit excavation is 6.949 m, so the upper part can be supported by a soil nailing wall. The supporting pile + anchor cable supporting structure is adopted in the lower part.

In the supporting model, the top height of the supporting pile is 5.4 m, the embedded depth is 13.5 m, the pile diameter is 0.8 m, the pile body material is reinforced concrete, and the concrete strength is C30. There are four rows of anchor cables, with horizontal spacings of 2.6 m, vertical spacings of 2 m, an incident angle of 15°, and an anchor cable length of 22 m. The lower part of the pit support pile and anchor cable structure is shown in Figure 2. ZH-1 to ZH-6 are foundation pit supporting piles. The supporting pile at ZH-6 is selected for simulation calculation, and the result is shown in Figure 3. When the foundation pit is excavated to 7.9 m and the first anchor cable is erected, the maximum earth pressure on the supporting pile is 433.41 kN, the maximum displacement is 1.18 mm, the maximum bending moment is 67.16 kN/m, and the maximum shear is 77.67 kN. After excavation to 9.9 m and the erection of the second anchor cable, the maximum soil pressure force is 438.68 kN, the maximum displacement is 2.51 mm, the maximum bending moment is 117.64 kN/m, and the maximum shear is 106.88 kN. After excavation to 11.9 m and the erection of the third anchor cable, the maximum earth pressure on the supporting pile is 444.36 kN, the maximum displacement is 6.29 mm, the maximum bending moment is 264.12 kN/m, and the maximum shear is 205.68 kN; after excavation to 13.9 m and the erection of the fourth anchor cable, the maximum earth pressure is 461.89 kN, the maximum displacement 15.9 mm, the maximum bending moment is 449.75 kN/m, and the maximum shear increases to 338.98 kN. From the above data, it can be seen that, with an increase in the depth of the foundation pit, the dead weight and lateral pressure of the soil increase, and the earth pressure on the supporting pile also increases, which leads to an increase in the displacement, bending moment, and shear of the supporting pile. It is further calculated that the radius of the sliding surface of the foundation pit is 24.26 m, and the safety factor of the overall stability of the foundation pit is 1.61, which is greater than the 1.30 required by the code, so the supporting pile and anchor cable structure can be used in the lower support.

3.4.2. Monitoring Data Analysis of the Proposed Scheme

(1) An analysis of horizontal displacement monitoring data of the supporting pile + anchor cable structure at the location of monitoring points on the construction site and the construction monitoring data at ZH-6 are shown in Figure 4. In the initial stage of the foundation pit excavation, the stress form of the supporting pile is in the cantilever state, so the horizontal displacement of the upper part of the pile is larger, while the lower part of the pile is embedded in the soil, so the displacement of the pile tends to be 0. With the excavation of foundation pit and the construction of an anchor cable, the horizontal displacement of the pile increases, the maximum displacement appears after the fourth anchor cable is erected, the maximum displacement is 16.3 mm, the maximum deformation of foundation pit supporting structure is less than the standard value 20 mm specified in the code, and the construction result is in accordance with the safety code.

In addition, comparing the maximum displacement value of 16.3 mm in the monitoring data with the maximum displacement value of 15.9 mm calculated by simulation, the relative error is 2.46%, indicating that the monitoring results are consistent with the scheme simulation calculation, which further verifies the theoretical and practical feasibility of the proposed scheme.

(2) An analysis of the surface settlement monitoring data around the foundation pit settlement monitoring points are set up at distances of 2 m and 8 m from the edge of each side of the foundation pit, the monitoring points are JC-1 to JC-12, and JC5 (2 m from the edge of the pit) and JC-6 (8 m from the edge of the pit) are randomly selected to analyze the monitoring data from excavation to backfilling. According to the settlement monitoring results at JC-5 and JC-6, with an increase in excavation depth, the settlement gradually increases, among which, the settlement at JC-5 is the largest and the final settlement at the observation point of 11.2 mm JC-5 is 6.2 mm. The settlement change rate of the two monitoring points gradually decreases, and finally tends to be stable, and both are within the safe range of foundation pit settlement.

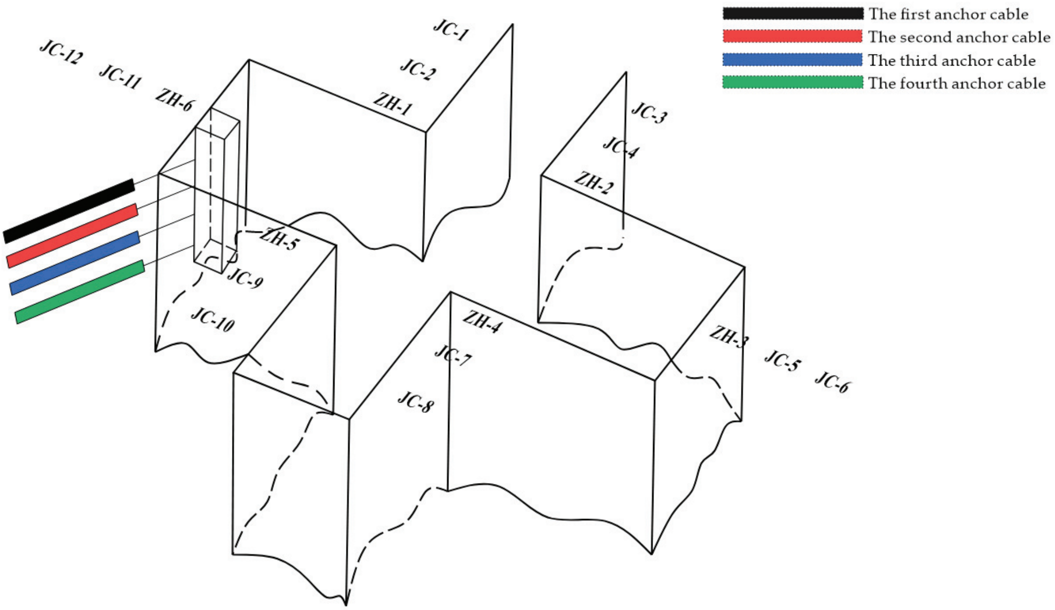

Figure 2. Three-dimensional drawing of partial support pilea and anchor cable structure under the pit.

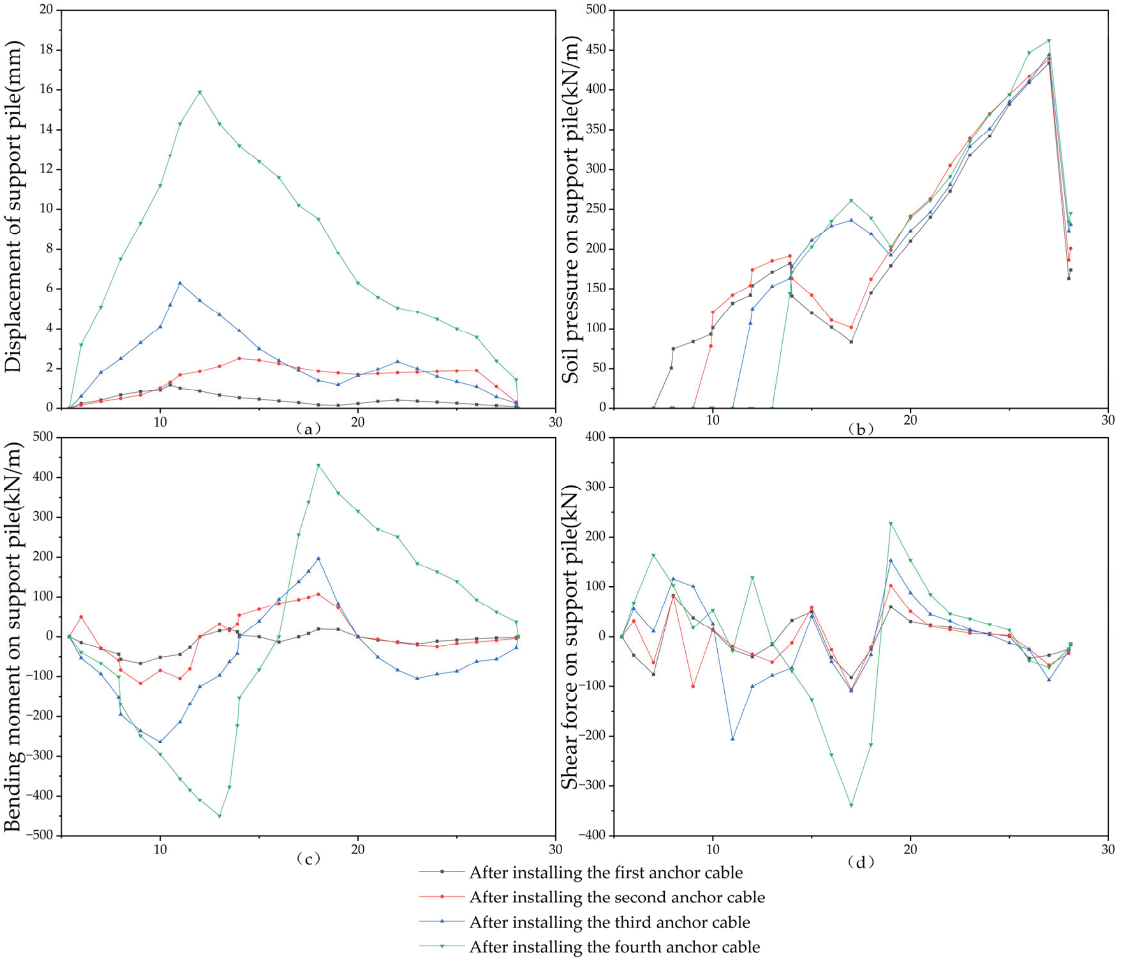

Figure 3. Simulation results. (**a**) Displacement of supporting piles at different burial depths under different working conditions; (**b**) soil pressure on supporting piles at different burial depths under different working conditions. (**c**) bending moments of supporting piles at different burial depths for different working conditions; and (**d**) shear of supporting piles at different burial depths for different working conditions.

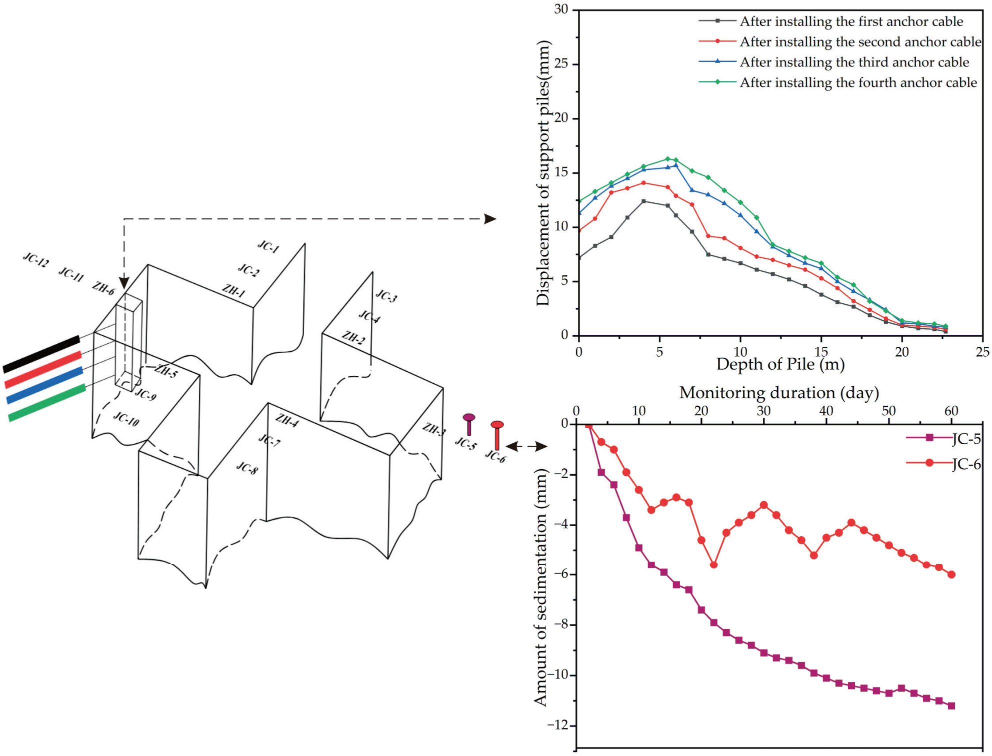

Figure 4. Pit monitoring results.

4. Discussion

The selection of a foundation pit support scheme is a complex decision-making process which is affected by many factors. Although a scheme selection framework which can be directly referenced and suitable for all situations has not been established, the appropriate multi-criteria decision-making method can provide strong support for the optimization of the foundation pit support scheme. Different optimization methods of foundation pit support schemes have unique characteristics and applicable conditions, so when selecting support schemes, it is necessary to consider the project characteristics, technical level, and other factors, and use appropriate decision-making methods to ensure the feasibility and applicability of the proposed scheme. Through a large number of literature studies, this paper systematically combs the mainstream optimization methods of foundation pit support schemes and summarizes their advantages and disadvantages and application, as detailed in Table 7. At present, the mainstream evaluation methods, such as the Analytic hierarchy process, Entropy method, TOPSIS, Fuzzy BP Neural Network, and so on, have certain conditions and applicability when they are used. When the evaluation index is not clear, the project data are limited, or the expert experience is insufficient, this will affect the accuracy of the evaluation results. The optimization model of the foundation pit support scheme constructed in this paper can overcome these conditions. A comparison of the calculation results of different methods is shown in Figure 5. By using the combination weighting of game theory to optimize the linear combination of subjective and objective weights, a more scientific comprehensive weight is obtained, which reduces the dependence on data, weakens the influence of subjective factors, and improves the accuracy of decision making. The fuzzy comprehensive evaluation method is used to evaluate the advantages and disadvantages of the scheme, and then determine the optimal support scheme, which can better deal with fuzzy and uncertain decision-making problems.

