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ASSESSING SOCIAL, TECHNICAL, AND OPERATIONAL MATURITY DIMENSIONS FOR DIGITAL TRANSFORMATION IN THE CONSTRUCTION PHASE

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ABSTRACT

The importance of digital transformation (DT) has risen significantly in the past few years in several industry sectors, including construction. Some potential benefits of DT in construction include improvements in productivity, efficiency, safety, quality, and collaboration. However, fully embracing DT opportunities involves committed efforts in Key Project Areas (KPAs), and identifying these areas is still challenging. Therefore, this work aims to assess social, technical, and operational maturity dimensions for digital transformation in the construction phase. These dimensions are the KPAs construction managers should focus on throughout the construction environment DT process. A questionnaire was administered to 54 construction professionals from industry and academia. Data collected was analyzed using ranking analysis from the Relative Importance Index (RII) calculation. Results revealed that the participants did not rank technical aspects as the most significant; rather, these aspects were regarded with slightly less importance than other dimensions. The balance among social, technical, and operational factors in the ranking indicates that construction professionals recognize the insufficiency of technology implementation alone for driving significant changes; instead, human resources must lead the process improvement with the support of digital technologies. These findings align with Industry 5.0 and Lean Construction concepts, reflecting some synergies between them.

KEYWORDS

Digital transformation, Construction phase, Industry 5.0, Lean construction.

INTRODUCTION

Digital transformation has become a high-priority agenda theme for organizations and governments due to its competitive advantage in many sectors, including construction (Zomer et al., 2019). According to Tilson, Lyytinen, and Sorensen (2010), digitalization is "a sociotechnical process of applying digitizing techniques to broader social and institutional contexts that render digital technologies infrastructural." It is a deep transformation of business

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activities, processes, competencies, and models to embrace the changes and opportunities offered by digital technologies and their influence across society (Demirkan et al., 2016).

The emergence of Industry 4.0 in the construction industry (Construction 4.0) seeks to transform it towards digitally developed businesses (Alaoul et al., 2018). The industry definition of Industry 4.0 for construction encompasses several interdisciplinary technologies and concepts that enable the digitization, digitalization, automation, and integration of the construction process at different phases (Oesterreich & Teuteberg, 2016). González et al. (2022) presented the novel concept of Lean Construction 4.0, a Process-People-Technology Functional Model based on the idea that Lean Thinking can be the steppingstone for an effective adoption of IR 4.0 in construction. According to this approach, IR 4.0 technologies can potentially eliminate or reduce any of the seven Lean wastes identified originally by Shingo et al. (2005) and Taiichi (1988), while Lean Thinking supports eliminating waste and adding value, supporting a solid and efficient Industry 4.0 development and implementation.

In 2020, the concept of Industry 5.0 was launched to address challenges faced by environments under Industry 4.0 transformations, such as lack of resilience, insufficient attention to sustainable production approaches, and overemphasis on technology (Olah et al., 2020; Sindwani et al., 2022; Zizic et al., 2022). Industry 5.0 advocates balanced human-machine cooperation focusing on the diverse stakeholders' well-being (i.e., society, companies, human resources, and clients) (Noble et al., 2022). The application of Industry 5.0 in construction is still in its early stages.

According to Sony and Naik (2020), human-machine collaborations should be guided by the sociotechnical transformation. The sociotechnical systems approach concentrates on incorporating technology into the work system rather than focusing mainly on technology (Sackey et al., 2015). It is based on the observation that a successful technology implementation involves fully understanding the organizational context (structure, work, and workforce) (Sackey et al., 2015). While the original approach (Trist, 1981) describes a sociotechnical system as a combination of the social and technical subsystems, Vlachos et al. (2021) add the operational system, which, according to Fernandes and Costa (2024), is more suitable for construction environments.

