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Developing a Value Proposition Model for Construction 4.0 Decisions: A Futures Triangle Approach

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Abstract

This paper introduces the Construction 4.0 Value Proposition Score (CVPS4.0)—a structured framework that enables Architecture, Engineering, and Construction (AEC) organizations to evaluate and communicate the value proposition of Construction 4.0 decisions. Grounded in the "Futures Triangle" theory, the study draws on existing research to identify three key dimensions: past barriers constraining AEC organizations, current trends driving industry change, and future transformations toward which the sector is evolving. In total, 45 barriers, 13 trends, and four transformations were identified as the foundation of the scoring framework. The model assesses how a decision influences each dimension, producing a composite score that reflects its overall value proposition. This score incorporates three considerations: the applicability of each factor to the organization, the degree of impact the decision has on it, and the relevance of the factor to the decision. The framework was validated through proof-of-concept with a subject-matter expert, who confirmed its value in supporting strategic, data-informed decision-making. As one of the first studies to evaluate the value proposition of Construction 4.0, this research offers both a practical decision-support tool and a consolidated reference on the forces shaping organizational change. CVPS4.0 provides AEC organizations with a proactive means to guide decisions, mitigate risks, and enhance long-term value creation.

Keywords: AEC; Construction 4.0; decision-making; futures triangle; industry; organization; people; process; construction technology; value proposition

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1. Introduction and Background

Construction 4.0 has been gradually transforming the construction industry and changing the way projects are designed, planned, constructed, and operated [1]. Inspired by the convergence of trends and technologies introduced by the fourth industrial revolution, "Industry 4.0" [2], Construction 4.0 is defined as the "digitization and industrialization of the industry" to "enable integration and connectivity of stakeholders across the construction project lifecycle, advance processes by employing mechanization and automation, and bridging the gap between the physical and cyber environments" [3]. This wave is designed to provide interconnection and interoperability to support effective communication and coordination among stakeholders, enhance information transparency, decentralize decision-making, and offer technological innovation throughout the project lifecycle [4,5].

Construction 4.0 is enabled through various technologies such as 3D printing and additive manufacturing, artificial intelligence and machine learning, augmented reality and

virtual reality, big data, cloud computing, digital twins, drones, and sensing and wireless technologies [6,7]. Studies have investigated the use of these technologies in an array of industry use cases, including planning, design, scheduling, management, logistics, health, safety, on-site operations, supply chains, inspection, and asset performance assessments and monitoring [8]. Such use cases also showed promising potential and benefits in terms of improving automation, decision-making, quality, productivity, efficiency, health and safety, sustainability, and smart and intelligent assets [7,8]. In addition to the benefits, major challenges also face Construction 4.0 and the successful adoption of its technologies [9]. Studies that surveyed practitioners in the industry highlighted several obstacles, including resistance to change, unclear benefits and gains, cost of implementation, lack of standardization, labor shortage, low investments, privacy and security concerns, and the fragmented and project-based nature of the industry [10–12].

1.1. Research Gap: Organizational Decision-Making and Construction 4.0

One of the earliest reports on Construction 4.0, published by Schober and Hoff (2016) [13], divided digital transformation into four key aspects: digital data, automation, connectivity, and digital access. The report also mentioned that organizations need to "move quickly and concern themselves with technological developments and think carefully about how to implement them". While extensive research has been conducted on technology and achieving the four key Construction 4.0 aspects, the focus on "thinking carefully" remains a missing aspect.

From a research perspective, the need for research that can guide organizations and decision-making has been iterated by multiple studies. Maskuriy et al. (2019) [14] investigated the construction industry's readiness for Industry 4.0 and concluded that a solid theoretical groundwork is needed to help organizations realize adoption and provide them with operational, tactical, and strategic management insights to approach technology adoption. A study conducted by Moshood et al. (2020) [15] recapped the challenges for Industry 4.0 in construction, and a major challenge revealed from existing research was that "decision-making efforts in construction companies concerning the digital revolution are undeveloped". Another study, by Karmakar & Delhi (2021) [16], summarized the state-of-the-art of Construction 4.0 and highlighted the necessity for research at the level of organizations and the need to develop methodological frameworks for dynamic Construction 4.0 implementation across the industry. Moreover, Shafei et al. (2022) [17] reviewed studies on Construction 4.0 technologies and decision-making and concluded that research on Construction 4.0 technologies is growing exponentially but only a few studies target decision-making, and research on technology adoption decisions remains limited and fragmented. More recently, Dou et al. (2023) [18] tracked the evolution of research on 10 emerging digital technologies and highlighted that the research effort has focused more on the development and application of technologies rather than technology management, including diffusion, adoption, and evaluation.

From a practical perspective, the Construction 4.0 transformative vision can sway organizations in different directions, causing both distractions and disruptions [19]. This calls for organizational leadership to be effective in responding to change by spreading accurate knowledge, identifying promising opportunities, and eliminating threats that can affect the organization's operations [20]. Consequently, construction organizations need to make informed, targeted, and sound decisions that begin by understanding the potential of the decision to maximize the value of its outcome [21].

Thus, it becomes important to provide the construction industry with Construction 4.0 decision-making research that allows organizations to understand why such decisions are important and how they can be implemented. Very few studies have contributed to

this need and proposed tools that organizations in the construction industry can utilize. For example, Mansour et al. (2021) [22] proposed ConFIRM to measure an organization's strategic readiness for Construction 4.0 using three dimensions—human capital, relational capital, and structural capital; Sorce and Issa (2021) [23] designed an extended Technology Acceptance Model (TAM) to understand the effect of individual attributes and company culture on the adoption of technologies in the construction industry; Rajendra et al. (2022) [24] used the Technology Readiness (TR) model to investigate the role of optimism, innovativeness, and insecurity dimensions in determining an organization's intention to adopt technologies; and Chen et al. (2023) [25] proposed an Organizational Digital Technologies Readiness Model that organizations can use to assess their readiness for adopting technologies. Despite the contribution of such studies to the decision-making research streams, the focus remained on assessing and understanding organizations' readiness to adopt technologies and not on the value of the decision itself that the organizations need to implement.

1.2. Research Solution: Value Proposition and Construction 4.0 Decisions

To successfully embrace Construction 4.0 and harvest its benefits, organizations must understand the value proposition of the Construction 4.0 decisions they make internally to ensure the desired outcomes are achieved [19]. The value proposition is a core element to understanding the potential of any decision, especially when related to transformative industry visions [26]. The term "value proposition" is also one of the most used terms in business, as it should be one of the organization's "most important organizing principles" [27,28].

Analyzing the value proposition is crucial to the value-creation process, where it allows decision-makers to understand the decision's contribution to their organization's vision and examine the extent of its impact on products, services, partners, stakeholders, and customers [26,28]. Moreover, studies have shown that analyzing the value proposition of decisions increases their chances of success through facilitating communication on evaluating, sharing, and utilizing organizational resources; reducing uncertainty and variability notably for uncertain outcomes such as those related to technology; documenting and standardizing the process by pushing decision-makers to think carefully and minimize risk exposure; influencing expectations to increase organizational commitment; and attracting the right talent [28–32].

2. Objective and Scope

This paper aims to address the gap by presenting the "Construction 4.0 Value Proposition Score (CSPS4.0)". CVPS4.0 is a holistic score that can comprehensively quantify the value proposition of a decision and compute the effect of this decision on an organization's Construction 4.0 vision:

- **What is CVPS4.0?**

The score allows construction organizations to compute the value proposition of their decision on the Construction 4.0 vision and its contribution to the organization.

- **What CVPS4.0 is not?**

The score does not replace existing organizational means, methods, approaches, or practices used for decision-making; it also does not replace any expertise offered by internal or external subject-matter experts.

- **Why is CVPS4.0 needed?**

The score provides organizations with a "scientific thinking" approach to their decisions regarding the Construction 4.0 vision. It furthers their understanding of the extended

impartial decision by providing clarity on the contribution of the decision to addressing the challenges that have been anchoring the organization, the contributions of pushing the organization to react to the trends of the present, and the contribution to pulling the organization towards a future vision.

- **When to use CVPS 4.0?**

The score should be used in the early stages of the decision-making process, but it can also be used at any point to understand the decision's impacts. It can also be used to access the communication platform that allows users to translate their thoughts into words and provide a common language for training and discussions.