Table 7. Mainstream methods.

Methods	Advantages and Disadvantages	Application	Typical Literature
AHP and fuzzy comprehensive evaluation	Advantages: relatively simple and easy to use, able to consider the hierarchical relationship between multiple factors Disadvantages: relies on the experience of experts, strong subjective factors, there may be the problem that the program selection results do not match the actual project.	It is suitable for simple works, low risk factor, and experienced experts.	[15,17,30]
Entropy method	Advantages: the concept of information entropy is taken into account, which is conducive to the comprehensive consideration of the uncertainty and inconsistency of various factors Disadvantages: high data requirements, needs a large amount of data support, in some cases may be affected by data distribution.	It is suitable for projects with more adequate data where uncertainty and information entropy need to be taken into account.	[25,31–33]
TOPSIS	Advantages: Can make up for the shortcomings of the respective methods to a certain extent, and improve the comprehensiveness and objectivity of decision making. Disadvantages: TOPSIS also has some limitations when dealing with uncertainty, high data volume requirements.	It is suitable for relatively simple and well-structured decision problems, especially when there are relatively sufficient data to provide more credible results for decision making.	[5,18,34]
Prospect theory and best–worst method	Advantages: considering the optimal and worst scenarios comprehensively, it helps to reduce the uncertainty of decision making. Disadvantages: need to clarify the optimal and worst scenario, higher requirements for the acquisition and accuracy of information, the calculation process is more complex.	Applicable to decision-making problems that require consideration of different scenarios.	[4,35]
Fuzzy neural network	Advantages: able to deal with nonlinear relationships, applicable to the evaluation of complex systems, able to adaptively adjust the model parameters. Disadvantages: high data requirements, needs a large amount of training data, model structure is more complex, poor interpretability.	Suitable for evaluation and prediction of complex support works and projects with adequate data.	[36–38]

In addition, because the supporting structure is completely placed in the geological environment, the geological environment is also an important constraint for the selection of the foundation pit support scheme: on the one hand, the supporting structure depends on the geological environment, and the geological environment has a direct influence on the selection of the supporting scheme. On the other hand, a variety of underground geological resources occur in the geological environment, so there is an indirect influence path between the geological environment and the choice of foundation pit support plan, with groundwater, geothermal energy, and underground space as the medium, as shown in Figure 6. According to the influence path of the geological environment on the support scheme of the foundation pit, the factors affecting the selection of the support scheme are analyzed and generalized, in order to provide help for the establishment of a framework for the selection of support schemes for deep foundation pits.

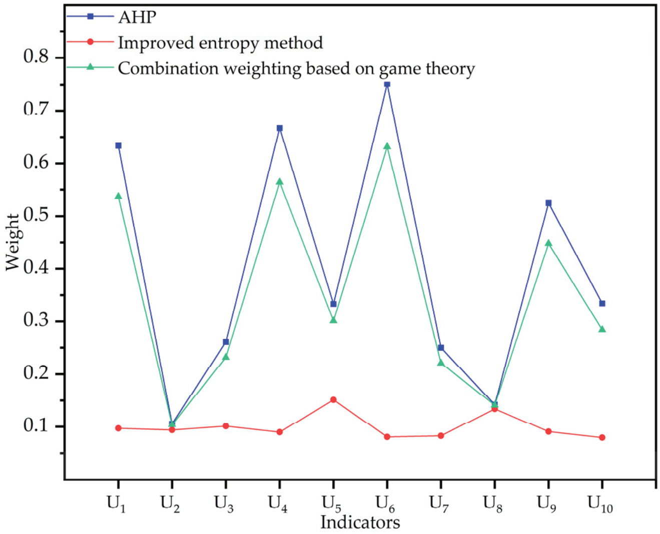

Figure 5. Comparison of the calculation results of different methods.

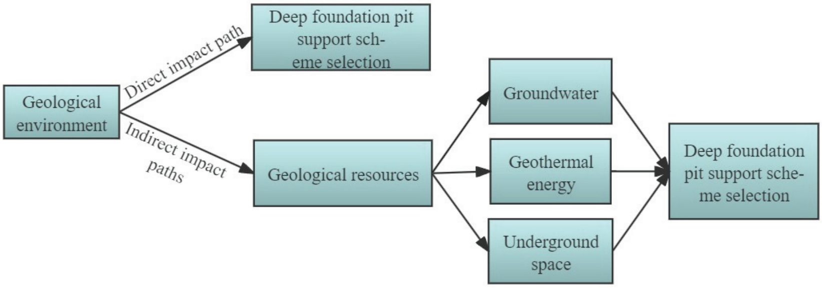

Figure 6. The influence mechanism of geological environment on deep foundation pit support scheme.

1. Direct influence mechanism

The direct influence of the geological environment on the selection of a foundation pit support scheme is mainly reflected in: (1) different soil types in geological environments having different requirements for foundation pit support schemes. For example, silt is prone to liquefaction under the condition of a high groundwater level, which leads to a poor stability and low safety factor of a foundation pit. In the view of silt, which has a poor water stability and high capillarity, support methods such as mixing piles, bored piles, and soil nailing walls can be adopted. On the other hand, sandy soil has a lower shear strength, so it requires a higher stability of foundation pit support, and the supporting methods suitable for sandy soil include excavation retaining walls, foundation pit supporting piles, and so on; sandy soil is easy to collapse and lose under a higher groundwater level, so it is suitable to adopt rigid supporting structures with strong impermeability, such as mixing pile walls, bored pile supports, and so on. (2) If the foundation pit is in the seismic zone or undergoes an active fault, the longitudinal and transverse seismic forces should be considered when selecting the foundation pit supporting structure to ensure that the supporting structure can effectively resist vibration when an earthquake occurs. Structures with a strong seismic capacity, such as seismic bracing walls, bracing beams, rubber bearings, or seismic isolation, should be considered.

2. Indirect influence mechanism

The indirect influence of the geological environment on the selection of a foundation pit support scheme is mainly realized by groundwater, geothermal energy, and underground space.

The effects of groundwater on the supporting structure of foundation pits include: (1) Some groundwater may contain special ions such as chloride ions and sulfate ions, which have a corrosive effect on the supporting structure, so when choosing the supporting scheme of a foundation pit, corrosion-resistant supporting structures such as stainless steel and glass steel should be used. (2) If the groundwater level below the foundation pit is high, it may lead to soil liquefaction and loss, and then affect the stability of the supporting structure. Impervious walls and mixing piles should be considered when selecting supporting structures, in order to control the groundwater level and prevent water infiltration.

The main effects of geothermal energy on foundation pit supporting structures are as follows: (1) Geothermal energy will increase the soil temperature and accelerate the soil creep rate, resulting in an uneven volume change of soil, leading to the deformation and stress concentration of the supporting structure. Finally, it has an impact on its stability and safety. (2) The supporting structure may produce the phenomena of thermal expansion and cold shrinkage due to the increase in the temperature of the surrounding soil, resulting in the deformation of the supporting structure, then affecting the friction between the supporting structure and the soil. Therefore, for areas rich in geothermal energy resources, structural materials with a good thermal expansion and cold shrinkage adaptability should be selected to reduce the uneven expansion and contraction caused by temperature changes.

The influence of underground space on the selection of a foundation pit support scheme is mainly reflected by: (1) Because underground space resources are limited, adjacent underground pipelines and underground structures will affect the selection of the foundation pit support scheme. While protecting the surrounding built underground engineering, more stable supporting structures should be selected to reduce the impact on the surrounding underground structures, such as spray deep geotechnical supports, mixing pile supports, deep foundation pit wall column supports, and other support methods. To sum up, when determining the foundation pit support scheme, we should not only choose the appropriate optimization method according to the situation of the project, but also pay attention to the influence of the geological environment of the research area on the supporting structure. Therefore, in the construction preparation stage, a geological survey should be used to determine the geological resources and soil properties within the scope of the foundation pit excavation, so as to ensure the effectiveness and safety of the support scheme. A follow-up study can proceed from these two sides to construct a set of selection frames, which can determine the foundation pit support scheme according to the technical level, characteristics, geological environment, and other factors of the project.

5. Conclusions

The selection of the appropriate pit support solutions is important for the duration, quality, and stability of construction projects, including deep foundation pit projects. Suitable support solutions help to improve construction efficiency, and by selecting support technologies that are suitable for the requirements of a particular project, the construction time can be shortened to meet the requirements of the project's compact schedule and improve the overall efficiency of the project. Considering the impact on the surrounding environment during the selection of the support scheme and adopting the appropriate support structure can help to minimize the negative impact on the surrounding ecosystem and existing buildings, and promote the development of the construction project in a sustainable direction. Therefore, this study proposes an option preference model to provide support for decision makers to deal with the issue of option decision making in construction projects. The applicability and superiority of the model constructed in this paper are explored through literature combing and method comparison. Meanwhile, the influence mechanism of the geological environment on the deep foundation pit support scheme is analyzed. The main research results are as follows.

1. The subjective and objective weights of the evaluation indexes of the deep foundation pit support scheme are calculated by using the AHP and improved entropy method, respectively, which overcomes the limitations caused by the single method and takes into account the situation that the index data cannot be obtained directly. Then, the comprehensive weight of each index is determined based on the combination weighting of game theory. Compared with the traditional method for obtaining the weight of the scheme evaluation index, the method used in this paper is more objective and scientific in determining the index weight. Finally, the fuzzy comprehensive evaluation method is used to evaluate the scheme. Uncertain decision-making problems such as foundation pit support scheme optimization are effectively dealt with, and a deep foundation pit scheme optimization model is constructed to provide decision support for similar projects.
2. The optimization model of deep foundation pit support schemes constructed in this paper is applied to an actual project, and it is determined that the optimal scheme of a city administration corridor project in area A is soil nailing wall + supporting pile + anchor cable. The deformation trend of the supporting pile under different working conditions is simulated, and the calculation results show that the pull-out safety factors of soil nails in the upper part of the foundation pit are all above 6 and the displacement of the supporting pile after installing anchor cables in the lower part meets the design requirements. The coefficient of safety of the supporting structure is 1.61, which is greater than the 1.3 required in the construction safety code, proving the theoretical feasibility and safety of the proposed scheme. Further analysis combined with the actual construction monitoring data shows that the relative error between the actual displacement of the supporting pile and the simulation results is 2.46%, the surface settlement is within the safe range, and the overall supporting structure has a good stability. The accuracy and rationality of the optimization model of the supporting scheme are fully verified.
3. By summarizing the advantages, disadvantages, and applicability of the current mainstream optimization methods for deep foundation pit support schemes and comparing the optimization model constructed in this paper, this reflects the applicability and superiority of the model in dealing with insufficient project data, facing fuzzy problems, limited expert experience, and so on. The indirect and direct influence mechanisms of the geological environment on the selection of deep foundation pit support schemes are identified and generalized, and then the influence factors and action path of the selection of support scheme are analyzed. Through the study of geological conditions, the support scheme suitable for the geological environment can be better selected, so as to improve the stability and safety of the project. At the same time, research ideas are provided to establish a framework for the selection of support schemes that can be directly referred to.

Overall, the deep foundation pit support scheme selection model proposed in this study combines multiple methods, making the scheme evaluation more objective and scientific, thus improving the science and reliability of engineering decision making. The scheme selection model constructed in this paper can be flexibly applied to the decision making of similar construction projects.

In the future work, it is recommended that scholars consider the geological environment and engineering conditions comprehensively to formulate the selection criteria of foundation pit support programs for direct reference by on-site construction personnel and relevant researchers. At the same time, it can also be combined with modern engineering simulation modeling technology to select deep foundation pit support schemes more scientifically in actual construction, so as to improve the safety of construction projects.

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A Final Cost Estimating Model for Building Renovation Projects

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Abstract: The construction sector in Greece has been developing radically in the field of building renovations. The foremost problem for projects in the building construction industry is producing an accurate and reliable cost estimate at the onset of construction. The artificial neural network (ANN) approach, using data available at the early stages of the project, can help resolve or prevent any kind of difficulty that could make the successful completion of a building less likely. ANNs have been highly efficient in gaining results which could prevent the failure of building constructions projects. The ultimate goal is to highlight the usefulness of the adoption of ANNs models to predict the final cost of a building renovation project. Thus, construction companies could avoid financial failure, provided that the gap between cost prediction and final cost for renovation projects is minimized. This paper presents an artificial neural network (ANN) approach for predicting renovation costs in Greek construction projects. The study, based on a comprehensive literature review and real renovation data from construction companies, employs IBM SPSS Statistics software to build, train, and test the ANN model. The model, which uses initial cost, estimated time, and initial demolition cost as inputs, is based on the radial basis function procedure. The model presents high performance with up to 2% sum of squares error and near zero relative error, demonstrating the ANN's effectiveness in estimating total renovation costs.