Furthermore, incorporating digital technologies into construction environments can enhance productivity, safety, quality, and project management (Maskuriy et al., 2019). However, Joppen et al. (2019) highlight the challenges of measuring these transformations. Even though many analyses describe changes due to digital transformation, the instruments for recording them with the support of indicators are still poorly discussed (Joppen et al., 2019). Unlocking the advantages of technological advancement involves understanding how these transformed processes should be assessed and managed using assessment tools such as maturity models (Kloviene & Uosyte, 2019). In addition, to fully embrace IR 4.0 opportunities, managers should devise a strategy focused on Key Project Areas (KPAs) (Maskuriy et al., 2019). Nevertheless, identifying these KPAs remains challenging, and the existing literature still needs to explore this gap further. Considering a new sphere of knowledge, it is not possible to identify them only from the literature, and exploratory research methods, such as case study interviews (De Bruin et al., 2005), surveys, and on-site immersions, should be considered in this process.

Therefore, this work assesses social, technical, and operational maturity dimensions for digital transformation in the construction phase. These dimensions are the KPAs that need to be measured and managed throughout DT in the construction phase. This paper presents one stage of broader research in the context of a Ph.D. thesis, which aims to propose a Maturity Measurement System for an Intelligent Construction Environment, positioning the construction industry in the digital transformation path from a sociotechnical perspective. The first product of the Ph.D. work was a conceptual model for measuring the maturity of digital transformation in the construction phase (Fernandes & Costa, 2024). This model introduced 24 maturity dimensions (categorized into sociotechnical subsystems), which are the critical aspects construction managers should focus on and manage throughout the digital transformation process of the construction environment. The assessment of these dimensions is presented in this paper. The model is further presented in the Literature Review section.

This work's primary practical contribution is a preliminary proposition of measurable domain areas essential for continuous improvement, assessed in terms of importance, which directs construction projects toward an Intelligent Construction Environment. Theoretical contributions include insights into the challenges the Industry 4.0 technology-centric approach poses, potentially hindering the proper integration of these advancements into the construction sector. Additionally, the study explores the role of Industry 5.0 principles in this context and their potential synergies with Lean Construction concepts.

THE SOCIOTECHNICAL APPROACH IN THE DIGITAL TRANSFORMATION CONTEXT

A system is a social construct encompassing several relationships between elements expressed differently (Patriarca et al., 2021). Emery and Trist (1960) originally used the term "sociotechnical system" (STS) to describe systems that involve a complex interaction among humans, machines, and the environment in the work system. This approach considers that a change in one part of the system will lead to changes in other parts (Sony & Naik, 2020).

In the digital transformation context, Sony and Naik (2020) point out that, in addition to the integration of the cyber and physical domains through technology, Industry 4.0 is also a social (human-related) and technical (non-human-related) system. The sociotechnical approach unveils new opportunities for prompt development based on recognizing the importance of human work in the innovation process (Kagermann et al., 2013). According to Hirsch-Kreinsen et al. (2018), Industry 4.0, from a sociotechnical perspective, comprises the subsystems of technology, organization, and people and the interface among them. Patriarca et al. (2021) present the evolution of a sociotechnical system toward a Cyber-Socio-Technical System (CSTS). The CSTS extends to the social relations between humans and cyber artifacts and the collaboration of multiple cybernetic artifacts (Patriarca et al., 2021).

Furthermore, Vlachos et al. (2021) present a sociotechnical system as a combination of social, technical, and operational subsystems, more apparent in lean automation implementations. Fernandes and Costa (2024) designed the construction environment under digital transformation based on this three-subsystems concept, which is composed of the following elements: human resources, culture, digital technologies, work infrastructure, production processes, and performance.

DIGITAL TRANSFORMATION IN CONSTRUCTION

Digitalization is revolutionizing several construction processes, including planning, designing, constructing, operating, and maintaining structures (Ozturk, 2021). Forcael et al. (2020) point out that the pillars of Construction 4.0 are the digitalization of the construction industry and the industrialization of construction processes. According to Sawhney (2020), Construction 4.0 is a framework that is a confluence and convergence of the following areas:

- Industrial production – Prefabrication, 3D printing and assembly, and offsite manufacturing.
- Cyber-physical systems – Robots and cobots (collaborative robots) for repetitive and dangerous processes, drones for surveying and lifting, movement and positioning, and actuators.

- Digital technologies – BIM, video and laser scanning, IoT, sensors, AI and cloud computing, big data and data analytics, reality capture, blockchain, simulation, augmented reality, data standards, interoperability, and vertical and horizontal integration.