- **Who can use CVPS4.0?**

The score can be used by innovators, champions, and decision-makers at any level in the organization to evaluate the impact of their decision on the organization's Construction 4.0 vision.

Research Theoretical Framework: Futures Triangle

For Construction 4.0 decisions to lead to actionable strategies, construction organizations must analyze how the decision helps them overcome the hurdles that they face internally and externally, supports them in reacting to the current trends and urgent needs that must be addressed, and assists them in preserving a future that keeps organizations innovative, competitive, and profitable [33]. Building on this notion, "Futures Triangle" theory was used to conceptualize CVPS4.0 as shown in Figure 1. The method was developed by [34], and it aims to map the competing dynamics between three time dimensions: past, present, and future. Each dimension represents a set of drivers or factors that interact to contribute to an organization's plausible future [34]:

- The past dimension is referred to as the "weight of the past", which represents the barriers and constraints that organizations face when implementing change.
- The present dimension is referred to as the "push of the present", which represents the current organization's reality and the present drivers that are pushing the organization to change.
- The future dimension is referred to as the "pull of the future", which represents the future scenarios that the organization aspires to achieve regardless of whether they are real or not.

The tensions and interactions between the three dimensions form a plausible future inside a time triangle with the ability to "start a process of thinking beyond the now" through brainstorming ideas on every dimension and exploring different alternatives and scenarios to build the desired future [35]. Examining these dynamics renders the "Futures Triangle" theory extremely viable during decision-making. The theory was employed in different sectors such as agriculture [36], banking [37], and education [38]. Several studies in the AEC industry also used the "Futures Triangle". The theory was used for planning scenarios that map the potential futures of the built environment [39], understanding the changing environment that is driving capital project organizations for transformative and agile change [40,41], applying successful digitization efforts to AEC organizations [21], and developing a process reengineering framework to integrate technology in construction processes [1].

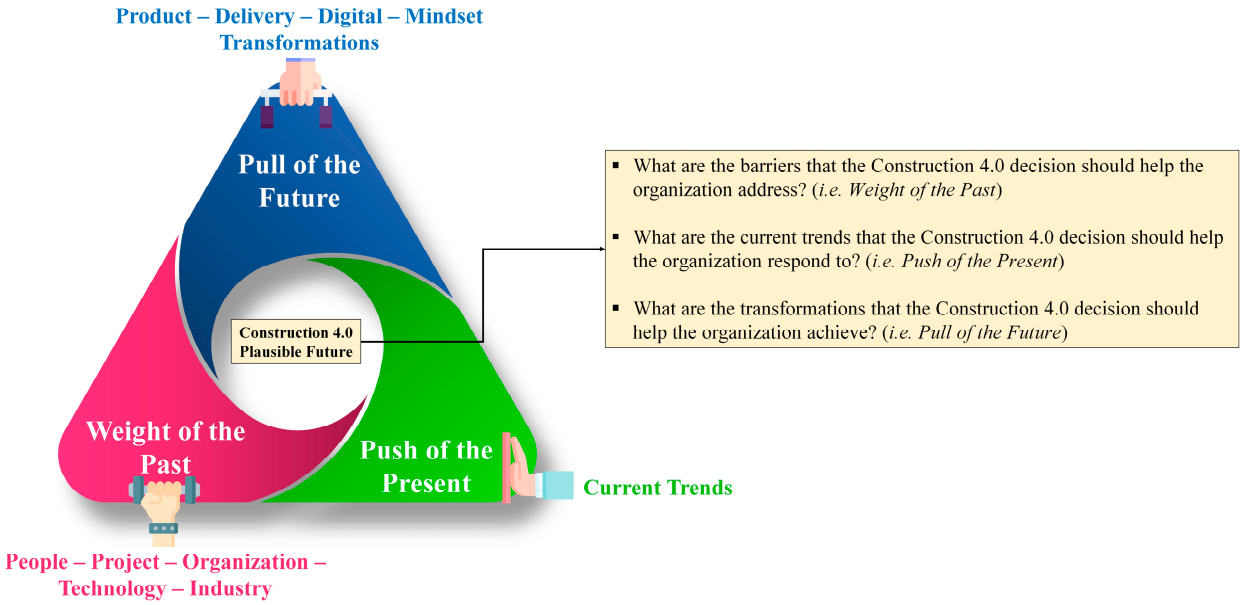


Figure 1. Conceptualization of CVPS4.0 via Futures Triangle.

3. Research Methodology

To achieve the desired objective, a three-step methodology was employed. First, existing research work was reviewed to identify the factors of the CVPS4.0 dimensions—i.e., the barriers (weight of the past), the current trends (push of the present), and the desired transformations (pull of the future). To do that, the Scopus database was used to identify relevant studies. Scopus is a valuable database for research due to its extensive coverage of peer-reviewed publications in the fields of engineering [42], its advanced search and citation analytics such as h-index and Source Normalized Impact per Paper (SNIP) to identify influential work efficiently [43,44], and its status as a globally recognized index for high-quality peer-reviewed research [45].

Relevant studies were identified by using a combination of keywords to identify AEC research ("Construction Industry", "AEC", "Built Environment", "Design", "Engineering", "Architecture"), screen for Construction 4.0 studies (such as "Industry 4.0", "Construction 4.0", "Technology", "Digitization", "Automation", "Technology Adoption", "Technology Implementation"), and develop the model and its elements (such as "decision", "value", "decision-making", "impact", "past", "barriers", "challenges", "present", "trends", "events", "future", "transformations", "goals", "objectives", "advantages"). The review also included reports and white papers published by government entities (like the European Union Construction Sector Observatory and the U.S. Bureau of Labor Statistics), industry partners (like Autodesk and Construction Industry Institute), and consultants (like McKinzey and PwC). The results of the review and the papers used are provided and explained in Tables 1–6. All the references were used to extract the elements of CVPS4.0—i.e., the barriers for the past dimension, the current trends for the present dimension, and the transformations for the future dimension.

After identifying the elements of CVPS4.0, a linear model was proposed and developed to quantify the value proposition of a Construction 4.0 decision. The model requires selecting the factors relevant to the organization, evaluating the impact of the decision on the selected factors, and weighing the impact of the three dimensions on the organization and the decision. The model was built into a spreadsheet to compute the value proposition and provide a visual summary of this impact.

Finally, a proof of concept for CVPS4.0 was conducted with a Construction 4.0 subject-matter expert (SME). The spreadsheet was first shared with the SME to analyze a Construction 4.0 decision that their organization is contemplating; then, a semi-structured interview was conducted to discuss the results. The SME is a virtual design and construction manager with more than 10 years of experience and extensive knowledge of Construction 4.0 technologies, as they are responsible for researching new technologies and implementing them in projects. The SME works at a large U.S. legacy construction firm that has been in business for almost 100 years, with projects spread across multiple states. The firm's revenue exceeds USD 1 billion annually with a diverse project portfolio including aviation, healthcare, education, residential, stadiums, and infrastructure. The SME used the proposed CVPS4.0 to evaluate and analyze the value of using robotics for site layout, wall layout; mechanical, electrical, and plumbing (MEP) layout; prefabrication of assemblies, and constructing assemblies on-site, as the construction firm is looking to adopt robots in projects in the next 2 years.

CVPS4.0 as a Linear Model

The research proposes a linear model to evaluate the value proposition for several key reasons. First, a linear model offers clarity and simplicity and illustrates exactly how each factor influences the outcome. This transparency facilitates understanding and justification for both expert and non-expert stakeholders, and, in many contexts, can outperform human judgment [46]. Additionally, a linear model prioritizes the most influential drivers, enabling decision-makers to discern the direction and relative magnitude of relationships among variables without being burdened by unnecessary complexity [47].

Moreover, CVPS4.0 incorporates factors from both current trends and anticipated future conditions, so its simplicity allows for the seamless integration of new factors as they emerge or gain relevance within an organization or industry [48]. Furthermore, this study addresses a significant research gap by providing a quantifiable approach to assessing the impact of Construction 4.0 decisions. Thus, the objective of CVPS4.0 is to serve as an initial benchmark through a simple linear model that offers a foundation for refinement and comparative analysis in future investigations.

Linear models are also widely employed for their comprehensiveness, simplicity, straightforwardness, and ease of incorporating multiple dimensions [49]. Examples of the use of linear models in construction management research and Industry 4.0 indices include the Project Quarterback Rating [50], the Augmented Reality Usage Potential [51], the generalized model for construction equipment management [52], and the Smart SME Technology Readiness Assessment [53].