Keywords: artificial neural network models; ANN; cost prediction models; cost estimation; building construction projects; building renovation projects

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1. Introduction

Construction projects always differ from manufacturing initiatives. Consequently, there are always risks and unknowns when estimating building costs [1–3]. Cost projection is additionally made difficult by the absence of a trustworthy database of building costs, as well as the contractors' reluctance to supply accurate cost information.

Additionally, each country has a distinct legal structure for project procurement and payment processes [4] which are typically based on insufficient budget estimation techniques.

As found by Antoniou et al. [4], on a global level, researchers have delved deeply into providing scientifically based construction cost estimate models for a variety of projects such as buildings, transportation infrastructure (roads, bridges, tunnels, metro stations), and utility and power networks. In their thorough analysis of the literature, they also demonstrated that the most popular techniques used in recent years for the creation of cost prediction models include linear regression (LR), Gaussian process regression (GPR), artificial neural networks (ANNs), support vector machines (SVMs), gradient boosting machines (GBMs), and building information modeling (BIM).

To help in this respect, researchers in Greece have attempted to collect data from infrastructure procurement authorities to provide cost estimation tools to public authorities during their initial funding seeking stages. By taking advantage of the abundance of material quantity and unit cost data available to the researchers from the Egnatia Motorway, a major European Union (EU)-funded motorway project, cost estimate models using both ANNs and LR have been provided to researchers and practitioners [5–7]. The independent variables in these studies were the ground conditions, the overburden height and the cross-section area for tunnels and deck width, deck length, pier height, and theoretical volume for bridges, and finally net width, net height, and the height of the overburden for culvert construction costs.

Trying to secure construction companies' prosperity, many researchers developed models using artificial neural networks (ANNs) which are a subset of the artificial intelligence (AI) field. Due to their demonstrated accuracy and effectiveness in control, estimation, optimization, decision making, and numerous other applications, ANNs are the most prevalent and widely used AI technology. They have the potential to be used to accelerate sustainable development in the construction industry. A wide range of ANN technique applications have been shown by Ahmed et al. [8] to assist the construction industry's sustainable growth. It may be stated that a comprehensive research strategy using information from all construction stages and industry segments is required for the sustainable growth of the construction sector.

The purpose of this paper is to introduce an ANN-based tool for cost prediction aimed at building renovation projects in Greece since, following an extensive literature review, it was found that, to the best of the authors knowledge, no such models exist.

The lack of an established model emphasizes the necessity of an innovative approach. The goal is to provide reliable cost estimates to support management decisions in the process of building renovations. There is not an available model to predict the final cost of building renovation projects; therefore, a new model will be introduced to predict the final cost. In order to develop such a cost estimation model, data should be gathered from previous renovation initiatives. By taking into account past project data, ANN models are able to produce forecasts that are more accurate since they are able to recognize patterns and connections. Even in the early stages of a project, they can adjust when there are few project details available. Adequate use of data, model training, and model validation are required when introducing an ANN model to estimate renovations costs. After an ANN model's implementation and identification, the optimum model could benefit contractors and engineers by making realistic predictions. There is currently no such model based on a specific group of work packages.

To contribute to this gap in scientific research, a significant dataset of actual project cost data was gathered from a Greek contractor engaged in building renovations. The acquired data were categorized, analyzed, and appropriately encoded for the creation of ANN models for cost prediction. To develop, train, and test the network, IBM SPSS Statistics software 28.0.0.0, was implemented. The final cost is the dependent variable. The independent variables include initial renovation cost estimate (tender offer), contractual duration, and estimated initial demolition cost as defined by the contract. The procedure followed is the radial basis function. The model's performance during training and testing was evaluated and discussed, showing high effectiveness with up to 2% sum of squares error and nearly 0% relative error in the training sample, which is almost 70% of the whole sample. Thus, it has been demonstrated that ANNs are a highly effective method for estimating overall cost, particularly in building renovation projects.

The present article is structured into the following sections: In Section 2, a thorough literature review about ANNs as a tool in the construction field in general and specifically for building projects is provided. In Section 3, data gathering and analysis procedures for the creation of the ANN models in order to forecast the final building renovation costs are developed. The findings are provided in Section 4 and discussed in Section 5. Section 6 includes findings and suggestions for further research.

2. Systematic Literature Review

2.1. Artificial Neural Networks as a Tool in Construction Field

As seen from the following, ANN models have been shown to be an effective tool for construction organizations in achieving accurate cost estimates for construction projects, particularly in building construction projects, and preventing them from failing.

The interest of researchers in using ANNs for estimating has risen enormously in the past two decades. Even from 1998, Zhang et al. [9] strongly believed that although ANNs offer a lot of potential, they also include a lot of unknowns. The implications of important elements on the prediction effectiveness of ANNs remains unclear to researchers. Nevertheless, ANNs have been widely used in construction research [10], as described in the following paragraphs.

Adeli [11] tried to show various applications of ANNs. The structural engineering, construction engineering, and management sectors were the focus of the ANNs. A substantial portion of ANN applications in civil engineering are built on the straightforward backpropagation procedure. The current study also focused on the integration of ANN with other computing paradigms, such as wavelet, fuzzy logic, and genetic algorithms. These combinations provided added value to the efficiency of ANN models.

Buscema [12] asserts that ANNs reflect multidimensional, complex, dynamic phenomena that are unexpected and uncontrolled in the sense of conventional cause and effect. Therefore, they are probably nonlinear in their core. They state that it is possible to use inadequate intervention strategies and draw erroneous inferences about what transpired when linear-based paradigms are used for planned intervention with nonlinear processes.

In the construction sector, ANNs have proven to be essential. Three different categories of issues have been addressed through ANNs: Prediction, classification, and time series. For this to happen, it is necessary firstly to train the ANN. There is an established method since ANNs, by virtue of their properties, do not necessitate a formal learning process. Multilayer perceptrons are the most prevalent type of ANNs. Their adaptability has been verified in many cases [13]. Interestingly, there are additional supervised ANNs that employ supervised machine learning (ML), performing as a nonlinear classification algorithm, such as radial basis function networks, a sort of supervised ANN. Nonlinear classification methods employ complex functions to do more in-depth analysis than basic ones.

There are many sectors in the construction field that have benefited from the use of ANN models, such as construction claims prediction [14–19], prediction of construction duration of highway projects [20], forecasting of construction project safety behavior [21], material quantity consumption prediction [22], cost prediction in pavement construction [23], estimation of life-cycle costing of a construction project [24], initial cost projections of constructing road tunnels [25], determining the cost and material quantities for underground metro stations [7], and many others.

2.2. Application of ANNs to Cost Estimation in the Particular Field of Building Construction

The most popular construction project type, for which many cost prediction models exist, remains by far buildings. In the relevant literature review carried out by Hashemi et al. [26], it became apparent that 40 out of 92 studies analyzed referred to buildings. Additionally, in their review, Antoniou et al. [7] found another 31 out of 51 studies, published in 2021 and 2022, providing construction cost estimation models for building projects. Out of these 31 studies, 11 employed ANNs in their models. Following a demonstrative, non-exhaustive content analysis of those found to provide construction cost estimates for buildings using ANNs, the following studies stood out as noteworthy.

Chua et al. [27] acknowledged that it is important for project owners, contractors, and designers to identify and understand specific characteristics that could contribute to the successful completion of a building project. They consequently employed an ANN technique in an effort to discover the important project management traits linked to effective budget performance. They suggested several variables, including the number of organizational ranks between the project manager and craft workers, the amount of comprehensive planning completed prior to construction, the frequency of control meetings during the construction phase, the frequency of budget updates, the use of a constructability scheme, team turnover, the amount of money spent on project management, and the technical experience of the project manager. Chua et al. [27] utilized 75 buildings construction projects, 48 from contractors and 27 from owner organizations. After training, the final model was utilized as an estimator to anticipate the extent to which a buildings construction budget would perform. This method enables the budget performance model to be developed even while the functional relationships between the inputs and outputs are not explicitly established [27].

ANNs predicting the total construction cost were used by Emsley et al. [28], based on data from 300 buildings. The data collected were project files, the building cost information, and the results of a widely disseminated questionnaire survey. Since their data included final account totals, their resulting model could also assess the entire cost to the client, including, apart from the construction costs, the client's external and internal expenditures. In order to assess the ANN models, they further employed models developed via LR approaches, thus reaching the conclusion that the primary positive aspect of the ANN approach was its propensity to simulate nonlinearity in the data. The strongest model produced a mean absolute percentage error (MAPE) of 16.6% that took client changes into account to an unknown extent. This contrasts well with conventional estimation, where values of MAPE have been determined to range from 20.8% to 27.9%.

The efficacy of ANN procedures to resolve cost estimating issues in the first stages of building design processes was studied by Günaydin and Doğan [29]. An ANN-based model with eight design variables designed to estimate the square meter cost of a building's reinforced concrete structural systems for four to eight story residential structures in Turkey was developed and verified utilizing cost and design data from 30 projects achieving a 93% accuracy rate.

Examining the performance of three cost estimation models, Kim et al. [30] also attempted to demonstrate that accurate cost prediction is a crucial element in building projects. Using historical cost data for 530 buildings, they applied ANNs, multiple regression analysis (MRA), and case-based reasoning (CBR). The residential buildings were completed by general contractors between 1997 and 2000 in Seoul, Korea. The CBR estimating model outperformed the ANN estimating model in terms of long-term usage, accessible information from results, and time alongside accuracy tradeoffs, even though the most efficient ANN estimating model provided more accurate estimating results than either the MRA or the CBR estimating models.

Cheng et al. [31] suggested using the Evolutionary Fuzzy Neural Inference Model (EFNIM), an AI procedure, to increase cost estimation accuracy. As such, the beneficial characteristics of ANNs, genetic algorithms, and fuzzy logic have been integrated into the EFNIM, enabling the model to identify viable options in challenging situations. The combination of these techniques maximized each method's positive attributes and helped compensate for their inherent weaknesses when utilized individually. Genetic algorithms were used for optimization; fuzzy logic dealt with uncertainties and approximate inferences; and ANNs were employed for fuzzy input–output mapping. As a result, Cheng et al. [31] offered two models that could calculate conceptual building costs at the commencement of projects.

Arafa and Algedra [32] implemented a model employing ANNs to determine the cost of building initiatives at an early stage. A database of 71 construction initiatives in the Gaza Strip was utilized. The aforementioned type of projects was non-governmental and governmental buildings, schools, kindergartens, and residential buildings. At the pre-design stage of the project, a number of critical parameters were determined for the construction cost of the buildings structure that could be acquired from the engineering drawings and data available. Seven variables were included in the input layer of the ANNs; the usual floor size, the number of stories, the number of rooms, the ground floor area, the type of foundation, the number of columns, and the number of lifts. The created ANN model had seven input neurons, one hidden layer, and a single output neuron that represented an early estimate of the building's construction cost. The trained model's findings demonstrated that ANNs could estimate the initial stages cost estimation of structures using just rudimentary project information, without the requirement for a more intricate design. The number of stories, the ground floor area, the type of foundation, and the number of lifts were found to be the most influential factors on early estimations of building costs.

An interesting point of view came from Wang et al. [33], who innovated by creating models utilizing support vector machines and ANNs to forecast project cost and schedule success using early planning data as model inputs. They discovered that early planning status may be successfully applied to predict project success by utilizing ANNs after collecting early planning and project performance data from a total of 92 building projects through a relevant industry questionnaire survey. A total of 12 retrofits and 80 new construction projects comprised the 92 building projects, out of which 32 projects were public and 60 were private. In comparison to models produced from single ANNs, those built using bootstrap-aggregated ANNs were shown to be more accurate and reliable.

For Shehatto and El-Sawalhi and Shehatto [34,35], ANN models for accurate building construction project cost estimates and cost data for each different construction stage were identified using a combination of quantitative and qualitative procedures based on a repository of 169 completed building projects in the Gaza Strip. The constructions utilized as data were historical cases of building projects from municipalities, government ministries, engineering institutions, contractors, and consultants. Eleven important factors were taken into account as independent input variables, and the project cost was regarded as the dependent output variable. The models that were developed were trained utilizing the NeuroSolutions application. Once again, their ANN models demonstrated that an ANN could properly estimate construction project costs without requiring substantial definitive designs since the average error for the upgraded model was generally satisfactory, less than 6%. The outcome of the sensitivity analysis indicated that the standard floor size and the number of stories had the most significant influence on building cost, according to the sensitivity analysis. They came to the conclusion that 11 factors should be regarded as independent inputs that affect project cost.

Elfaki et al. [36] strongly believed that cost estimation in building projects fluctuates due to variety of distinct variables. These considerations may be divided into two separate categories: (1) Variables particular to estimators, and (2) variables specific to designs and projects. They concentrated on the need to create a projection of costs strategy that could account for all estimating components from every perspective and contained a usual validation approach that could be used to gauge the degree of accuracy of cost estimation proposal.