While the term Construction 4.0 straightforwardly applies the Industry 4.0 concept in the Construction Industry, Fernandes and Costa (2024) argue that digital transformation in construction environments should be driven by Industry 4.0 and Industry 5.0 principles. These authors presented the concept of an Intelligent Construction Environment as "an efficient, resilient, human-centered, and sustainable environment composed of a complex sociotechnical system that uses digital technologies as tools for continuous improvement (Fernandes & Costa, 2024). According to this study, its elements dynamically interact to achieve the following principles: Human centricity, Flexibility, Resilience, Transparency, Collaboration, Decentralization, Virtualization, Horizontal and vertical integration, Real-time capability, Sustainable management, Predictive capacity, and Interoperability.

Fernandes and Costa (2024) also presented 24 social, technical, and operational dimensions to measure the maturity of digital transformation in construction environments in the construction phase (Figure 1). These dimensions are the critical aspects construction managers should focus on and manage throughout the digital transformation process of the construction environment. The dimensions proposed are as follows:

- Social subsystem: Coordination, Sustainability, Innovation, Training, Participative decision-making, Communication, Occupational health and safety, and Promotion of formal education.
- Technical subsystem: Digital technology implementation and management, Development and maintenance of digital solutions, Collection, storage, processing, analysis, and management of massive and complex data, Data Security, Robots and cobots, Construction site layout, and Workspace.
- Operational subsystem: Complexity management, Production planning and control, Storage and logistics management, Timely prediction, Supply chain management, Quality management, Performance management, Cost reduction, and Timely action.