4. Model Dimensions and Factors

Through synthesizing the existing literature, the following barriers, trends, and transformations were identified to represent the CVPS4.0 dimensions—i.e., the weight of the past, push of the present, and pull of the future, respectively.

4.1. Vertex of the Past: Weight of Project, People, Organization, Technology, and Industry

For the past few decades, the construction industry has suffered and continues to suffer from long-standing problems across various aspects. The relation between such problems and Construction 4.0 is interchangeable. On one hand, the existence of such problems can hinder the success of Construction 4.0. On the other hand, the vision cannot be successful unless it addresses the existing problems. Thus, these long-standing problems form the "weight of the past", and they can be broken into five aspects: projects, people, organizations, technology, and the industry.

4.1.1. The Aspect of Projects

The nature of construction projects highlights unique industry problems. Most projects are contract-based with limited flexibility in cost, schedule, and resources. Projects are also based on short-term relationships, where all parties unite for a short period to construct the project and relationships dissolve after it. Tasks are planned months if not years before they are executed, and most of the tasks are performed in uncontrolled and open environments. Moreover, the settings of construction sites are dynamic and not stationary, with various locations, surroundings, and distances from suppliers and service providers. Such a unique nature of projects makes them susceptible to major problems that have long affected construction projects, leading projects to finish behind schedule, over budget, and with high accident rates. Table 1 identifies the different project problems that weigh on the Construction 4.0 vision and elaborates on each of them in the context of the literature.

Table 1. Weight of the Past—Projects.

Project Barriers	Description
Overruns	Cost overruns and schedule overruns are major problems that constantly face construction projects, where projects are highly likely to go over budget and finish behind schedule [54,55].
Design Delays	Delays in design due to several factors such as starting late, delivering adequate drawings, lack of designer executive vision and inadequate experience, approval delays, and the unforeseen complexity of the project [56]. This comes in addition to design changes during construction due to inconsistencies, owner modifications, regulatory changes, and early tenders that give preference to budget over quality, energy efficiency, or environmental considerations [55].
Poor planning and scheduling	Poor planning and scheduling affect the availability of materials, equipment, tools, people, and other resources [55].
Poor safety performance	High accident rates cause fatal and non-fatal injuries resulting from the construction site's complex environment, low safety training, poor construction health and safety plans, and bad safety practices [55].
Material Issues	The long durations of construction projects may affect material supply and cost due to inflation and the possibility of shortage or scarcity, in addition to possible scenarios where the suppliers are unreliable, and/or the material can be delivered late or with low quality to the site [56,57]. Other material-related issues include no consideration of reusable material in the design stage, unsafe handling, and wrong material storage [58].
Equipment Issues	Machinery and equipment needed for the construction project can face delays, shortages, and defects—all of which can hinder the project's progress [56].
Undefined Value	Poor understanding of customer needs, lack of customer focus, and lack of understanding of what can add value to the project and what does not [59]. The common motion of measuring time and cost and meeting codes is not enough to make a project successful [59]. This is also associated with a lack of design and planning for quality [59].
Poor Communication	Poor communication and coordination between parties include weak communication means, unstructured or extensive useless meetings, and unstructured colleagues [60,61].
Decision Delays	Delays in making the critical decision whether at the level of the client, owner, contractor, consultant, or designer [56,57].
Poor Risk Management	Poor risk management and improper risk transfer and mitigation between key players [62].

Table 1. *Cont.*

Project Barriers	Description
Uncertainties	Uncontrollable risks such as weather conditions, natural disasters, political up-risings, problems with the community, unforeseen site conditions, and traffic surrounding the site [57].
Permit Delays	Delay in obtaining permits from involved authorities [63].
Claims and Litigation	A high number of litigations and claims are caused by conflicts due to different reasons such as overruns, change orders, delays, and mistakes and discrepancies in contracts [64,65].
Lack of 3Rs	Lack of 3Rs—Reduce, Reuse, and Recycle—strategies for waste management: minimization, collection, separation, storage, transportation, treatment, and disposal [58].
Slow Inspection	Slow quality inspection process for completed work whether control of production, quality checks, and internal or external quality assurance [60].
Site Management	Poor site management and quality control [66].

4.1.2. The Aspect of People

The construction industry is people-intensive, where most project tasks depend on several people performing different work, including administration, designing, engineering, inspection, and trades. In fact, the cost of labor can be as high as 40% of the total project budget. Thus, major people problems that are explained in Table 2 can form the weight of the Construction 4.0 vision.

Table 2. Weight of the Past—People.

Project Barriers	Description
Resistance to Change	Resistance to change and unwillingness to alter the existing culture and common practices that people feel safe in or are used to [67]. Moreover, there exists reluctance to innovation and creativity, and cultural barriers due to the traditional view and flexible vision [68]. Even though people prefer to see changes in the industry, they do not want to change what they are doing [59]. This can be due to managers fearing losses due to changes in the system, or employees fearing the unfamiliar practices and the new expectations of productivity and work quality [59].
Skill Shortage	Inadequately skilled labor with high job rotation, the rising average age of employees, and little turnover [55]. The sector is also unattractive to young employees due to different reasons such as safety, wages, and working conditions [57].
Seasonal Employment	The workforce in the construction industry is vulnerable because of the common use of temporary or seasonal employment mainly at the level of trade [69]. This leads to a fragile and short-term relationship between the organization and workers, with negative consequences such as inherent risk to life and limb and uncertain work hours [69].
Low Education and/or Literacy	Many workers, especially immigrant workers, have low language proficiency and/or low literacy, which makes it tougher to communicate on construction sites [70,71].

4.1.3. The Aspect of Organizations

Construction 4.0 disrupts all levels of the organization, creating a need to rethink processes and re-evaluate business models. Thus, organizations can become a weight as explained in Table 3.

Table 3. Weight of the Past—Organizations.

Project Barriers	Description
Supplier Dependency	Construction companies depend a lot on their suppliers in an estimated 60–70% of activities but lack "systematic or methodological agreements of interaction or co-development" with those suppliers [55,72].
Ineffective Knowledge Management	Ineffective knowledge management where companies limit the access to information and data from previous and ongoing projects, which in turn prevents lessons learned from spreading across organizational teams, such as "technical information, budget, execution times, deviations, incident handling, and on-site problem handling" [55].
Repetitive and Routine Activities	Repetitive routine activities in construction companies can sometimes become inefficient [55]. The lack of innovation and continuous improvement of such activities can be the result of restricted or unavailable data collection and a limited sharing of information [55].
Lack of Standardization	Lack of standardization notably for repetitive processes, where no standards are created or shared in the organization to gain knowledge and improve [66].
Lack of Supportive Programs	Absence of supportive programs that encourage and promote creativity, critical thinking, innovation, and motivation [68].
Administrative Bureaucracy and Organization Structure	Internal administrative procedures and bureaucracy within project organizations affect documenting, filing, reporting, archiving, and accessing information [60]. Hierarchies in the organization structure also hinder communication and coordination between teams, limiting learning processes, design efforts, innovation, and teamwork [59].
Lack of Long-Term Philosophy	The absence of long-term philosophy and planning, where achieving short-term financial goals takes precedence over basing decisions on long-term visions and focusing on value for customers [59].
Unsustainable Recruitment	Inappropriate methods of recruitment include limited internal hiring, phantom jobs, unrealistic requirements, and an emphasis on passive candidates [68,73].

4.1.4. The Aspect of Technology

Since Construction 4.0 brings the biggest changes to the technology aspect of the construction industry, it becomes extremely critical to address the technology-related barriers that can hinder the Construction 4.0 vision. Such barriers to technology weigh on the Construction 4.0 vision as explained in Table 4.

Table 4. Weight of the Past—Technology.

Project Barriers	Description
Uncertain ROIs	Implementation of technology can be costly in terms of hardware and software, which can make technology less appealing to organizations, especially those with uncertain ROIs [74,75].
Lack of Awareness	Lack of awareness of technology benefits and capabilities [1,75].
Need to Refine	Technology should be refined and enhanced to suit the dynamic and complex nature of construction environments, especially since sites are considered uncontrollable environments [1,74].