Also, Ongpeng et al. [37] utilized an ANN model with the objective to forecast the entire structural cost of construction projects in the Philippines. They employed information from 30 construction projects, which were gathered and separated into three parts: 60% for training, 20% for verifying performance, and 20% for a totally autonomous test of network generalization. The number of stories and basements, the total ground area, the concrete volume, the formwork area, and the reinforcing steel mass were the six independent variables they incorporated in their ANN model that was implemented in MATLAB for simulation. The superior model for the overall structural cost was created using the feedforward backpropagation approach. Six variables used as inputs, six hidden layer nodes, and one output node completed the most efficient ANN structure. After adequate training, the resultant ANN model correctly forecasted the overall building construction costs. The researchers suggested that variables like surface area, number of floors and basements, concrete volume, formwork area, reinforcing steel mass, post-tensioned area, pile volume, etc., all determine the structural or civil engineering cost. On the other hand, other building costs include the architectural costs that depend on the style and caliber of the materials used for the floor, walls, ceiling, doors, windows, painting, etc. Finally, water and sewage networks, electrical installations, air-conditioning and heating systems, and the installation of lifts complete the whole engineering cost of the building.

It is important to note that the most popular method for stakeholders in the construction industry to determine the preliminary costs of building is the Unit Area Cost Method (UACM). The predicted costs using this technique, considering only construction area, differed significantly from real costs, as Bayram et al. [38] observed. They nonetheless compared the cost estimates derived using the widely utilized ANN techniques of multilayer perceptron (MLP) and radial basis function (RBF). Additionally, the outcomes of the MLP and RBF were measured and compared with the ones from the UACM. After analyzing data from 232 public buildings completed in different regions in Turkey from 2003 to 2011, it was found that the predicted values using both techniques were greater than the actual values with a 0.28% variance when using the RBF and a 1.11% variance when using the MLP. With a variation of 28.73%, the estimated costs from the UACM are significantly higher than the actual expenses. It was discovered that RBF outperformed MLP, while both ANN algorithms performed better than the UACM [38].

During the pre-design stage, Ambrule and Bhirud [39] tried to examine and address issues with cost estimation at the initial phase of building development, and attempted to utilize ANNs for cost forecasting of building projects. A graphical user interface (GUI) model of cost estimation for enhanced concrete buildings was also created and tested during the preliminary design period. Ambrule and Bhirud [39] determined that the ANN GUI model may help managers in making recommendations about project implementation in the very beginning stages of the engineering process.

Another mathematical model based on ANN was developed by Abd and Naseef [40] to estimate total building construction costs based on the initial estimates of the cost of 25 construction elements. Their data were derived from 501 Iraqi building projects built between 2005 and 2015 and included the total amount spent on foundation excavation, landfill construction, filling with sub-base construction, construction of moisture proof layer, construction of components, typical concrete for paths, structural concrete foundation, etc. The correlation coefficients between the factor findings were approximately 100%, the error rate was around 5.81%, and the degree of accuracy was 94.19%, indicating that the algorithm used for the ANN performed extremely well in estimating the expenses for a construction building endeavor in Iraq.

Researchers in India also attempted to develop an ANN model for construction cost prediction of buildings. Specifically, Chandanshive and Kambekar [41] obtained quantity and cost data from 78 buildings, which included small- and medium-sized residences and bungalows constructed between 2017 and 2019, built in or around Mumbai (India), via questionnaires and the opinions of building designers and building specialists. Eleven independent variables related to quantities of specific construction works were included: ground floor area, typical floor area, number of floors, structural parking area, volume of elevator walls, volume of exterior walls, volume of exterior plaster, flooring area, number of columns, foundation type, and number of households. The only output parameter was the total cost of the project in Indian national Rupees. For their model, they created a multilayer feedforward ANN model that had been programmed using a backpropagation procedure. Early ending and Bayesian regularization algorithms were used to improve the ANN's efficiency for generalization and prevent excessive fitting. The Bayesian regularization methodology's ability to perform was determined to be superior than early halting during the building cost prediction. The trained ANN model's findings demonstrated that it was capable of successfully foreseeing the total building construction cost [41].

In another emerging economy, this time that of Yemen, a study was carried out to provide a cost prediction tool based on ANN models by Hakami and Hassan [42], based on historical data from 136 buildings constructed from 2011 to 2015. They included 17 independent variables to be implemented in their model to produce a preliminary total construction cost estimate. The 17 independent variables were project category, number of stories, area of floors, type of groundwork, number of elevators, exterior finishing type, interior decoration, conditioning system type, HVAC, electrical work type, mechanical work type, basement floor, floor height, slab type, site area, tile type, and project location. They created, trained, tested, and ran evaluations of sensitivity on the structure utilizing the NeuroSolutions 6 application. The outcomes of the educating, evaluating and sensitivity examination were highly acceptable, with high efficacy and validity, and less than 1% error.

The only cost forecast model found for public buildings alone was provided by Sitthikankun et al. [43], who explained that there are two commonly employed techniques for estimating public building expenses: a preliminary estimation with an advantage of a quick cost estimate and a disadvantage of a high final cost variance, and an exhaustive prediction with the benefit of a more precise cost estimate but negative effects related to the need for a definitive completion and the associated need for time to complete, thus missing set funding deadlines. In their study they utilized data from 50 public building projects completed in 2020 in Thailand. The 11 independent variables used were total usable floor area, average perimeter length, average story height, total building height, number of floors, total roof area, total bathroom area, ground floor slab area, total area of openings, type of roof, and type of slab structure. The findings were forecasted using the ANN approach. Two hidden layers with ten and eight nodes each, respectively, formed the final method, with a root mean squares error (RMSE) value of 0.331 million Thai Baht. After the most recent data source was validated, the correlation factor R^2 was found to be 0.914, demonstrating the preciseness of the modelling approach as a substitute for public bidders to minimize tolerances and spend less time estimating building expenses more effectively.

All of the aforementioned studies attempted to provide cost estimation models for the construction of new buildings. One study was found that investigated the cost–performance of building reconstruction, also called renovation projects; Attalla et al. [44] tried to investigate this challenging environment and proposed a model based on ANN to calculate a cost performance index based on data known at the beginning of the construction phase. In their study, data was gathered about the causes of excess expenses and low-quality work from 50 reconstruction schemes via a poll of industry specialists. Each project-related real expenditure variance from projected values and the specific project control methods that were implemented were documented. Overruns in fees to the client and the expense of repairs to the building contractor were utilized as two indicators of financial variance. Eighteen independent variables were finally chosen out of thirty-six that were believed to have an effect on the cost performance all related to project management tools and techniques, including cost, schedule, quality, safety, communication tools, and techniques, as well as scope definition, and tendering and project completion procedures. They employed an ANN (Neuro Shell2) and statistical analysis (Systat) to create their models. Although the performance of both approaches was comparable, the model generated by the ANN was more susceptible to a wider range of factors. It was this study that inspired this research work to develop an ANN model for actual cost prediction of building renovation projects based on cost and schedule estimates known at the start of construction in order to predict final cost deviations. To the best of the authors' knowledge, this is the first published ANN model for final cost prediction of building renovation projects.

A summary of the above techniques, data sources, etc. used by the aforementioned researchers are summarized in the following table (Table 1).

In the following section, the valuable knowledge from the extended review mentioned above is used and an effort is made to develop an ANN model in order to have more accurate cost estimation in building renovation projects.

Table 1. Summary of ANN approaches for building cost estimation found in the existing literature.

Publishing Year	Authors/Ref.	Country	Data Base Source	Data Size	Data Type	Inputs	Outputs/Research Object	ANN Architecture/Training Algorithm	ANN Tools
1997	Chua et al. [27]	Singapore, USA	Questionnaires	75 buildings	Qualitative	8 independent variables: Project manager and craft workers' organizational ranks, quantity of finished detailed design at the initial phase of construction, frequency of the phase-of-construction control meetings, total amount of funding spent on managing a project, team rotation, constructability scheme usage, financial updates on a continuing basis, and project manager's expertise	Project budget performance–cost estimation	MLP/BP	Neural Works Professional II/PLUS
2002	Emsley et al. [28]	UK	Real project data, questionnaires	288 buildings	Quantitative and qualitative	6 Project strategic variables: Building standards, type of commitment, procurement approach, procurement methodology, time frame, goals 4 Site-related variables: Geographical features, location access, specific type of place, site typology 31 Design-related variables: Internal doors, rooftop characteristics, cooling systems, interior walls, ceiling coatings, structural variety, specific installations, interior wall completes, electrical infrastructure, types of stairways, number of elevators, surroundings, quantity of stories over ground, exterior doors, subsystem, number of stories under the surface, the external walls, structural units, additional floors, mechanical installations tasks, finishes on floors, piling, wall-to-floor proportion, frame technique, windows, preventive structures, functionality of structures, rooftop structure, height, roofing finishes, and GIFA	Construction cost estimation and client's external and internal expenditures	MLP, RBF, and GRNNs.	Trajan NN Simulator Release 4.0E
2003	Attalla and Hegazy [44]	Canada	Questionnaires	50 buildings	Quantitative and qualitative	18 independent variables: Concept of the reconstruction project, as-built designs, expenditures and baseline for spending plan, boards for design, requirements and criteria for quality, prior qualification of contractors, unit costs, cash disbursements, coordinating timetable, bar diagrams, critical path technique, augmental benchmark, variance in costs, independent evaluation companies, frequent site meetings, efficient reaction system, collaborative health and safety committee, evaluation by the customer, maintenance, and operator	Cost estimation of reconstruction projects	Statistical analysis and ANN/MLP/BP	Neuro Shell 2 and. Systat software

Table 1. *Cont.*

Publishing Year	Authors/Ref.	Country	Data Base Source	Data Size	Data Type	Inputs	Outputs/Research Object	ANN Architecture/Training Algorithm	ANN Tools
2004	Kim et al. [30]	South Korea	Real project data	530 buildings	Quantitative	9 independent variables: Cross floor area, stories, duration, roof types, fdn types, total unit, utilization of basement, actual costs, finishing grades	Project cost estimation	ANN/MLP (GAs)/BP	Neuro Solutions for Excel Release 4.2, NeuroDimension, Inc., Gainesville, FL, USA
2004	Gunaydın and Dogan [29]	Turkey	Real project data	30 buildings	Quantitative and qualitative	8 independent variables: Total area of the building, ratio of the typical floor area to the total area of the building, number of floors, ratio of ground floor area to the total area of the building, console direction of the building, foundation system of the construction, location of the core of the building, floor type of the structure	Cost estimation of reinforced concrete structural systems of four–eight storey residential building	Feedforward ANN/BP	NeuroSolutions by NeuroDimensions Inc.
2009	Cheng et al. [31]	Taiwan	Real Project data	28 buildings	Quantitative and qualitative	6 Quantitative factors: total floor area, floors underground, floors above ground, number of households, household in buildings, site area 4 Qualitative factors: Soil condition, seismic zone, electromechanical infrastructure, interior decoration	Project cost estimation	Evolutionary Fuzzy Neural, MLP, inference System mechanisms (EFNISM) and process of developing construction cost estimators ((EWCCE)/BP	EWCCE system via World Wide Web
2011	Arafa and Alqedra [32]	Palestine	Real project data	71 buildings	Quantitative and qualitative	7 independent variables: Number of stories, number of rooms, usual floor size, ground floor area, type of foundation, number of columns, number of lifts.	Early building cost estimation	MLP/BP	Matlab v.2009b
2012	Wang et al. [33]	Taiwan	Questionnaires	92 buildings	Quantitative	Early planning data and project performance data	Final cost estimation Schedule success	SVMs and ANNs * ensemble techniques	1. NeuroSolutions TM by NeuroDimension, 2011, 2. LS-SVMlab
2014	Roxas and Ongpeng [37]	Philippines	Real project data	30 buildings	Quantitative	6 independent variables: Number of stories, total ground area, number of basements, concrete capacity, reinforcing steel mass, and formwork area	Project cost estimation	MLP/BP, weights and bias values updated according to Levenberg–Marquardt	Matlab (R2010a)
2014	El-Sawalhi and Shehatto [35]	Gaza	Questionnaire, interviews, literature review	169 buildings	Quantitative and qualitative	11 independent variables: Type of project, number of floors, area of typical floor, type of foundation, type of slab, type of external finishing, type of air-conditioning, type of electricity, type of tilling, type of sanitary, and number of elevators	Total cost estimation	MLP/BP (Tanh transfer function and momentum learning rate)	NeuroSolutions 5.07
2016	Bayram et al. [38]	Turkey	Real project data	232 buildings	Quantitative	5 independent variables: Approximate cost, contract value, entire constr. zone, number of floors, and structure height	Project cost estimation	MLP and RBF	Matlab v.7.9.0