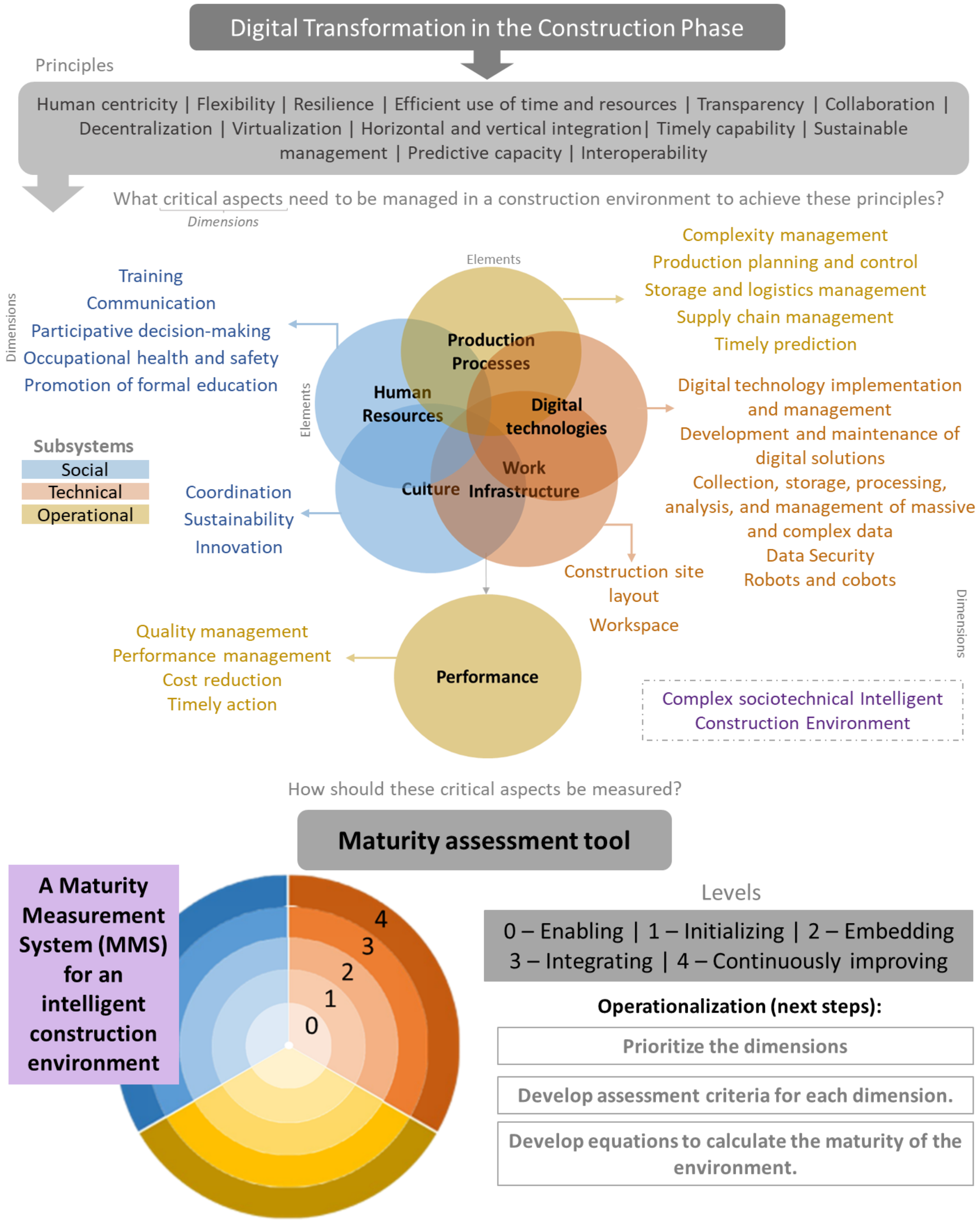

Figure 1 – The conceptual model for measuring the maturity of an Intelligent Construction Environment (Source: Fernandes and Costa, 2024).

The definition of each of these dimensions is presented in Fernandes and Costa (2024).

RESEARCH METHOD

The methodological approach adopted in the development of this study was a survey, which consists of a data collection procedure from a sample of individuals through responses to questions (Check & Schutt, 2012). The data collection instrument used was a questionnaire, and the sample was composed of construction management professionals from industry and academia. The survey aimed to assess the maturity dimensions proposed by Fernandes and Costa (2024) in terms of importance. Thus, the research team required the participants to answer the following question: "On a scale from 1-10, what weight should these dimensions have in their respective subsystems for assessing the maturity of an Intelligent Construction Environment?".

DATA COLLECTION

The study's development initially involved designing a structured questionnaire in the Google Forms platform. It consisted of 5 sections, which are the following: (a) Cover letter, including the research purposes and the definition of an Intelligent Construction Environment, and agreement terms; (b) Respondent profile, including major, occupation area, position, affiliated organization/university, and highest degree attained, (c) Social Dimensions, (d) Technical Dimensions, and (e) Operational dimensions. In the three last sections, the respondents were required to assign a weight from 1 to 10 to each dimension, according to the following degree of importance: 1-4 - Low Importance, 5-7 - High Importance, 8-10 – Essential. In addition, participants could also propose adding or removing dimensions and share notes or comments through open-ended questions. The instrument was tested with the GETEC (Research Group in Construction Technology and Management) research group on January 26, 2023. The pilot application involved 15 people, including 3 Ph.Ds., 3 MSCs, 1 Civil Engineer, and 8 Undergraduate Students (Civil and Electrical Eng.), and it was aimed at evaluating the understanding of the questions and the response time.

Then, the questionnaire was sent in English and Portuguese by e-mail to a list of 50 potential respondents from Industry and Academia. Then, after two weeks, the questionnaire was disseminated through LinkedIn, with the aim of engaging additional relevant members not initially included in the email list and to serve as a reminder for those who had received the email but did not respond. The intended participants were professionals in civil engineering and architecture from industry and academia. It was initially shared on August 4th, 2023, and remained collecting responses until September 1st, 2023.

A total of 55 responses were obtained - 43 from the Portuguese (Brazilian respondents) and 12 from the English form (Respondents from Denmark, India, Chile, Colombia, Portugal, South Africa, and the United States), of which 54 were considered valid because one was identified as a duplicate. Eight of the 54 respondents were not initially included in the email list.