Table 4. *Cont.*

Project Barriers	Description
Unclear Legalities	Unclear legal framework and distribution for responsibilities and legal concerns regarding technology shortcomings [74,76].
Unclear Synergies	Unclear synergies and consistency between technologies, and the difficulty in adapting technology to work processes and organizational culture [75].
Lack of Lifecycle Adoption	Digital technologies are not equally spread and adopted in each of the different phases of the construction value chain. For example, not utilizing digital tools in the design phase might limit construction companies from using them in the next phases, as it would require additional work and investments to digitize the project [75,77].
Low R&D Investments	Low level of investments from construction companies in innovation and the absence of R&D departments to evaluate technology benefits [75,78].
Industry and Providers Gap	A growing gap between ICT providers, IT companies, and undigitized construction companies can further enhance the digital gap, as lower returns mean fewer resources to invest in digital technologies and training [75].
Security and Privacy Concerns	Rise in concerns over security risks when accessing common IT platforms, security breaches when using sensing technologies and devices, data privacy and confidentiality, and cybersecurity in the form of data ownership and autonomy when software data are stored in foreign databases [75,79].
Ownership and Governance	The absence of clear legal guidance causes legal and contractual uncertainty regarding the use, ownership, and sharing of responsibility when using data and digital technologies like 3D models [80].

4.1.5. The Aspect of Industry

The construction industry is characterized as "traditional", where it continues to depend on its traditional ways of doing business. Examples include traditional planning and scheduling using critical path methods, traditional project delivery methods, mainly design-bid-build, and traditional financial management in managing cash flows and payments. The traditional approaches cause the industry to trail behind in technology adoption and become heavily dependent on labor to complete tasks that can be enhanced by using technology. The industry barriers are explained in Table 5.

Table 5. Weight of the Past—Industry.

Project Barriers	Description
Extensive Regulations	Extensive public and private regulations that control the construction project environment can control the way tasks are executed and limit innovation such as consumer protection, safety, technical standards, and environmental standards [55]. This comes in addition to regulations that limit design flexibility and slow down innovative changes.
Restrictive Project Delivery Methods	Domination of restrictive types of project delivery methods and contracts used to execute projects, notably design-bid-build, lacks the involvement of stakeholders from the beginning of the project due to separating design from construction, undermines collaboration and integration, hinders the application of new techniques, and creates adversarial relationships between one party over the other [57,81].

Table 5. *Cont.*

Project Barriers	Description
Bad Image and Intentions	Fragmentation is due to the high diversity of agents involved in construction projects, where temporary alliances form between unequal companies that have different equipment, profiles, training, and culture [55]. In many cases, companies have different interests, and they care about finishing tasks as fast as possible to utilize resources for other projects [54]. Moreover, the temporary placement of the parties might not be enough to foster cooperation, build trust, and continuously improve, which decreases efficiency and effectiveness [59].
Corruption	The image of the construction industry translated into being less prestigious than other industries, with fewer career advancements, lower salaries, poor health and safety records, sensitivity to economic conditions, absence of technology, and fraud and corruption [82]. Different forms of corruption in the construction industry include bribery, fraud, collusion, bid rigging, embezzlement, kickbacks, conflicts of interest, dishonesty and unfair conduct, extortion, negligence, front companies, and nepotism [83]. A review of corruption in construction projects found that most studies were tailored to infrastructure projects in developing countries [84].
Negligence of Asset Management	Negligence of asset management and project lifecycle, where parties focus their concerns and resources on the ongoing project phase—whether it is design, planning, construction, commissioning, operation, decommissioning, or demolition—instead of focusing on the entire project lifecycle [55,85].
Poor Financial Management	Poor financial management between parties especially in scheduling and completing payments, and poorly managing financial documents, generates credibility issues and hinders the project's progress [55–57].
Domination of SMEs	The domination of SMEs in the construction industry restricts investment potential and pushes companies to rely on funding programs or collaborative partnerships to innovate [74]. SMEs struggle to attract a limited skilled workforce, as reflected in the low investment in developing/upgrading ICT skills: training and upskilling employees demand financial resources, which SMEs do not necessarily have; and once trained, those same employees' profiles will be of great interest to larger companies that can offer better wages than SMEs [75,80].

4.2. Vertex of the Present: Push of Current Trends

The vertex of the present, or the "push of the present", represents the current trends that are pushing the industry to a Construction 4.0 vision. These trends can either provide opportunities to innovate and implement Construction 4.0 solutions and/or accelerate the Construction 4.0 implementation. The trends are explained in Table 6.

Table 6. Push of the Present—Current Trends.

Project Barriers	Description
Lagging Productivity Growth	The industry's global annual labor productivity growth over the past 20 years was less than 1 percent, a rate that is significantly less than the productivity growth of the global economy, which was estimated at 2.8 percent per year [86].
Aging Workforce	According to the latest statistics of the Bureau of Labor Statistics (BLS), 44% of the total workforce in the construction industry in the U.S. (4.8 million workers) is above 44 years old, and the median age of the construction workforce is 42.5 [86,87].

Table 6. *Cont.*

Project Barriers	Description
Slow Innovation and Digitization	A fragmented value chain combined with a risk-averse culture impedes innovation and digitization in the construction industry. Building Information Modeling (BIM) adoption rates, for example, have reached just 60 to 70 percent in 35 years, with most of the adoption happening in the last few years [86].
Knowledge Loss	The project-based nature of the construction industry poses a challenge for construction stakeholders to effectively capture, share, use, and re-use knowledge, resulting in knowledge loss in the lifecycle of a construction project and among different projects [55]
Labor Shortage	Construction companies continue to grapple with labor shortages. Research shows that about 41% of the current US construction workforce is expected to retire by 2031. The construction industry lost 1 million workers during the initial COVID-19 pandemic shutdown and has yet to win back 1/5 of those workers. Most contractors (80–90%) also reported moderate to high difficulty finding skilled workers [86,88,89].
Reduced Flow of Young Workers	Data from BLS shows that the younger construction workforce (age 16–25) composes only 10% of the total construction workforce [87].
Great Resignation	The COVID-19 pandemic perpetuated the “Great Resignation” or “Big Quit”, where employees revaluated their work–life balance and quit their jobs [90]. The construction industry was also affected, with an average “quit rate” of 3.0 in November 2021—i.e., for every 100 construction workers that were working, three construction workers were quitting [90,91].
Strong Growth	An increase in approved spending bills notably in the infrastructure sector—such as the Infrastructure Investment and Jobs Act (IIJA) in the USA—is expected to increase construction spending and generate new demand for construction services, equipment, and materials [92].
Technological Advancement and Investments	As Construction 4.0 is poised to revolutionize the construction industry through technological advancements, construction companies are focusing on mergers and acquisitions (M&A) to form alliances with technology vendors and build new capabilities [93].
Diversity, Equity, and Inclusion (DEI)	Demographic changes are impacting the workforce, and major construction organizations are making DEI a priority through policies, initiatives, and actions [94].
Lean Construction	The rise of Lean construction with an increase in the adoption of Lean tools, principles, and methods [95].
BIM	BIM has transitioned from a “nascent idea” to an “industry-defining method” in the past decade. Adoption of BIM is significantly accelerating among different firms, including those in architecture, MEP, structural, civil, and construction, with higher intensity of usage in their projects [96].
Sustainability and Circular Economy	An increased push toward sustainable construction is due to the intensified attention on climate change, carbon emissions, energy consumption, water usage, and waste and pollution [97]. This is resulting in sustainability assessments of construction projects with an emphasis on environmental, social, economic, and governance dimensions [98]. Sustainability is also at the core of circular economy trends in the building and construction sectors, with an increase in research that emphasizes energy, materials, sustainable development, urbanism, green buildings, and green supply chains [99].

4.3. Vertex of the Future: Product, Delivery, Digital, and Mindset Transformations

The vision of Construction 4.0 can lead the organization to four major transformations: product transformation, delivery transformation, digital transformation, and mindset transformation.