Table 1. *Cont.*

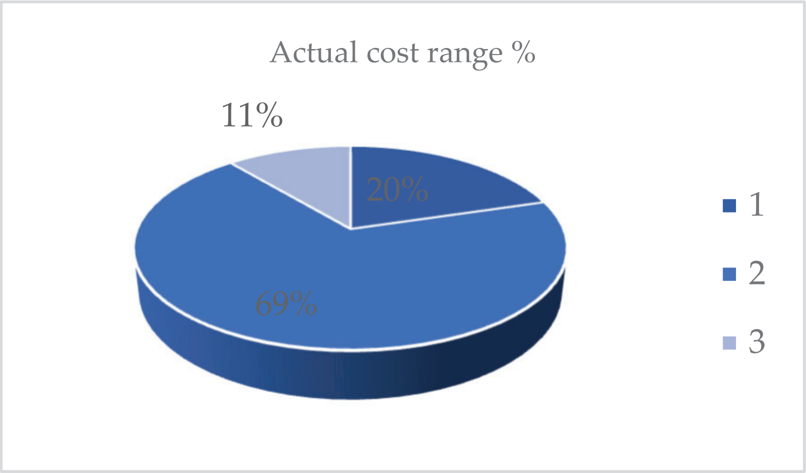
Publishing Year	Authors/Ref.	Country	Data Base Source	Data Size	Data Type	Inputs	Outputs/Research Object	ANN Architecture/Training Algorithm	ANN Tools
2017	Amprule and Bhirud [39]	India	Not specified	Not specified	Not specified	Not specified	Early cost estimation	ANN GUI model in general	Not specified
2019	Abbas Mahde Abd et al. [40]	Iraq	Real project data	501 projects	Quantitative and qualitative	25 independent variables: Excavation the groundwork works, filling with foundation workings, landfill works, construction works under moisture proof layer, construction works above moisture proof layer, building works of sections, ordinary concrete for walkways, reinforced concrete foundation, reinforced concrete column, reinforced concrete lintel, reinforced concrete slabs, reinforced concrete beams, reinforced concrete stair, reinforced concrete for the sun bumper, plaster finishing workings, cement finishing workings, plastic paints, pentolite paints, pigment color, stone packaging, workings of placing marble, ceramic works for floor, ceramic works for walls, flattening (2 opposite layers), tiling	Project cost estimation	ANN not specified	Matlab
2019	Chandanshive et al. [41]	India	Questionnaires	78 buildings	Quantitative and qualitative	11 independent variables: Ground floor zone, typical floor zone, quantity of floors, structural parking zone, size of elevator walls, size of exterior walls, size of exterior plaster, flooring area, number of columns, foundation category, and amount of households	Project cost estimation	MLP/BP Bayesian regularization Levenberg–Marquardt	Matlab v.R2015a
2019	Hakami and Hassan [42]	Yemen	Real project data, literature review	136 buidings	Quantitative and qualitative	17 independent variables: Project type, number of stories, area of floors, type of groundwork, quantity of elevators, external finishing type, inner decoration, conditioning system category, HVAC, electrical work category, mechanical work type, basement floor, flooring height, slab category, site zone, tile type, and project position	Project cost estimation	MLP/BP	SPSS IBM v.19.0-NeuroSolutions v.6
2021	Sitthikankun et al. [43]	Thailand	Real project data	50 buildings	Quantitative and qualitative	11 independent variables: Whole usable floor area, average perimeter length, average story height, total building height, number of floorings, total rooftop area, whole area of openings, entire rest room area, ground flooring slab area, category of rooftop, and kind of slab structure	Project cost estimation	A 2 hidden layers (10 and 8 nodes) ANN structure	Rapid Miner Studio

Note: ANN for artificial neural network; MLP for multilayer perceptron; RBF for radial basis function; BP for back propagation (algorithm); GA for genetic algorithms; GRNNs for generalized regression neural networks; M3 for square meter; SVM for support vector machine; LRV for logistic regression model; GUI for graphical user interface, when not specified by the relevant researcher. * Bootstrap aggregating and adaptive boosting ANNs classifiers.

3. Methodological Approach

In the current paper, an effort was made to produce ANN models. A sample of 52 building renovation projects were collected from a single construction company specializing in building renovations. The aforementioned company holds a lot of experience in structure renovations, so it is a great opportunity to retrieve functionally accurate data from their knowledge base. The projects were selected as the company followed the same system of structural analysis in each of their works. They all were private projects. An analytical cost was the result of a survey and detailed measurement of each building project. The initial cost was sanctioned by both parties, constructor and proprietor. The total cost of each project was based on the current prices of the Greek financial and construction fees.

According to Figure 1, the data source including 52 building renovation projects was the main source of information for the current research. As foreseen, the major portion of that category of projects (69%) had a cost range up to EUR 50,000. Nevertheless, 20% of those projects only reached EUR 20,000 and 11% went up to EUR 450,000. Thus, the information from such a cost variety of building renovation projects was an opportunity to examine the accuracy of an ANN to estimate the cost in both low- and high-budged building renovation projects.



Definitions

1. Up to EUR 20,000 (11 projects)
2. EUR 20,000–50,000 (35 projects)
3. EUR 50,000–450,000 (6 projects)

Figure 1. Range of initial cost values.

Acknowledging the above notions, a database including initial renovation cost estimate (tender offer), contractual duration, and demolition costs as defined by the contract, were created. IBM SPSS Statistics software [45] was used to create a database with the above technical parameters. The structures are mostly residential apartment buildings in urban areas, mainly in the Municipality of Thessaloniki. The key motive for the renovations was the demand for energy upgrading, but other reasons included modernization, redesigning, and, rarely, change of use. The buildings are often plus several years of age, especially those that were in the center of the city. The projects started in 2018 and were completed in 2023.

Initially, a correlation analysis was performed. The results are presented in Table 2.

Table 2. Correlation analysis.

		Tender Offer	**Project Contract Duration**	**Initial Demolition Cost per Contract**
Final Renovation Cost	Pearson Correlation	0.989	0.826	0.479
	Sig. (1-tailed)	0.000	0.000	0.000
	N	54	54	54

According to Table 2, there is a considerable correlation between the final renovation cost and the tender offer and project contract duration variables. A medium correlation exists between final renovation cost and demolition cost per contract. The correlation between tender offer and project contract duration is important, due to the fact that the relationship between these two parameters remains directly proportional. The longer the duration of the project, the higher the cost of its construction. Thus, the final cost of the renovation project would be affected. The initial demolition cost is one of many categories in a building renovation project that could have a significant role in determining the final cost. Demolition is the main initial stage of renovation constructions and an accurate initial estimation would have a significant impact on the project's final cost. Thus, its contribution to the final project's cost estimation depends on its magnitude and accuracy of prediction. In addition, the amount of demolition work that will be required on a project has a significant variation depending on the size of the project and the type of work the client requested, and also the building's age and condition. Thus, the following model that will be created will be based on these correlated variables.

The dependent as well as independent variables are defined. The model was created, trained, and tested using IBM SPSS application. The radial basis function was the method adopted. In accordance with the company's records, the dependent variable is the final renovation cost of each project. The independent variables include initial renovation cost estimate (tender offer), contractual duration, and demolition costs as defined by the contract. A total of 38 projects were chosen for the training sample and 14 for the testing sample. The relationship of 70% of the project sample for training and 30% of the project sample for testing is an acceptable percentage according to the above-mentioned literature review and the results obtained. Changes are focused on the number of neurons (units) within the hidden layer. The analysis initiates with a single neuron and continues by adding one neuron with each consecutive time and analysis. The radial basis function, which connects the values of the units in one layer to those in the next, is the activation function for the hidden layer. The activation function for the output layer is the identity function; as a result, the output units are just the weighted sums of the hidden units. In the present model's architecture, the activation function for the hidden layer is the normalized radial basis function, which employs the SoftMax activation function to normalize all concealed unit activations such that they add up to 1. The multiplier applied to the radial basis functions' width is the overlapping factor. The overlapping factors were automatically calculated. The value is 1+0.1d, wherein d is the amount of input data.

The study reached an ANN with 50 neurons in the hidden layer. In essence, the research produced 50 models. The analysis revealed that, based on sum of squares error and relative error, the ANN with 40 neurons in the hidden layer provided the best results. The trained model's gathered information indicated that the ANN approach was efficient in forecasting the expenditure prediction of structures utilizing minimal project data and without the requirement for a more extensive design. Figure 2 presents the flowchart of the proposed methodological approach.

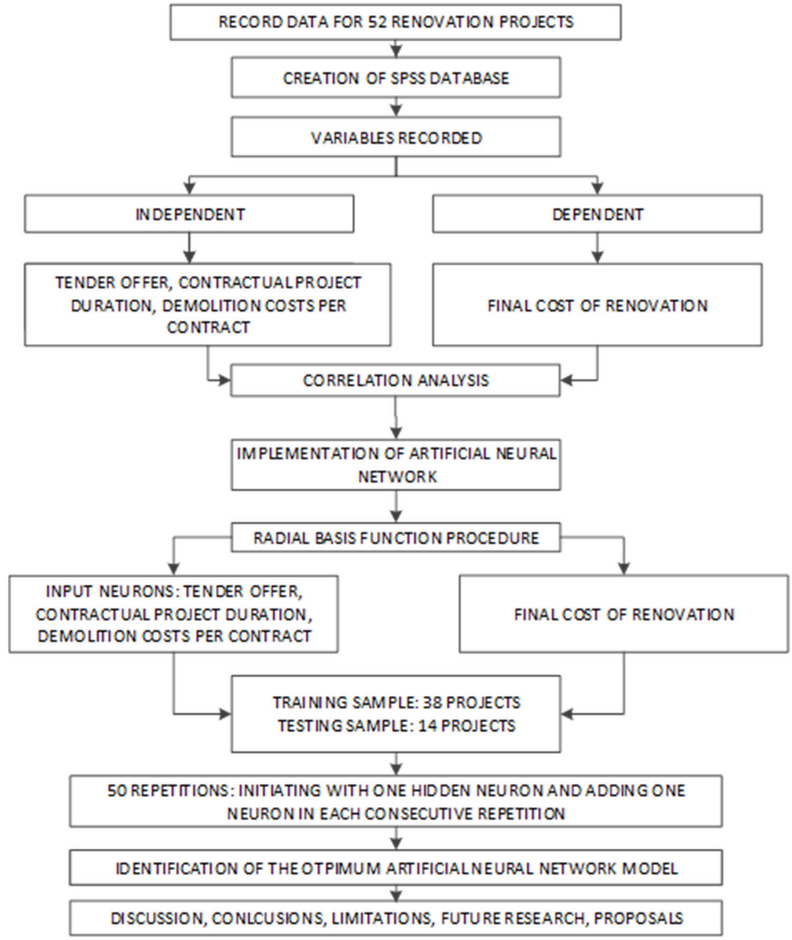


Figure 2. Proposed methodological approach.

4. Results

A total of 52 distinct projects were included in the data collection. This extensive collection of data provided the structure for the testing process that had been established in place in the network. This test procedure's main goal was to make it simpler to compare the actual costs utilized for these kinds of projects with the cost estimates produced by the artificial neural network model.

This dataset's projects each represented a distinct instance with a unique set of variables and results. These projects' actual costs were thoroughly collected and assembled, offering the testing process a solid and trustworthy baseline.

In Figure 3, the predicted final cost in comparison to actual cost in the training sample had a respectable performance. The actual costs of the sample projects ranged significantly. As a result, the effort of the ANN to produce prediction models was really challenging. As seen below in Figures 4 and 5, the sum of squares error and the relative error in the training sample remained low.

The analysis revealed that according to the training sample and based on the sum of squares error and the relative error, the ANN with 40 neurons in the hidden layer had the best performance. In this ANN model, the sum of squares error remains at 2% and the relative error is near to 0 at the training phase of the model, as presented in Figure 4.

In Figure 5, it can be seen that the relative error remains near to 0. Thus, according to the training sample and based on the relative error, the ANN with 40 neurons in the hidden layer still provided the optimum results.

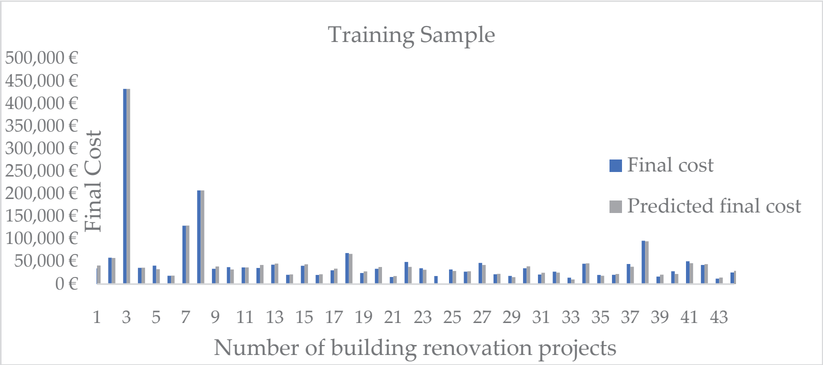


Figure 3. Final cost and predicted final cost (testing sample).

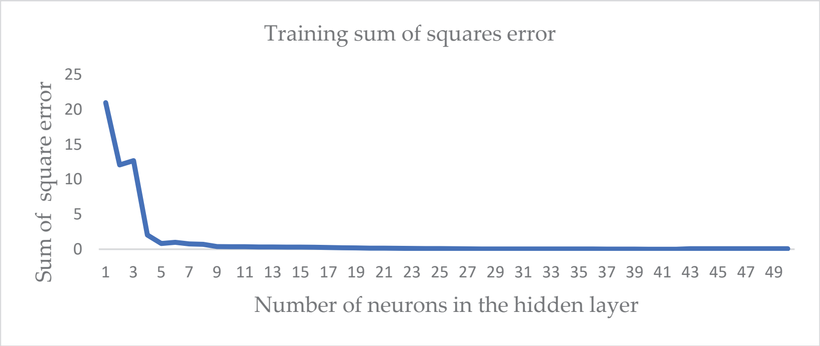


Figure 4. Training sample sum of squares error based on the number of neurons within hidden layer.