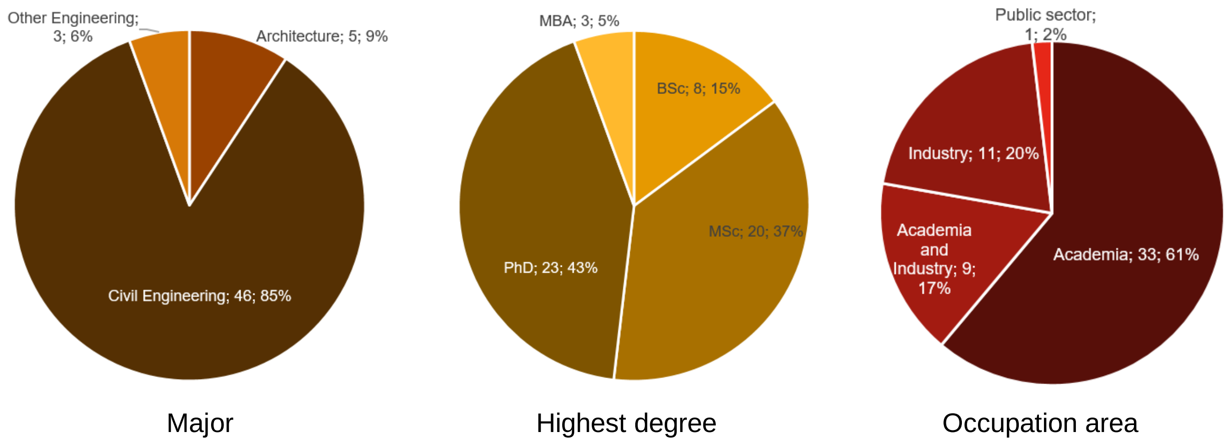

Figure 2 – Characterization of the respondents

DATA ANALYSIS

Data analysis first involved the calculation of Cronbach's alpha, denoted as Cα, a reliability coefficient. It was developed by Lee Cronbach in 1951 to measure the internal consistency of a test or scale (Tavakol & Denik, 2011). Internal consistency refers to the degree to which all items in a test measure the same concept, indicating the interconnectedness of test items, while reliability quantifies the extent of measurement error in the test (Tavakol & Denik, 2011). Cronbach's alpha is mathematically defined as the adjusted proportion of total variance of item scores explained by the sum of covariances between item scores, ranging from 0 to 1 when all covariance elements are non-negative (Heo et al., 2015). A higher Cronbach's alpha (Cα), approaching 1, indicates greater reliability. The following reliability scale (George & Mallery, 2003) was adopted in this work:

$\alpha \geq 0.9$ Excellent

$0.9 > \alpha \geq 0.8$ Good

$0.8 > \alpha \geq 0.7$ Acceptable

$0.7 > \alpha \geq 0.6$ Questionable

$0.6 > \alpha \geq 0.5$ Poor

$0.5 > \alpha$ Unacceptable

The Cronbach's alpha (Cα) was calculated in the SPSS software, resulting in a value of 0.901, which indicates excellent reliability.

Subsequently, data were analyzed using ranking analysis from the Relative Importance Index (RII) calculation. It is a non-parametric technique for analyzing structured questionnaire responses (Chung et al., 2021). The RII ranges from 0 to 1, enabling the identification of the most influential factors within a given set (Watfa et al., 2022). It has been widely employed in assessments of construction-related research and technology adoption drivers (Watfa et al., 2022). The dimensions' RIIs were calculated using the following equation:

$$\text{Relative Importance Index (RII)} = \frac{\sum W}{A \times N}$$

Where:

W = the weight assigned by the respondents to each dimension.

A = the highest weight that could be assigned.

N = the total number of respondents.

The data were converted to a Likert scale (1-5) to simplify the calculation process. The importance scale adopted to analyze the RIIs was the following (Chung et al., 2021):

High ($0.8 \leq RII \leq 1.0$),

High-Medium ($0.6 \leq RII < 0.8$),

Medium ($0.4 \leq RII < 0.8$),

Medium ($0.2 \leq RII < 0.4$),

Low ($0 \leq RII < 0.2$).

The findings obtained are presented in the next section.

FINDINGS

Table 1 summarizes the list of dimensions, with the respective subsystem, percentage of answers in each level of importance, the correspondent RII, and rank. The dimensions' RII values ranged from 0.652 to 0.956, classifying all dimensions with a high (87,5%) or high-medium (12,5%) importance level. The dimension "Communication" was ranked as the most important, followed by "Training" and "Production Planning and Control." These three dimensions were the only ones with an RII exceeding 0.9. Notably, none of these dimensions are technical, suggesting that the respondents do not prioritize technical aspects as the most crucial factors, indicating an alignment with Industry 5.0 principles.

Table 1 – Ranked dimensions.