4.3.1. Product Transformation

Product transformation is related to the main output of any construction project, which is the physical built environment asset that needs to be constructed [100,101]. The biggest change in utilizing the technological advancement of Construction 4.0 is to add more control to the construction site and transition from the traditional "stick-built" on-site environment to a more regulated "factory-like" environment [102,103]. This environment can be regulated by the integration, interconnectivity, and interoperability between technological advancement brought forward by Construction 4.0 whether tasks happen on-site, off-site, or between both [4,104]. Such advancement can include an interaction between five main pillars: robotic systems such as robots and drones, modeling and virtualization technologies such as BIM and augmented reality, data and information management through cloud systems and IoT, sensing technologies including RFID and tracking technologies, and artificial intelligence [103,105]. Moreover, the increase in the use of off-site construction such as prefabrication and modular construction can also mitigate the "effect of a one-of-a-kind peculiarity of the construction industry", improve standardization and workflow reliability, eliminate waste, and increase the ability to reuse resources [59]. The success of product transformation would allow organizations to clearly define the objective of the project and transparently share the objective between involved parties to assign the right people, perform the right tasks, and employ knowledge management for continuous improvement [56]. It will also help project stakeholders enhance communication and coordination and develop the competencies needed to manage finances, risk, resources, logistics, space, and sites [57,61,62].

4.3.2. Delivery Transformation

Delivery transformation is related to managing the delivery of the constructed project. The technological advancement introduced by Construction 4.0 can enhance the utilization of more integrative approaches to delivering construction projects, such as Integrated Project Delivery (IPD), Lean Project Delivery Systems (LPDS), Target Value Design (TVD), Last Planner system (LPS), and Location-Based Management Systems (LBMS) [95,106]. Collaborative delivery methods and approaches will enable the early inclusion of project stakeholders and key players from the beginning of the project [107]. This would reflect better project performance in different aspects, including health, safety, security, planning, and control [61]. Such delivery methods can also be enhanced with government provisions that legalize quality improvement and technology adoption, support people and training, support green initiatives, and reward adoption practices that support continuous improvement and minimize waste in materials and resources [59]. There is also a rise in the need for "sustainable and environmentally cautious" construction processes and projects. Such cautiousness includes reducing waste and limiting pollutants, chemicals, hazardous exposures, emissions, disturbance of natural landmarks, land degradation, disturbance of wildlife, and consumption of natural resources [58,81]. Construction 4.0 technologies can be at the center of this sustainable change [108].

4.3.3. Digital Transformation

Digital transformation is mainly related to linking the real physical environment to the cyber environment. The virtual or digital copies of the real world are an important pillar of

Construction 4.0, and the use of technologies can provide a cyber-physical connection with minimal human interference [2,109]. For example, during the construction phase, when a construction project initiates with a BIM model, this model can provide information to on-site personnel via augmented reality [110], regulate equipment, and track material via wireless sensors and RFID tags [111], and get updated to achieve an as-built model via drones or laser scanning [112]. In another example, during the maintenance and operation phase, data collected from the physical asset through technology such as sensors, laser scanning, and drones, can also be fed into the as-built BIM for decision-making and monitoring using AI and machine learning [113,114]. This relationship can also extend beyond the asset itself to the asset and its connection to its ecosystem in concepts known as Digital Twins [115]. Such a digital transformation can promote a more innovative working environment for the construction industry by replacing conventional conditions and improving collaborations among project players and between them and their customers [74]. With the dependency on gathering, sharing, analyzing, and storing data, it becomes important to develop standardized data formats and interoperability for the effective and successful deployment of technologies [75]. This can be achieved by identifying information required at various stages of the project and standardizing templates and formats for data types that can be understood and used by all actors involved in the project before, during, and after construction [75].

4.3.4. Mindset Transformation

Mindset transformation is related to changing the perspective of people, organizations, and the industry itself. People are the core of the construction industry, and no change initiative would succeed without them [1,116]. The technological advancement brought forward by Construction 4.0 does not replace people but rather changes their roles and responsibilities [1]. Organizations should "adopt and adapt technology that supports an organization's people and processes", where the starting point is to understand "where are real needs that technology can address to help achieve your goals?" and "pulling the technology based on the opportunity, instead of pushing the technology because it is the latest fad" [117]. Organizations should also access a qualified workforce by attracting, developing, and retaining skilled and qualified talents who are trained in the fields of ICT safety, digital communication, data processing, and digital content creation [75]. The new workforce should be trained to communicate and work in digital environments and with digital data, understand the concept of data protection, and understand the precautions to take for safely managing sensitive data [75]. At the level of the industry, a mindset transformation would include adding (1) a transparency mechanism where the public can access information to monitor project performance and hold decision-makers accountable, (2) an ethical code with ethical training programs and rewards for ethical behavior, (3) project governance with good leadership and possible separation of project ownership from regulatory functions within government, (4) audit and information technology, and (5) a debarment system to record companies and individuals guilty of corruption to combat dishonesty and fraud [83].

5. Model Proposition

The equation for the model is shown in Formula (1), where it represents the summation of the product of the evaluation of every dimension by its weight.

$$CVPS4.0 = \sum_{d=1}^{3} LC_d \times LE_d \quad (1)$$

where d represents the dimensions ($d = 1$ for "weight of the past", $d = 2$ for "push of the present", and $d = 3$ for "pull of the future"), LE_d represents the distribution of the "Level of Effort" of the organization on every dimension, and LC_d represents the "Level of Contribution" of the decision on every dimension. The calculation process is explained in the three steps below.

5.1. Step 1—Calculating the Level of Contribution (LC_d) for Every Dimension

For every dimension, the decision-maker investigates three aspects. First, they determine whether each past barrier, current trend, or future transformation applies to the organization. Second, they assess whether the decision enables the organization to address the applicable past barriers, respond to the applicable current trends, and achieve the applicable future transformations. If the decision does not address a barrier, respond to a trend, or achieve a transformation, the third aspect involves determining whether that barrier, trend, or transformation is even relevant to the decision. This third aspect ensures that a decision's value is not reduced simply because it was never intended to address the factors under consideration. The logic is illustrated in Figure 2.

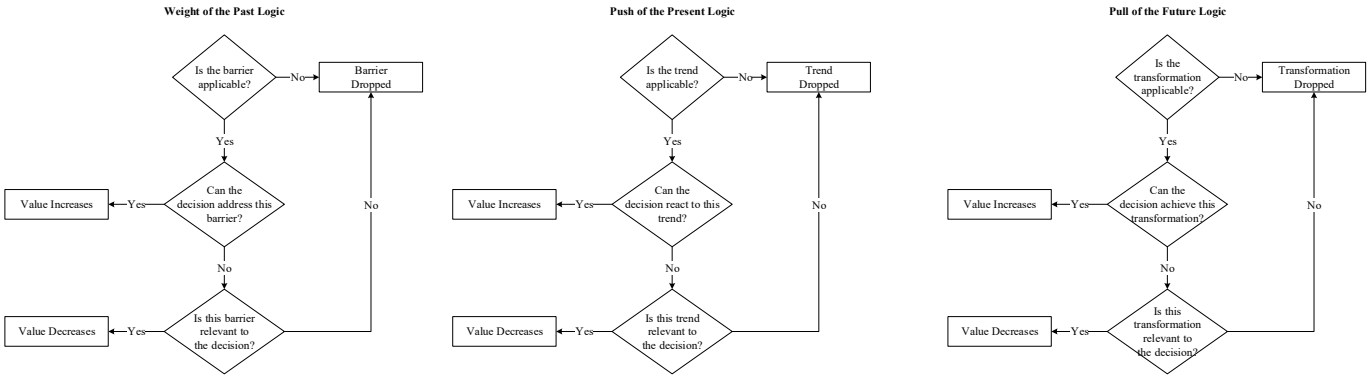


Figure 2. Logic for CVPS4.0 calculation.

After that, the user-selected choices in every dimension are transformed into an $(i \times j)$ matrix where i is equal to the number of factors (representing one row per factor) and j is equal to 3 (representing one column for every investigated aspect). All "Yes" answers are given a value of 1, and all "No" answers are given a value of 0. Then, the (LC_d) for every dimension is calculated using Formula (2a) and Formula (2b) where b stands for barriers presented by the "Weight of the Past", t stands for trends presented by the "Push of the Present", and f stands for future transformations presented by the "Pull of the Future".