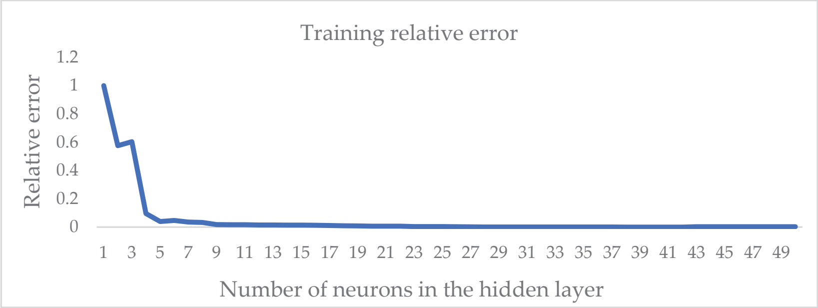


Figure 5. Training sample relative error based on the number of neurons within hidden layer.

5. Discussion

The present research focuses on the usage of ANN models, specifically the radial basis function procedure, when implemented as a technique for forecasting costs in the building construction sector. This approach concentrated on the field of renovation in order to pre-estimate the total cost of a construction project.

The current paper is based on extensive literature review, concerning the implementation of ANNs in construction projects. Additionally, a noteworthy amount of actual data regarding renovations has been collected from the construction field in Greece. The data from 52 construction projects are solely in the field of building renovation projects that have been performed within the last 5 years, precisely from 2018 to 2023. The gathered data were categorized and processed in accordance with ANN restrictions. Network construction, training, and testing were done with IBM SPSS Statistics software. The dependent variable is the final cost. The independent variables include initial renovation cost estimate (tender offer), contractual duration, and demolition costs as defined by the contract. The method followed was the radial basis function. A total of 70% of the sample was chosen for training and 30% for testing. The models' performance was carefully assessed during the training phase. According to the parameters utilized to assess the models' performance, the evaluation showed a high level of effectiveness. The sum of squares was discovered to be as high as 2%. Figure 4's low error rate shows that the model was able to predict the outcomes with slight variance based on the input data. It was also evaluated the model's performance using the relative error in addition to the sum of squares error. Figure 5 illustrates the relative error, which was found to be almost 0. The model's superb precision is further demonstrated by this almost zero relative error, illustrating that the ANN can produce forecasts that precisely correspond to the resultant data.

It is indispensable not to overlook, though, that the current study's scope was rather constrained. In particular, this study only included components that were easily recognized in the early stages of planning. This indicates that some variables or elements that might have surfaced later in the projects were left out of this model. This method allowed researchers to remain concentrated on the most easily accessible data, but it additionally indicates that not all possible variables on the project results may be properly accounted for in the model.

In summary, even though this particular model has proved to be highly effective in the training phase, more thorough research that considers new variables and aspects that are apparent in the latter stages of project planning and execution may prove advantageous in subsequent studies.

6. Conclusions and Future Research

It may be inferred from the research and discussion that ANNs have been highly effective in their implementation for cost estimates with a substantial degree of accuracy. The Greek construction sector might employ this method to more quickly and reliably estimate the expenses of their construction projects. Additionally, this proposed approach may be adopted by other countries, which would greatly benefit. The quantity and quality of independent variables—in this study, the initial renovation cost estimate (tender offer), contractual duration, and demolition costs as defined by the contract—are just a few of the many uncertainties that the ANN model has to face. The data used in the present research was collected over the last five years.

The construction sector, in particular, uses ANNs as useful tools for cost estimation. Reliability and the number of cases, finished projects in this case, are important factors that affect an ANNs capacity to predict expenses.

An ANN's capability to learn from a grander amount of data, which improves prediction accuracy, increases with the dependability and quantity of successfully completed projects. This is so that they can develop forecasts for the future using the principle of machine learning from historical data. Thus, an ANN's performance is directly impacted by both the quantity and quality of the data it receives.

However, reliable and high-quality expenditure data is essential for the ANN to learn and produce accurate forecasts. Since there are many variables that might have a significant effect on construction costs, this information should cover structures in diverse situations. The building's location, the materials utilized, and the design's complexity are a few examples of these variables.

With a large and varied dataset, researchers may experiment with various modelling and prediction strategies. This enables scientists to optimize ANNs, enhancing their potential to forecast project costs with greater accuracy. Essentially, the ultimate objective is to create an accurate building cost forecast model, which can be very helpful with financial and budgetary management in the construction sector.

For instance, researchers could use this data to perform in-depth analyses and investigations. They may look at patterns, pinpoint recurring problems, and provide creative answers. This could result in the creation of more cost-effective building methods, the identification of potential cost savings, or the enhancement of project management procedures.

In addition, such databases could be very beneficial to construction companies. They might learn more about the real expenditures and schedules connected with comparable projects if they have access to data from previous initiatives. They might be able to anticipate their own projects more precisely as a result, which would lower the possibility of delays or cost overruns.

Furthermore, not only would the databases hold unprocessed data, but they would also provide input for models of artificial neural networks (ANNs) and other computational techniques. By analyzing the data and drawing conclusions from it, these models might produce forecasts for future initiatives. This could greatly improve the cost estimate accuracy for upcoming building projects, resulting in more dependable planning and budgeting.

Under this situation, building firms could become more proficient in carrying out their projects. If they were allowed access to precise budgets and schedules, they could better use their resources and finish their projects on schedule. This might boost the construction industry’s profitability and level of competition.

Furthermore, anticipating a project’s ultimate cost or even its cashflows could help avert possible financial disaster. Businesses could make sure they have adequate funds to pay for the expenses, refrain from taking on initiatives they may not afford, and choose the best financing solution in their favor. This could be beneficial to help companies maintain their financial stability and see their projects through to completion.

In conclusion, the evolution of databases that are accessible to the public and contain information from finished state projects has the potential to completely transform the building sector. It might help construction companies and researchers tremendously, make accurate cost estimations easier, increase productivity, and shield businesses from financial ruin. In terms of using data to the advantage of the construction sector, it is a major advancement.

The reliability and number of cases (completed projects) have a significant impact on the cost estimation performance of an ANN model, since ANNs learn from them. Therefore, there is a need for trustworthy and high-quality expenditure information of buildings of various circumstances in order to explore modelling and prediction approaches and establish an accurate forecast model of building expenses.

The effectiveness of an ANN model depends on the type and structure of the ANN that was used, the training procedure, and the way that data are organized and interpreted, in addition to the quality of the training data.

In the present research it has been observed that it was not required to place great emphasis on correlation testing between the independent input parameters (initial renovation cost estimate (tender offer), contractual duration, and demolition costs as defined by the contract) and the dependent parameter (estimated final cost). The above parameters are related analogously as parameters of the same projects. Thus, their correlation is significant and their inclusion in the model will lead to improving the model’s efficacy. Data that have been used in the current study required a lot of research since databases are often unavailable or unreliable. It should be noted that a holdout sample was not created or used in the current study.

It was pointed out that ANNs have been utilized to address issues that are challenging to solve with conventional mathematical techniques. With respect to traditional ANNs, findings from the integration of ANNs with additional approaches such as genetic algorithm, fuzzy logic, ant colony optimization, artificial bee colony, and particle swarm optimization showed greater performance. This was especially true when attempting to predict the costs associated with building initiatives.

Furthermore, another important step forward would be the creation of publicly accessible databases, including information from State-completed initiatives. For many different stakeholders, these databases may be a veritable information gold mine.

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Article

Tools and Techniques for Improving Maturity Partnering in Indonesian Construction Projects

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Abstract: The construction industry is naturally complex and constantly changing, with various factors impacting project results. Among the different methods developed to navigate this complexity, partnering is believed to increase project value and performance. Therefore, this research aimed at analyzing and formulating elements as well as indicators at each phase of a partnership-based project life cycle, serving as tools and techniques for measuring the depth of partnering in construction projects. The methodology used included both qualitative and quantitative methods (mixed method). In the qualitative method, the literature from relevant journals, books, and previous research was reviewed. This process was followed by an expert assessment through a Focus Group Discussion (FGD) to define elements and indicators for measuring the depth of partnering in construction projects. Meanwhile, the quantitative method comprised analyzing secondary project data to compare projects with in-depth partnering in order to deliver better value. The result of this research was the development of Key Performance Indicators (KPIs) to measure maturity partnering in partnership-based projects. Typically, the tools were adjusted to different phases of the project life cycle, starting from project initiation, comprising all stakeholders. Consequently, the outcome of this research could be used by organizations in the construction industry to develop partnering in partnership projects in Indonesia.

Keywords: project performance; partnering; partnership project; project life cycle; tool and techniques

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1. Introduction

The construction industry is faced with several problems, including low productivity [1] and high waste [2]. According to Koskela (2000) and Chan et al. (1997) [3,4], chronic issues in the construction sector include low productivity, safety concerns, poor working conditions, unsatisfactory quality, a fragmented industry, a lack of coordination among participants, and excessive trading. In addition, there are issues related to production such as work quality, design changes, and material quality and availability, as well as utilization.

In a study conducted by Valverde (2011) [5], several factors contributing to low productivity on construction projects in various countries including Indonesia are (1) poor workmanship, (2) the unavailability of materials, (3) a lack of project information, (4) equipment availability, and (5) faulty work [5]. Other reasons for low productivity include labor expertise and experience, the availability of materials at the construction site, poor site management, political and safety situations, ineffective supervision, a lack of labor skills, bad weather, and unclear instructions. It is crucial to be aware that these factors have an impact on the cost performance of construction projects [6].

Alwi (2002) [2] stated six main factors causing waste in the construction industry in Indonesia, which include design changes, slow decision making, a lack of skilled workers, inadequate construction methods, and poor coordination among professional management. Therefore, waste management requires attention and action from all included parties. When managing and reducing waste, contractors are advised to (1) build long-term relationships with producers and suppliers in order to develop shipping methods that avoid excess supplies and delays; (2) consider the use of local materials and natural resources as much as possible; (3) conduct regular training programs for supervisors and workers to help in understanding the concept of waste; (4) conduct the construction process transparently to ensure everyone concerned can identify problems during the project; and (5) establish cooperation and regular meetings between project participants and construction personnel at various levels, thereby strengthening mutual trust and cooperation as partners.

Many efforts have been made to improve the performance of construction projects, and one effective approach is through partnering. This philosophy is believed to provide value and improve project performance in terms of cost, quality, time, safety, and the environment [7–10]. Research by Sari [11–13] proved that partnering established from the beginning of the project increases performance and provides added value for all stakeholders. Moreover, project management problems are experienced by owners, contractors, and subcontractors, based on the background of each stakeholder. A typical solution to achieve the objectives of stakeholders is trust and partnering [7,14]. Specifically, partnering can increase project performance, reduce costs, and improve quality.

Previous research has not fully discussed the ways in which partnering can be applied in construction projects to produce value for each stakeholder. Meanwhile, previous findings only focused on partnering factors [15,16], levels [12,13,17–20], interactions [13,21], challenges [13], waste reduction, and financial risk reduction [22–25]. Therefore, this research aims to improve our understanding of the way partnering is implemented in projects, considering depth as an indicator of success. It is important to acknowledge that this exploration will build on previous findings to strengthen our understanding of partnering.

1.1. Partnering

Partnering is practiced in private and government projects where there is collaboration between government and business entities. This type of partnering represents a positive collaboration between the groups, with two main models which are solicited and unsolicited.

Pinto Nunez et al. (2018) [24] stated that partnering needs to be measured in order to assess program performance, determine benefits and costs, help in decision making, and the future planning of partner programs [24]. In addition, the process assists in identifying areas that need improvement, thereby increasing partnering processes in the future [24,26]. Tools and techniques for partnering can support the aims of all project participants, creating a more cooperative and effective team [27,28]. However, implementing partnering can be complex and challenging, implying that a clear understanding of effective practices and project characteristics is necessary to ensure success [27,28]. Partnering guidance showed a positive result, including cost saving, qualitative optimization, and increased communication and trust between clients and contractors [29]. Challenges often arise from defining partnering as a coherent and universal strategy and from changes in attitudes and behavior [22,30]. Therefore, effective partnering implementation requires considering factors that strengthen certain work, appropriate tools and techniques, as well as a strong commitment from top management [31].

Hosseini et al. (2016) [29] showed that one obstacle to implementing partnering in the construction industry is a lack of understanding of effective practices. The successful implementation of partnering requires understanding the practices and characteristics of the project [13,24,30]. Furthermore, measuring partnering performance includes continuous evaluation throughout the project, which includes assessing specific targets, correct milestones, and available resources [31]. This measurement helps project managers to track when the project is progressing as intended or otherwise [31]. Therefore, evaluating the depth of partnering requires tools and techniques to measure every indicator at each stage in the life cycle of the project.