Dimension	Subsystem	% of answers in each level of importance (1-4)	(5-7)	(8-10)	RII	Rank
Communication	Social	0.00%	1.85%	98.15%	0.956	1
Training	Social	0.00%	9.26%	90.74%	0.933	2
Production planning and control	Operational	0.00%	14.81%	85.19%	0.933	2
Digital technology implementation and management	Technical	0.00%	16.67%	83.33%	0.896	4
Data Security	Technical	1.85%	20.37%	77.78%	0.896	4
Quality management	Operational	0.00%	16.67%	83.33%	0.896	4
Workspace	Technical	3.70%	22.22%	74.07%	0.881	7
Performance management	Operational	1.85%	16.67%	81.48%	0.881	7
Innovation	Social	0.00%	24.07%	75.93%	0.874	9
Timely action	Operational	1.85%	18.52%	79.63%	0.867	10
Supply chain management	Operational	5.56%	14.81%	79.63%	0.863	11
Development and maintenance of digital solutions	Technical	0.00%	37.04%	62.96%	0.859	12
Storage and logistics management	Operational	3.70%	22.22%	74.07%	0.859	12
Timely prediction	Operational	3.70%	27.78%	68.52%	0.856	14
Occupational health and safety	Social	3.70%	27.78%	68.52%	0.852	15
Collection, storage, processing, analysis, and management of massive and complex data	Technical	1.85%	29.63%	68.52%	0.852	15
Cost reduction	Operational	3.70%	27.78%	68.52%	0.844	17
Coordination	Social	3.70%	33.33%	62.96%	0.837	18
Construction site layout	Technical	3.70%	38.89%	57.41%	0.83	19
Participative decision-making	Social	5.56%	33.33%	61.11%	0.826	20
Sustainability	Social	5.56%	29.63%	64.81%	0.822	21
Complexity management	Operational	7.41%	40.74%	51.85%	0.785	22
Promotion of formal education	Social	11.11%	42.59%	46.30%	0.774	23
Robots and cobots	Technical	20.37%	57.41%	22.22%	0.652	24

Following them, the dimensions “Digital technology implementation and management,” “Data Security,” and “Quality management” share the fourth position. This alignment suggests that managers recognize the significance of protecting data, which encompasses preventing unauthorized access, using and disclosing stored information, and ensuring data privacy. Managing this aspect is crucial, especially considering that it is one of the foremost concerns associated with the progression of digital technologies in workspaces.

It is worth highlighting that among the top 9 dimensions, there are three of each subsystem (social, technical, and operational). Even if a "hypothetical" RII is calculated for the subsystems, based on the respondents' average weights assigned to dimensions within each subsystem, similar values are found among them: 0.830, 0.822, and 0.837 for the social, technical, and operational subsystems, respectively. This symmetry suggests that equal importance is given to social, technical, and operational aspects of the digital transformation process. It implies a recognition that effective management and successful outcomes in this context require a holistic consideration of not only technological factors but also social and operational features.

Nevertheless, the dimension “Robots and cobots” was ranked as the least important, followed by “Promotion of formal education” and “Complexity management.” These were the only dimensions with an RII lower than 0.8. The lower RII was attributed to “Robots and cobots,” which may be related to the construction sector's resistance to the replacement of human labor by technologies in production, as presented in Fernandes and Costa (2024), coupled with concerns about the potential financial impacts associated with such changes. Regarding the “Promotion of formal education,” one respondent emphasized that the education dimension should prioritize pursuing learning opportunities over attaining a degree, considering the latter is not necessarily essential. Several respondents argued about the meaning of “Complexity management,” which potentially influenced its assigned weight and contributed to the low RII of this dimension.

In response to open-ended questions, participants provided various additional comments. In the **social subsystem section**, the main suggestions involved the inclusion of dimensions related to mental health, strategy, transparency, and governance. It was also proposed addressing elements such as cultivating a culture of exchanging experiences among employees, establishing a non-judgmental environment, and relocating sustainability and participative decision-making from the operational (construction site) to the organizational level, suggesting that the latter two aspects should be strategically addressed at a broader organizational scale.