Formula (2a) is used to calculate the "practical contribution" where the decision value is not penalized for the barriers, trends, or transformations that are not relevant to it, and Formula (2b) is used to calculate the "organization-tailored practical contribution" where the decision value is penalized for the barriers, trends, or transformations that are not relevant to it.

$$LC_d = \begin{cases} \sum_{i=1}^{45} \frac{b_{i,2}}{b_{i,2} + b_{i,3}} \; for \; d = 1 \\ \sum_{i=1}^{13} \frac{t_{i,2}}{t_{i,2} + t_{i,3}} \; for \; d = 2 \\ \sum_{i=1}^{4} \frac{f_{i,2}}{f_{i,2} + f_{i,3}} \; for \; d = 3 \end{cases} \quad (2a)$$

$$LC_d = \begin{cases} \sum_{i=1}^{45} \frac{b_{i,2}}{b_{i,1}} \; for \; d = 1 \\ \sum_{i=1}^{13} \frac{t_{i,2}}{t_{i,1}} \; for \; d = 2 \\ \sum_{i=1}^{4} \frac{f_{i,2}}{f_{i,1}} \; for \; d = 3 \end{cases} \quad (2b)$$

Figure 3 shows an example of computing LC_2 for a sample decision (level of contribution for Push of the Present, i.e., dimension 2). In the sample decision:

- The trend of "Lagging Productivity Growth" applies to the organization, and the decision helps the organization react to it, resulting in $t_{1,1} = 1$ and $t_{1,2} = 1$;
- The trend of "Knowledge Loss" applies to the organization, but the decision does not help the organization react because the trend is not relevant to the decision (in other words, the decision is not designed for this trend), resulting in $t_{4,1} = 1$, $t_{4,2} = 0$ and $t_{4,3} = 0$;
- The trend of "Reduced Flow of young Workers" applies to the organization, but the decision does not help the organization react even though the trend is relevant to the decision (in other words, the decision has the potential to react to the trend but it is falling short of doing it), resulting in $t_{6,1} = 1$, $t_{6,2} = 0$, and $t_{6,3} = 1$.
- The same concept applies to all other trends. After assessing all trends, LC_2 (Formula (2a)) is 0.571, indicating that the decision has a practical contribution of 57% (excluding the trends that the decision is not designed to react to), and LC_2 (Formula (2b)) is 0.444, indicating that the decision has an organizational contribution of 44% (including the trends that the decision is not designed to react to).

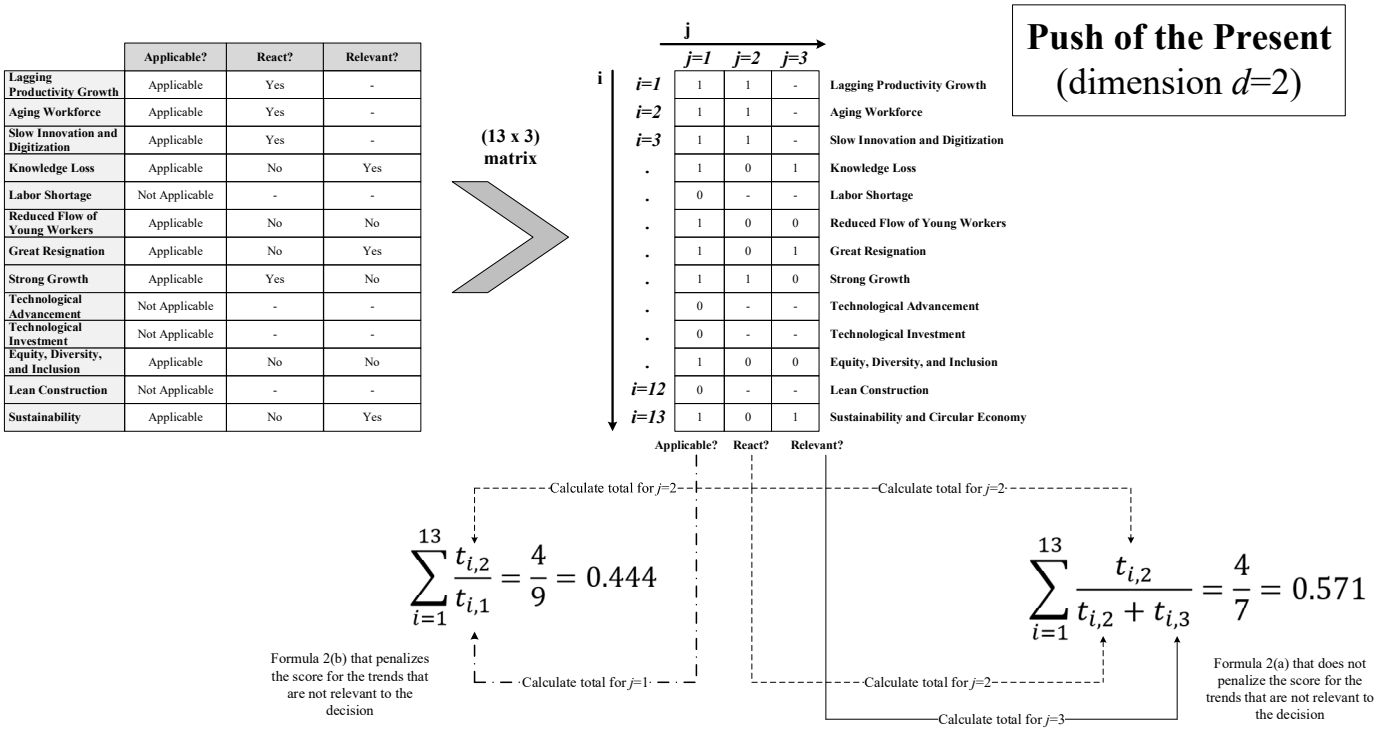


Figure 3. Sample example for LC2 computation (i.e., level of contribution for dimension 2: Push of the Present.

5.2. Step 2—Calculating the Level of Effort (LE_d) for Every Dimension

While the past, present, and future dimensions contribute to the decision-making process, the level of effort the organization places on every dimension is not necessarily

equal. The AEC industry involves a big number of players such as owners, vendors, architects, contractors, consultants, and subcontractors, and they all differ in age, size, resources, culture, processes, and notably decision-making regarding Construction 4.0 [16,55,105]. Moreover, an organization's experience, knowledge management competency, lessons learned, relationships with customers and suppliers, and satisfaction of clients have a significant influence on achieving a successful performance and in turn making sound decisions [118,119].

Thus, users need to identify how the effort of their organization should be divided between reducing and overcoming barriers (LE_1), reacting to current trends (LE_2), and responding to future transformations (LE_3). If the effort is distributed equally, then $LE_1 = LE_2 = LE_3 \approx 0.33$. If the effort is not distributed equally, then the user needs to specify the distribution of the level of effort or perform Analytic-Hierarchy-Process (AHP) by performing the three simple pairwise comparisons. The AHP was embedded in the worksheet to compute the effort distribution once the user performs the three pairwise comparisons (comparing past to present, comparing past to future, and comparing present to future). AHP was selected due to its simplicity and popularity as a decision-making tool in construction management to rank and weigh alternatives [120,121].

5.3. Step 3—Calculating the Score

The value proposition score will be computed using Formula (1). The CVPS4.0 score will be the score that uses Formula (2a) for the level of contribution of every dimension. The organization-tailored value proposition score will also be provided as a holistic reference. The maximum value proposition score that a decision can achieve is 1, while the minimum score is 0. The closer the score is to 1, the more value the decision provides to the organization's Construction 4.0 vision. The following score classification can be considered:

$$If\ the\ CVPS4.0 = \begin{cases} 0 \leq CVPS < 0.25 \rightarrow Decision\ has\ marginal\ value \\ 0.25 \leq CVPS < 0.5 \rightarrow Decision\ warrantes\ further\ investigation \\ 0.5 \leq CVPS < 0.75 \rightarrow Decision\ shows\ promising\ value \\ 0.75 \leq CVPS \leq 1 \rightarrow Decision\ has\ significant\ value \end{cases}$$

6. Model Proof of Concept

To prove the concept of the model, a spreadsheet-based tool was developed and shared with a subject-matter expert (SME) to evaluate the value of a Construction 4.0 decision. The SME used the proposed model to evaluate and analyze the value of using robotics for site layout, wall layout; mechanical, electrical, and plumbing (MEP) layout; prefabrication of assemblies, and constructing assemblies on-site. The results of the evaluation are explained below, and the detailed evaluations are provided in Figure A1 and Table A1 (in Appendix A).