1.2. Maturity Partnering Technique

Thompson (1998) [17] stated that maturity partnering can be measured, and its characteristics are identifiable in project activities [20,30]. A higher level of maturity partnering in an organization leads to several achievements which include the following [18,20]:

(1) The development of a comprehensive and joint measurement system;
(2) Collaborations in performing work from start to finish;
(3) Cultural integration in work management;
(4) Transparency in cooperation;
(5) Trust is very high, and risk sharing occurs.

Pinto [24] also signified the importance of major elements in partnering, such as commitment, trust, respect, communication, and fairness. According to Sari (2022), [13] achieving mature partnering and TARIF values (Trust, Accountability, Responsiveness, Independence, and Fairness) requires good governance in an organization. Furthermore, the process of measuring maturity partnering helps to effectively track progress and provide early warnings in the establishment [18]. This is a system used to identify and correct progress when necessary [18]. Detecting problems early offers decision makers more options for resolving issues, which tends to reduce project costs and strengthen partnering relationships among stakeholders [18]. Pinto [24] further explained that maturity partnering is divided into four levels, each requiring metric guidance for deeper measurements.

Figure 1 shows the four stages of measuring maturity partnering in a project, which include the no partnering level (no program), simple, defined, managed, and institutionalized [24]. At the institutionalized partnering level, partnering has become an institutionalized value. Furthermore, partnering is joined into the strategy of organization with structured partnership documentation [24]. Partnering is validated as a long-term system associated with business objectives, leading to improved innovation performance over time [24]. Figure 2 shows that there is an increase in the level of maturity partnering and desire in an organization, with respect to the level of trust, commitment, communication, and respect [17,27].

1.3. Partnering in Project Life Cycles

Partnering is most effective when implemented according to the phases of a project life cycle [13]. There are different objectives at every phase of a project; therefore, partnering is present throughout. Sari (2023) [13] stated that the depth of partnering can be increased in each project delivery system at any stage of the project life cycle. Pinto (2018) [24] also stated that partnering deepens activities at each stage of the project. In the initiation phase, clear objectives are crucial to improve early collaboration, achieved through strengthening training and leadership. During project design and implementation, Asmar (2015) [9] proved, with maturity partnering, that even at the initiation phase, before 0% project design, stakeholders can determine the scope together, known as Integrated Project Delivery (IPD). Therefore, partnering is essential in every project life cycle to measure and evaluate the effectiveness of each strategy.

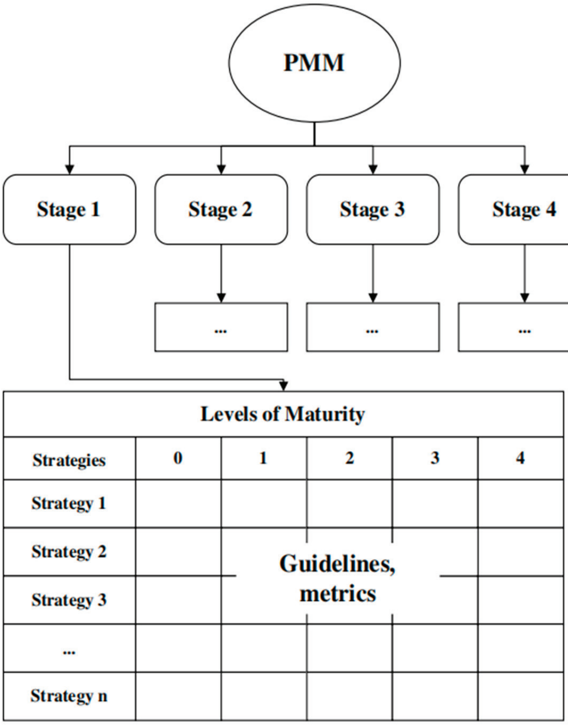


Figure 1. Maturity partnering schematic [24].

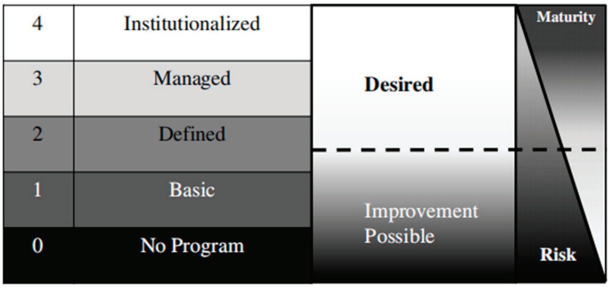


Figure 2. Maturity partnering map [24].

1.4. Delphi Method

The Delphi method includes selecting qualified experts, creating relevant questions as well as analyzing the answers of professionals [32,33], and selecting high-quality experts is crucial in this method [34,35]. Typically, research using the Delphi method includes 5–20 experts [34–36], and at least two rounds are conducted to make a decision. These experts are professionals with diverse knowledge [37], who are concerned with decision making in the respective companies of the professionals and have at least five years of experience.

Another important aspect in every Delphi research is ensuring that the results are based on consensus among the participants in each round. According to Hallowell and Gambatese (2010) [37], consensus is determined by the absolute deviation from the responses of the experts, showing a deviation of 5% from the median. Using absolute deviation and the median instead of standard deviation and means helps avoid biases.

2. Materials and Methods

The methodology used in this research was a mixed method consisting of qualitative and quantitative exploration methods, as shown in Figure 3.

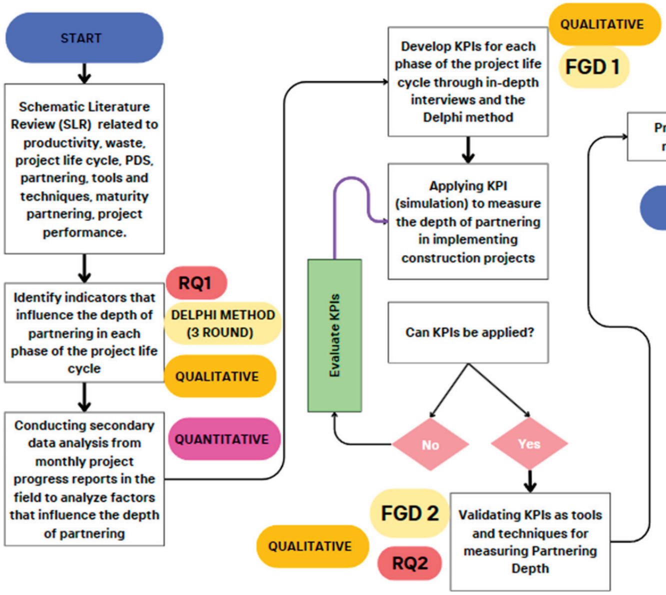


Figure 3. Steps of this research.

The research steps shown in Figure 3 consisted of the following:

Step 1: Conducting a Schematic Literature Review (SLR) to determine research gaps and novelty, analyses related to productivity, waste, project life cycles, project delivery systems, partnering, tools and techniques, maturity partnering, as well as project performance.

Step 2: Identifying indicators that influence the depth of partnering in each phase of the project life cycle. In this stage, identification was conducted through literature and previous research. Furthermore, the Delphi method was performed in 3 rounds to draw consensus from experts who have tacit knowledge of the field.

Step 3: Conducting secondary data analyses from the monthly progress report of the project to determine the depth of partnering in the DB project.

Step 4: Preparing KPIs for each phase in the project life cycle, accompanied by in-depth interviews with actors in the field. Following this, an FGD was performed to finalize the prepared KPIs.

Step 5: Applying KPIs in the project comprised generating a field report and measuring the depth of partnering using prepared KPIs. After the application of KPIs, the finalization process was initiated.

Step 6: Validating KPIs that have been confirmed in an expert FGD to finalize tools and techniques for measuring the depth of partnering in DB projects.

Step 7: Preparing the research report.

The schematic from the research methodology in this exploration was delivered through Research Questions (RQs) from the aims of this finding. There were two indicators to be achieved in this research that are described in Table 1.

Table 1. Research question strategy.

RQ	Problem	Input	Process	Output
RQ1	How do the indicators that are developed in every project life cycle phase to prepare tools and techniques deepen partnering for both private and government projects?	Variables from literature review	Literature research and validation from experts.	Indicator mapping of project life cycle on DB and DBB projects.
RQ2	How does building KPIs determine maturity partnering in every project life cycle phase and project performance?	Variables from literature review and output of RQ1.	Delphi method and in-depth interviews.	KPIs mapping to determine maturity partnering.

Table 1 shows two questions that were answered in the research conducted through the literature review and the Delphi method. To execute the Delphi method, the following were included:

1. Nine experts who were heterogeneously competent in construction management. The criteria for each expert were given limitations, including that the project managers were selected with experience as a manager of at least 5 (five) years in large category projects, namely a minimum of over IDR 100 billion. Similarly, senior designers were also limited to a minimum of 10 years of experience.
2. The Delphi method was conducted in three rounds to reach consensus to state the factors and variables that affect the depth of partnering in a DB project.

Below are the profiles of the experts included in the Delphi method.

Table 2 shows a list of the profiles of the participants in the Delphi method, which was conducted in three rounds.

Table 2. Profile of participants for FGD.

Actor	Resp.	Position/Role
Owner	1	Chief Executive Officer
	2	Chief Executive Officer
Designer	3	Senior Designer
	4	Senior Designer
Contractor	5	Chief Executive Officer
	6	Project Manager
	7	Operational Director
Academic	8	Professor of Construction Management
	9	Professor of Construction Management

3. Results

3.1. Schematic Literature Review

The schematic literature review focused on the factors and variables that influenced the level of maturity partnering in construction projects. These factors were divided into each phase of the project life cycle, which included initiation, design, construction work, and completion. Crane (1999) [18] concluded that the indicators for measuring partnering maturity consisted of five indicators.

The next step was separating the factors in Table 3 in every project life cycle phase by combining literature reviews from other members. The schematic literature review used for each life cycle phase of the project can be seen in Table 4.

Table 3. The indicators in measuring maturity partnering.

Cost	Schedule	Safety	Quality	Litigation
• Cost performance index • Project in cash flow plan • Billable ratio (engineering) • Engineering work hour/unit of product • Third-party work sampling to determine contractor effectiveness • Value engineering savings • Engineering as a percentage of total installed cost • Duplication of effort • Cost growth • Overhead as a percentage of total installed cost	• Schedule performance index • Milestones met • Immediate notification of delays • Preassembly of equipment (percentage of total) • Timely issue of engineering documents and equipment • Availability of spare parts/change parts • Cycle time (product to market) • Time to process change orders, purchase orders, requests for information, etc.	• Lost time and non-lost time incidents • Occupational Safety and Health Administration • Recordable incidents • Drug testing results • Safety training performed on time • Same-day correction of safety problems	• Conformance to specifications • Achievement of operating objectives • Percent of rework • Plant output • Participation in design by construction/manufacturing personnel • Start-up performance • Number of engineering changes • Customer feedback • Audit deviations • Errors and omissions • First-pass yield	• Outstanding claims • Number of conflicts elevated to each level

Table 4. Schematic literature review.

No.	Affecting Factor	References
Initiation		
1	Cost performance index	[38–40]
2	Project in cash flow plan	[38–40]
3	Third-party work sampling to determine contractor effectiveness	[38–40]
4	Cost growth	[38–40]
5	Project value on environmental awareness and environmentally friendly	[41]
6	There was stakeholder participation since before the project started	[21,42]
Design		
1	Value engineering savings	[43,44]
2	Engineering as a percentage of total installed cost	[43,44]
3	Conformance to specifications	[4,45]
4	Waste management by considering material optimization and transportation	[41,46–49]
5	Supplier/subcontractor participation in design process	[13,19,21]
Construction		
1	Billable ratio (engineering)	[50]
2	Engineering work hour/unit of product	[51]
3	Engineering as a percentage of total installed cost	[10]
4	Duplication of effort	[52–54]
5	Overhead as a percentage of total installed cost	[55–60]
6	Schedule performance index	[55–60]
7	Milestones met	[55–60]
8	Immediate notification of delays	[55–60]

Table 4. *Cont.*

No.	Affecting Factor	References
Construction		
9	Preassembly of equipment (percentage of total)	[55–60]
10	Timely issue of engineering documents and	[55–60]
11	equipment	[55–60]
12	Availability of spare parts/change parts	[55–60]
13	Cycle time (product to market)	[55–60]
14	Time to process change orders, purchase orders, requests for information, etc.	[55–60]
15	Lost-time and non-lost-time incidents	[55–60]
16	Occupational Safety and Health Administration	[55–60]
17	recordable incidents	[55–60]
18	Drug testing results	[55–60]
19	Safety training performed on time	[55–60]
20	Same-day correction of safety problems	[55–60]
21	Conformance to specifications	[55–60]
22	Achievement of operating objectives	[55–60]
23	Percentage of rework	[55–60]
24	Plant output	[55–60]
25	Participation in design by construction/manufacturing personnel	[55–60]
26	Start-up performance	[55–60]
27	Number of engineering changes	[55–60]
Closing		
1	Customer feedback	[18]
2	Audit deviations	[18]
3	Errors and omissions	[18]
4	First-pass yield	[18]
5	Outstanding claims	[18]
6	Number of conflicts elevated to each level	[18]
7	Time limit on building handover, maximum 5% penalty from contract	President decree no 54, point 93
8	Project maintenance cost	[61]
9	Green SOP in managing environmentally friendly building	[61]
10	Certificate of functional fitness published by local government before handover to owner	[61]

3.2. Delphi Method Round 1: Affecting Factors of Maturity Partnering

Round 1 of the Delphi method consisted of interviewing experts in order to provide opinions on the factors influencing the quality of maturity partnering in a project. During this phase, experts had five days to identify five influencing factors to prepare tools and techniques for measuring the level of partnering maturity. In addition, literature review mapping was also provided for the reference of the experts, without limiting previous experience in the field. The results of Delphi Round 1 are shown in Table 5, consisting of 26 factors.