6.1. Level of Contribution

The value that the decision to adopt robotics contributes to the weight of the past aspect depends on its ability to address the project, people, organization, technology, and industry-related barriers identified in Tables 1–5. Starting with project-related barriers, all 16 barriers applied to the contracting firm. As reported by the SME, the decision can address four of the barriers (*overruns*, *poor safety performance*, *poor communication*, *lack of 3Rs*, and *site management*), but is not designed to address nine barriers (*design delays*, *material issues*, *equipment issues*, *undefined value*, *decision delays*, *poor risk management*, *permit delays*, *claims and litigation*, and *slow inspection*), and falls short of addressing the following two barriers:

- *Poor Planning and Scheduling*: The early stages of implementing robotics can speed up the execution of the task, but enhancing the planning and scheduling phase is more of a long-term benefit. Information needs to be collected from piloting and using the robots on different projects to be able to potentially utilize it in optimizing the process of planning and scheduling activities.
- *Uncertainties*: As of where the technology stands now, it cannot operate by itself without the presence of people on the site. With uncertain events like weather and natural disasters shutting down the construction sites, the robots will not be operating as well.

As for people-related barriers, all four barriers apply to the contracting firm. The decision can address three of them (resistance to change, skill shortage, and *seasonal employment*), notably with the robot's ability to solve labor and skill shortage. The decision is not designed to address only one barrier (*low education and/or literacy*).

Five of the eight organization-related barriers apply to the contracting firm. Robots' ability to perform the repetitive tasks and add standardization can address two of the barriers (*repetitive and routine activities* and *lack of standardization*), but the use of robotics is not designed to address the remaining three applicable barriers (*supplier dependency*, *ineffective knowledge management*, and *administrative bureaucracy and organization structure*).

Five of the 10 technology-related barriers are also applicable to the contracting firm. The decision can address three of the barriers (*uncertain ROIs*, *need to refine*, and *ownership and governance*), is not designed to address one of them (*security and privacy concerns*), and falls short of addressing the following barrier:

- *Lack of lifecycle adoption*: The technology will be adopted to perform tasks that are only performed in the construction phase of the project. The technology could be used in other phases in the long term (such as using its data to optimize planning and scheduling or using the project for operation or demolition phases), but this is not part of the current state of the decision.

As for industry-related barriers, two barriers apply to the contracting firm, and both can be addressed by the decision (*extensive regulations* and *restrictive project delivery methods*).

Regarding the push of the present, the decision to use robotics can add value to the different current trends that are affecting the contracting firm. The contracting firm is affected by 12 of the 13 current trends (all except *equity*, *diversity, and inclusion*). The use of robotics can help the firm react to 11 of the applicable trends, but it is not designed to react to one trend (*knowledge loss*).

Regarding the pull of the future, all four transformations are part of the firm's vision to change its status quo. The decision to use robotics helps the firm achieve all four transformations as well.

Thus, to calculate the level of contribution of the decision to the Construction 4.0 value proposition score:

- For the weight of the past, the decision can help the firm address 15 of the 32 applicable barriers, is not designed to address 13, and falls short in addressing 4 barriers. Thus:

$LC_1 = 15/(32-13) = 0.79$ using Formula (2a) for $d = 1$ for the decision's practical contribution (excluding whether the decision is not designed to address the barrier)
$LC_1 = 15/32 = 0.47$ for the decision's organization-tailored practical contribution (excluding whether the decision is not designed to address the barrier)

- For the push of the present, the decision can help the firm react to 11 of the 12 applicable trends and is not designed to react to 1 trend. Thus:

$LC_2 = 11/(12-1) = 1$ for the decision's contribution excluding whether the decision is not designed to react to the trend

$LC_2 = 11/12 = 0.92$ for the decision's contribution including whether the decision is not designed to react to the trend

- For the pull of the future, the decision can help the firm achieve 4 of the 4 applicable transformations. Thus:

$LC_3 = 4/4 = 1$ for the decision's contribution excluding whether the decision is not designed to achieve the transformation
$LC_3 = 4/4 = 1$ for the decision's contribution including whether the decision is not designed to achieve the transformation

6.2. Level of Effort

According to the SME, the levels of effort placed for this decision on the weight of the past, the push of the present, and the pull of the future are not equal. An AHP exercise was carried out to calculate the distribution as illustrated in Figure A1. With an accepted consistency ratio of 0.7% (which is less than the 10% threshold), the results of the pairwise comparisons (highlighted in blue in the figure) translate into the following:

- For the weight of the past, $LE_1 = 0.088$
- For the push of the present, $LE_2 = 0.669$
- For the pull of the future, $LE_3 = 0.243$

6.3. Score (CVPS4.0)

The Construction 4.0 value proposition score for this decision is as follows:

Using Formula (2a), $CVPS4.0 = 0.088 \times 0.79 + 0.669 \times 1 + 0.243 \times 1 = 0.979$, excluding whether the decision is not designed to address the barrier/react to the trend/achieve the transformation.

As for the organization-tailored practical score using Formula (2b), the $reference\ score = 0.088 \times 0.747 + 0.669 \times 0.92 + 0.243 \times 1 = 0.922$, including whether the decision is not designed to address the barrier/react to the trend/achieve the transformation.

Thus, the decision adds value to the contracting firm as its CVPS4.0. Even with the decisions that technology is not designed to address, the score is significantly high.

6.4. SME Feedback

The SME found the spreadsheet tool and the score extremely helpful for the decision-making process. First, the SME expressed that the list of barriers, trends, and transformations was very comprehensive, which allowed them to re-evaluate the decision from different perspectives. Second, the SME found great value in the ability to communicate the score with upper management and/or leadership. For many decisions, especially technology decisions, it is hard to communicate or express the value when no feasibility or ROI studies are or can be performed, and this score can serve as a holistic substitute. Moreover, the comprehensive lists of barriers, trends, and transformations can also be used to communicate the strengths and weaknesses of the decision and how it reflected in the resulting score.

7. Conclusions

This study proposed a "Construction 4.0 Value Proposition score" or "CVPS4.0", a holistic score that can be computed and used by Architecture, Engineering, and Construction (AEC) organizations to understand, analyze, and communicate the value proposition of Construction 4.0 decisions. The score is based on the "Futures Triangle" theory, as the model investigates the decision's ability to address barriers faced by the organization, react to current trends that are driving the organization to change, and achieve transformations

that are pulling the organization toward a better future. A total of 45 barriers, 13 trends, and four transformations were identified and defined through a literature review performed using the Scopus database. A proof of concept for the score was presented with a Construction 4.0 SME, where the expert analyzed the value of using robotics for site layout, wall layout; mechanical, electrical, and plumbing (MEP) layout; prefabrication of assemblies, and constructing assemblies on-site. The SME found the exercise and the score extremely helpful for the decision-making process, notably in thinking about the value, brainstorming use cases, and communicating the decision to obtain buy-in from upper management.

7.1. Research Contribution

The study provides major contributions to the AEC body of knowledge in two ways. First, the study provides a reference to the past barriers, current trends, and future transformations shaping organizations in the era of Construction 4.0. This comprehensive overview serves as a shared knowledge base for interdisciplinary research in the area of Construction 4.0, improves the accessibility of dispersed knowledge into one source, and provides a standardized baseline for cross-study comparisons.

Second, the proposed model to holistically quantify the value of Construction 4.0 decisions represents the first attempt to evaluate a decision's value proposition using a scientific thinking approach. This model enables decision-makers to prioritize investments in Construction 4.0 innovations, support data-driven strategic planning, ensure stakeholder alignment and buy-in, identify possible risks associated with technological adoption, and foster continuous improvement to maximize the potential of their decisions.

7.2. Research Limitations

Similarly to other decision-making models, this research has certain limitations. The primary objective was to utilize the existing research corpus to present a linear model capable of quantifying the value proposition of Construction 4.0 decisions. While a proof of concept was presented to demonstrate the model's practicality, the intent was to ground the model in the existing literature rather than through the collection of quantitative data or real-life applications. Consequently, future research should aim to test the model across diverse AEC organizational types, sizes, and geographic contexts. Although the linear model is appropriate for the purpose of this study, such models are inherently simple, assume independence unless interaction terms are explicitly included, and may have limited predictive power in complex environments. Therefore, while CVPS4.0 represents an important contribution to bridging a research gap in organizational decision-making for the AEC sector, it should be viewed as a foundational framework upon which more sophisticated models can be developed.