Table 5. Delphi Round 1 results.

No.	Factors Affecting the Development of KPIs
1	Objectives and benefits of partnering
2	Object aim/project delivery system
3	Identified type of interaction
4	Activity goals in PDCA
5	Identified performance indicators
6	Underlying requirements and values
7	There was stakeholder participation before the project started
8	Project value regarding environmental awareness and environmentally friendliness
9	Cost performance index
10	Cost growth
11	Effectiveness in partnering
12	Savings due to value
13	Successful engineering compared to the total cost used
14	Conformity to specifications
15	Waste management during design
16	Repetitive work
17	Performance index schedule
18	Time needed for extra work
19	Conformity to specifications
20	Percentage of cost overruns
21	Suitable milestone schedule
22	Openness
23	Responsibility
24	Avoided conflicts of interest
25	Effectiveness in partnering
26	Loss due to project accidents that affected KPIs in formulating the tools and techniques in partnering projects

3.3. Delphi Method Round 2: Refining Affecting Factors

Round 2 comprised conducting FGD to discuss all the determined factors and importance. Subsequently, questions were asked to validate the importance level of each factor by selecting "Very Important", "Important", and "Not Important" for each phase of the project life cycle. The results of Delphi Round 2 are provided in Table 6.

Table 6. Delphi Round 2 results.

No.	Factors	Very Important	Important	Not Important
1	Aims and benefits of partnering	70%	30%	
2	Object goals/project delivery system	60%	40%	
3	Identified type of interaction	30%	70%	
4	Activity goals in PDCA	40%	60%	
5	Identified performance indicators	50%	50%	
6	Underlying requirements and values	40%	30%	30%

Table 6. *Cont.*

No.	Factors	Very Important	Important	Not Important
7	There was stakeholder participation since before the project started	50%	40%	10%
8	Project value on environmental awareness and environmentally friendly	50%	50%	
9	Cost performance index	20%	80%	
10	Cost growth	10%	70%	20%
11	Effectiveness in partnering	60%	40%	
12	Savings due to value	50%	50%	
13	Successful engineering compared to the total cost used	60%	40%	
14	Conformity to specifications	40%	60%	
15	Waste management during design	10%	90%	
16	Repetitive work	20%	70%	10%
17	Performance index schedule	40%	80%	
18	Time needed for extra work	40%	40%	20%
19	Conformity to specifications	50%	50%	
20	Percentage of cost overruns	40%	60%	
21	Suitable milestone schedule	60%	40%	
22	Openness	40%	60%	
23	Responsibility	50%	50%	
24	Avoided conflicts of interest	60%	40%	
25	Effectiveness in partnering	60%	40%	
26	Loss due to project accident	30%	50%	20%

From Table 6, each factor had an importance level above 50%. Therefore, all 26 factors were used to prepare tools and techniques to measure maturity partnering.

3.4. Delphi Method Round 3: Utility and Validation Affecting Factors

Utility and validation were conducted on the affecting factors identified in Delphi Round 2. In Round 3, experts were asked to assess utility on a scale from 1 to 5, with 0.1 showing "**Low Suitable**" and 5 showing "**High Suitable**". Furthermore, factors scoring below the average of 2.5 were not used as KPIs in developing tools and techniques for measuring maturity partnering. Table 7 shows the results of the utility and validation of the influencing factors.

Table 7. Delphi Round 3 results.

No.	Factors	Utility 1–5 Degree
1	Aims and benefits of partnering	5
2	Object goals/project delivery system	4
3	Identified type of interaction	4
4	Activity goals in PDCA	3
5	Identified performance indicators	4
6	Underlying requirements and values	4

Table 7. *Cont.*

No.	Factors	Utility 1–5 Degree
7	There was stakeholder participation since before the project started	4
8	Project value on environmental awareness and environmentally friendly	3
9	Cost performance index	3
10	Cost growth	2
11	Effectiveness in partnering	4
12	Savings due to value	3
13	Successful engineering compared to the total cost used	3
14	Conformity to specifications	3
15	Waste management during design	3
16	Repetitive work	3
17	Performance index schedule	4
18	Time needed for extra work	4
19	Conformity to specifications	4
20	Percentage of cost overruns	3
21	Suitable milestone schedule	4
22	Openness	4
23	Responsibility	4
24	Avoided conflicts of interest	5
25	Effectiveness in partnering	4
26	Loss due to project accident	2

According to Table 7, a consensus was obtained from experts that two factors were not used, namely no. 10 and no. 26.

4. Discussion

Validation was conducted on the factors and variables affecting the preparation of tools and techniques for maturity partnering in construction projects. The next step was to prepare an assessment of each factor using a Pinto-based metric, categorized as non-programmed, basic, defined, managed, and institutionalized. The scoring system ranged from 0 to 5, with detailed explanations provided as follows (Table 8).

Through in-depth interviews conducted at six project locations with varying project performances in DB projects, conclusions were based on the empirical field and the result of the in-depth interview. In the data analysis of field projects, it was found that project performance was lower when partnering levels were lower and partnering had not been implemented institutionally. Furthermore, the lack of intensive cooperation between owners and contractors as project stakeholders led to design changes during project implementation. Differences in understanding project documents led to the project lacking partnering from the beginning.

4.1. Project Data Progress Mapping

Mapping was created on six DB project locations that were located in Indonesia. The project value was more than IDR 100 billion, which is approximately USD 6.25 million, and the detailed data are shown in Table 9.

Table 8. Maturity partnering scoring [24].

Level	Description
Level 0	No partnering and no practice or partnering principle in the project.
Level 1	Partnering was conducted informally. It was not visible in the strategy prepared, and there was no team appointed as PIC for communication between stakeholders. Very limited partnering practices were used based on previous experience. Minimal efforts in reducing risks or taking risks for short-term benefits were employed. Ad hoc strategies were implemented by people who have partnering skills, and the process was not well controlled.
Level 2	There was a written plan for the partnership policy and strategy. There was a kick-off process and a meeting to discuss partnering in-depth, including previous plans and the appointment of a PIC to lead the partnering program being performed. Performance metrics were developed in partnering to achieve set project objectives, evaluating in-depth performance achievements, and there was feedback on problems solved by partnering.
Level 3	Organization-wide standards and strategies were applied to many projects. The partnering process occurred from the project initiation phase to establish shared aims and was managed using performance metrics. Achievement of organizational performance was visible, and productivity followed the objectives set. There was comprehensive documentation of meetings and coordination regarding the partnering conducted.
Level 4	Have and use strategies, documentation, and partnering were associated, integrated, as well as structured. A validated continuous improvement system to achieve project objectives and each phase innovates to increase value. The focus was on continuously improving performance through change management (e.g., incremental and innovative changes).

Table 9. List of projects.

No.	Title	Value (USD Million)	Location
1	DB "A"	12.5	DKI Jakarta
2	DB "B"	10.0	DKI Jakarta
3	DB "C"	16.5	Bukittinggi, West Sumatera
4	DB "D"	18.3	DKI Jakarta
5	DB "E"	9.0	DKI Jakarta
6	DB "F"	16.5	East Kalimantan

Project data were obtained in six locations spread nationally in Indonesia. The statistical results are shown in Table 10, in line with the list in Table 9.

Table 10. Statistical scoring.

Criteria	DB "A"	DB "B"	DB "C"	DB "D"	DB "E"	DB "F"
MEAN	0.268%	1.217%	7.544%	5.849%	9.399%	6.537%
MEDIAN	0.534%	3.137%	5.487%	6.092%	7.98%	4.719%
%MEAN and MEDIAN	49.811%	61.207%	37.475%	3.989%	17.815%	38.525%
STD	0.9%	1.5%	2.1%	3.2%	3.8%	3.4%
Deviation of MEAN	−0.7%	−0.3%	5.5%	2.6%	5.6%	3.1%

The data on DB "A" and DB "B", in the standard deviation graphics, show that the value deviated from the mean.

Figure 4 shows that the project performance was in accordance with the mean, median, and standard deviation. In this context, the DB "A" and DB "B" values were away from the mean. A similar value was also reflected in the in-depth interview results, where no partnering in a project caused poor project performance.

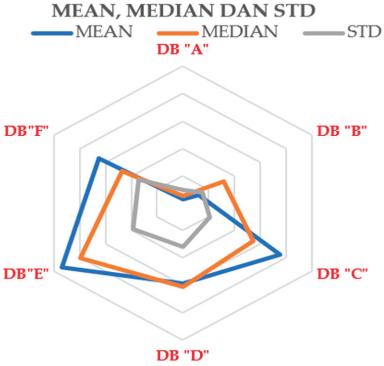
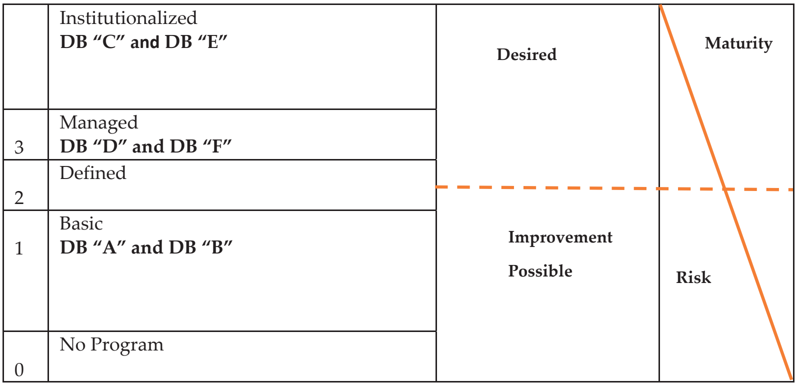


Figure 4. Statistical data of projects.

4.2. Maturity Partnering Simulation

Mapping and in-depth interviews were conducted on six projects to determine the position and scoring of each project. DB "A" had characteristics at the basic partnering level. Typically, partnering was not visible in the strategy prepared, and there was no team appointed as PIC for communication between stakeholders. Consequently, very limited partnership practices were used based on previous experience. Moreover, ad hoc strategies were implemented by people who have partnering skills, and the process was not well controlled, and some steps were not thoroughly communicated to achieve deep partnering. The positions of the owner and general contractor were still "competitive", and they supervised each other in achieving project performance. Additionally, project performance was behind schedule according to the planned project schedule, and project overhead had also increased. The same increment was conducted on five other projects to determine the maturity level of partnering for each project. Based on the results of the in-depth interviews and project data mapping, a conclusion was made from the six simulated projects as follows:

In Figure 5, it is shown that the DB "C" and DB "E" projects had an institutionalized level of implementation, where strategies and partnering mapping were in place from the start of the project. Subcontractors were required to prepare offers and implement the best value-for-money strategy in the offers. Additionally, in DB "D" and DB "F", partnering work occurred at a managed level, where the standardization of it had been established but had not yet fully become a culture in the organization. Partnering was still at the basic level, where there was still competition between the included parties in the DB "A" and DB "B" projects.



	Institutionalized **DB "C" and DB "E"**	**Desired**	**Maturity**
3	Managed **DB "D" and DB "F"**		
2	Defined		
1	Basic **DB "A" and DB "B"**	**Improvement** **Possible**	**Risk**
0	No Program		

Figure 5. Simulation of partnering.

5. Conclusions

In conclusion, several inferences can be made from the prior discussion, which include the following:

1. Maturity partnering in a project improved service delivery and provided better value. This process led to better performance and faster completion times on projects. Although partnering could be a strategy to achieve better project performance, projects with deep partnering achieved better performance based on the trust placed in each stakeholder before project implementation.
2. The depth of the partnering was measured, and its maturity increased by examining the initial point of the existing partnering. This initial step allowed for the partnering to be expanded gradually, moving towards a deeper and more institutionalized direction. Partnering that was implemented institutionally became part of the organizational culture and achieved more specific organizational aims.
3. The indicators developed in measuring the depth of partnering were considered to be influencing factors in increasing the depth of it in DB projects.
4. KPIs were arranged as scoring in measuring maturity partnering using tiered levels, whereby project positioning on maturity partnering was measured. In addition, KPIs were a clear measure for determining the depth of a project based on standards that had been established together.
5. Project organizations that were aware of the maturity partnering position increased the level of it to improve quality and strengthen the culture in the project organization. The level of partnering depth was measured continuously to transform the partnering into an organizational culture useful for improving construction project performance.
6. The limitation of this research was that KPIs were structured to be implemented in Design and Build projects, but it was possible to modify developments for other delivery projects such as Design Bid Build and Integrated Project Delivery.

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