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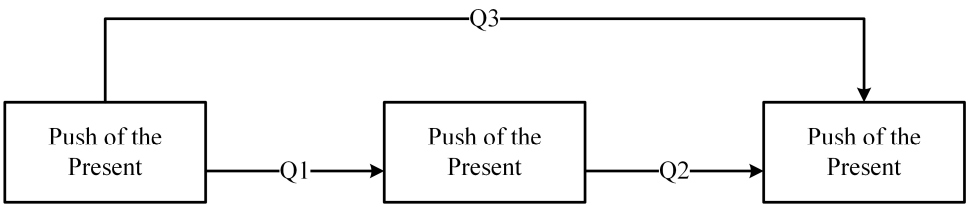
Conflicts of Interest: Makram Bou Hatoum was employed by the company Pyrovio. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CVPS4.0	Construction 4.0 Value Proposition Score
AEC	Architecture, Engineering, and Construction

Appendix A



Q1: To what extent is the Push of the Present (PP) more important than the Pull of the Future (PF)?

- PP and PF are equally important
- **PP is moderately more important than PF (i.e. PP is 3 times more valued than PF)**
- **PP is strongly more important than PF (i.e. PP is 5 times more valued than PF)**
- PP is very strongly more important than PF(i.e. PP is 7 times more valued than PF)
- PP is extremely more important than PF (i.e. PP is 9 times more valued than PF)

Q2: To what extent is the Pull of the Future (PF) more important than the Weight of the Past (WP)?

- PF and WP are equally important
- **PF is moderately more important than WP (i.e. PF is 3 times more valued than WP)**
- PF is strongly more important than WP (i.e. PF is 5 times more valued than WP)
- PF is very strongly more important than WP(i.e. PF is 7 times more valued than WP)
- PF is extremely more important than WP (i.e. PF is 9 times more valued than WP)

Q3: To what extent is the Push of the Present (PP) more important than the Weight of the Past (WP)?

- PP and WP are equally importantT
- PP is moderately more important than WP (i.e. PP is 3 times more valued than WP)
- PP is strongly more important than WP (i.e. PP is 5 times more valued than WP)
- **PP is very strongly more important than WP(i.e. PP is 7 times more valued than WP)**
- PP is extremely more important than WP (i.e. PP is 9 times more valued than WP)

Figure A1. AHP results from subject-matter expert.

Table A1. Results of the case study, evaluations as performed by the subject-matter expert.

Factor	Applicable?	Contribute?	Why/Why Not Relevant?
Overruns	Yes	Yes	Using robots will speed up the layout process.
Design Delays	Yes	No	The decision is not designed to address this barrier.

Table A1. *Cont.*

Factor	Applicable?	Contribute?	Why/Why Not Relevant?
Poor Planning and Scheduling	Yes	No	It will require piloting as well as using robotics on some projects to gather enough data that can be used to optimize planning and scheduling, notably for the layout processes. This is more of a long-term benefit than a short-term one.
Poor Safety Performance	Yes	Yes	Using robotics will decrease the hazardous risks that workers may face when performing these tasks.
Material Issues	Yes	No	The decision is not designed to address this barrier.
Equipment Issues	Yes	No	The decision is not designed to address this barrier.
Undefined Value	Yes	No	The decision is not designed to address this barrier.
Poor Communication	Yes	Yes	The successful use of robotics would require proper communication between workers on-site, and strong collaboration to create accurate design plans off-site.
Decision Delays	Yes	No	The decision is not designed to address this barrier.
Poor Risk Management	Yes	No	The decision is not designed to address this barrier.
Uncertainties	Yes	No	As long as layout robotics cannot operate with workers present next to them or on-site, the ability to perform work in uncertain events remains limited.
Permit Delays	Yes	No	The decision is not designed to address this barrier.
Claims and Litigation	Yes	No	The decision is not designed to address this barrier.
Lack of 3Rs	Yes	Yes	Using robotics will decrease waste generation.
Slow Inspection	Yes	No	The decision is not designed to address this barrier.
Site Management	Yes	Yes	Using robotics will improve site management and enhance quality control.
Resistance to Change	Yes	Yes	Addressing this barrier is conditional—only success stories from using robotics on layout tasks can address resistance to this technology.
Skill Shortage	Yes	Yes	Using robotics can solve the problem of the unavailability of skilled workers.
Seasonal Employment	Yes	Yes	Using robotics can solve the problems caused by skilled workers.
Low Education and/or Literacy	Yes	No	The decision is not designed to address this barrier.
Supplier Dependency	Yes	No	The decision is not designed to address this barrier.
Ineffective Knowledge Management	Yes	No	The decision is not designed to address this barrier.
Repetitive and Routine Activities	Yes	Yes	Robotics is designed for performing repetitive tasks on-site.
Lack of Standardization	Yes	Yes	Robotics can standardize the performance of on-site activities, notably those of a repetitive nature.
Lack of Supportive Programs	No	-	
Administrative Bureaucracy			
and Organization Structure	Yes	No	The decision is not designed to address this barrier.
Lack of Long-Term Philosophy	No	-	

Table A1. *Cont.*

Factor	Applicable?	Contribute?	Why/Why Not Relevant?
Unsustainable Recruitment	No	-	
Uncertain ROIs	Yes	Yes	The use of robotics on-site can provide enough data to perform ROIs.
Lack of Awareness	No	-	
Need to Refine	Yes	Yes	The use of robots adds more control to the construction project environment.
Unclear Legalities	No	-	
Unclear Synergies	No	-	
Lack of Lifecycle Adoption	Yes	No	The current use of robotics will restrict it to the construction phase. When more data is captured, it can be used in other phases such as design and operations.
Low R&D Investments	No	-	
Industry and Providers Gap	No	-	
Security and Privacy Concerns	Yes	No	The decision is not designed to address this barrier.
Ownership and Governance	Yes	Yes	The successful use of robotics will require detailed plans and drawings, and designers should provide accurate 3D models.
Extensive Regulations	Yes	Yes	Extensive public and private regulations control the project documents and the construction project environment, and in turn, restrict how certain tasks can be executed. The successful use of technologies like robotics can loosen such regulations and support innovative best practices that make construction tasks more efficient,
Restrictive Project Delivery Methods	Yes	Yes	The successful use of robotics will require early communication and collaboration between project stakeholders to ensure accurate 3D models and drawings from the designer's side.
Bad Image and Intentions	No	-	
Corruption	No	-	
Negligence of Asset Management	No	-	
Poor Financial Management	No	-	
Domination of SMEs	No	-	
Lagging Productivity Growth	Yes	Yes	The use of layout robotics will improve the productivity of critical tasks and in return improve the projects' performances.
Aging Workforce	Yes	Yes	The use of layout robotics can automate processes and reduce labor and skill requirements.
Slow Innovation and Digitization	Yes	Yes	The use of layout robotics will increase digitization, especially with the need for accurate designs, drawings, and 3D models.
Knowledge Loss	Yes	No	The decision is not designed to address this barrier.
Labor Shortage	Yes	Yes	The use of layout robotics can automate processes and reduce labor and skill requirements.

Table A1. *Cont.*

Factor	Applicable?	Contribute?	Why/Why Not Relevant?
Reduced Flow of Young Workers	Yes	Yes	The use of layout robotics would create a tech-savvy reputation and provide the organization with use cases to attract the young generation.
Great Resignation	Yes	Yes	The use of layout robotics can automate processes and reduce labor and skill requirements.
Strong Growth	Yes	Yes	The use of layout robotics will improve project performance and allow the company to attract more projects.
Technological Advancement and Investments	Yes	Yes	The use of layout robotics will increase digitization and promote automation and improvements in technology.
Equity, Diversity, and Inclusion (EDI)	No	-	
Lean Construction	Yes	Yes	The use of robotics standardizes the performed tasks, reduces waste, and adds value to the project.
Building Information Modelling	Yes	Yes	The use of robotics depends on collaborative and accurate 3D models and in turn BIM.
Sustainability	Yes	Yes	The use of layout robotics reflects sustainable construction approaches.
Product Transformation	Yes	Yes	The use of robotics will transform the construction site by adding more control to the project environment.
Delivery Transformation	Yes	Yes	The use of robotics will promote the early collaboration and involvement of project stakeholders to successfully use the robots for the desired tasks.
Digital Transformation	No	Yes	The use of robotics will promote digitization as it will rely on cyber data and 3D models to automate the execution of tasks on-site (i.e., in the physical project environment).

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