In the **technical subsystem section**, some respondents suggested that layout and workspace should be addressed as a single dimension, while others suggested a construction site dimension including all these aspects. Others recommended repositioning social dimensions, including occupational health and safety and communication, within the technical subsystem to align these aspects more closely with the technology and workspace dynamics. One participant suggested ensuring the accessibility of digital tools for workers across all hierarchical levels.

In the **operational section**, most comments were related to the dimensions “Cost reduction” and “Complexity management.” Respondents argued that the emphasis should not be on cost reduction but on effective cost management, acknowledging that digital transformation may demand initial short-term increases. Regarding “Complexity management,” several participants argued the meaning and purpose of this dimension, which implies that complexity studies in construction are still not properly disseminated, and the term is still not familiar among both industry and academic professionals. However, other respondents suggested that all the other dimensions already cover its aspects. One respondent emphasized that the most significant opportunities for improvement within the operational subsystem lie in this dimension, as traditional approaches already address time, cost, schedule, and quality concerns. Moreover, some participants suggested consolidating “Timely prediction” and “Timely action” into a single dimension, arguing the interdependence of these aspects.

DISCUSSION

In the past few years, the upsurge and fast dissemination of Industry 4.0 concepts and technologies have triggered several debates regarding applying these novelties in construction. It is already a consensus that this industry is behind in adopting these features, which can be attributed partly to its inherent characteristics, artisanal nature, heavy reliance on human labor, and the intrinsic complexity of its production environments. However, the IR 4.0 excessive focus on technology is also an obstacle to integrating these advancements into the construction sector. Fernandes and Costa (2024) argued in their study that digital transformation in construction must be driven by IR 4.0 and IR 5.0 principles, and the findings of this survey align with this perspective.

The results of this study revealed that the participants did not prioritize technical aspects. Instead, these aspects were regarded with slightly less importance than other dimensions. More specifically, none of the top three ranked dimensions (the only ones with an RII higher than 0.9) were technology-related; the first two were social dimensions related to human resources, while the third was an operational dimension concerning the production process element. Moreover, the balance among social, technical, and operational aspects in the rank suggests that construction professionals recognize that technology implementation by itself is not enough to promote significant changes; instead, human resources must lead the process improvement with the support of digital technologies.

Part of this awareness can be attributed to the construction industry's extensive journey in studying and implementing the principles of the lean production philosophy, which emphasizes people engagement, learning, and leadership, from shop-floor workers to managers, in process improvement. In fact, Lean Construction and Industry 5.0 share core values. For Mladineo et al. (2021), Lean management can be seen as an Industry 5.0 enabler. According to Faisal et al. (2024), combining these concepts may enable a cost-effective, sustainable, and efficient production system that enhances worker capabilities by optimizing productivity and minimizing waste.

The synergies between Lean management and Industry 5.0 principles (human centricity, resilience, and sustainability) have been individually explored in some studies. Solaimani and Sedighi (2020) identified that lean construction positively impacts all three pillars of sustainability in construction projects. Hamerski et al. (2023) pointed out that the Last Planner System, despite some limitations, can contribute to a resilience performance in construction. Mladineo et al. (2021) showed that most key success factors of Lean management and Lean tools implementations in SMEs are people-oriented, reflecting the human-centric approach to organizational and process improvement, as required by Industry 5.0. Nevertheless, these synergies have not been studied directly and holistically yet, which suggests an interesting gap to be explored in future works.

CONCLUSION

This work aimed to assess social, technical, and operational maturity dimensions for digital transformation in the construction phase. For that, it presented the results of a survey questionnaire administered to 54 construction professionals from both industry and academia. Data analysis involved ranking the dimensions by calculating their Relative Importance Index (RII) from the weights assigned by the respondents. Results show that technical dimensions were not ranked as the central ones, and the outcomes indicate an equilibrium among the importance of social, technical, and operational factors for digital transformation in the construction phase. Findings align with Industry 5.0 and Lean Construction concepts, indicating synergies among them. Although these synergies have been individually explored in some studies, they have not been studied directly and holistically yet, which suggests an interesting gap to be explored in future works.

This work is one of the stages in the development of a Ph.D. thesis, which aims to propose a Maturity Measurement System for an Intelligent Construction Environment. The findings presented in this paper support the assignment of weights and refinement of maturity measurement dimensions, which is the initial step in transforming the proposed conceptual model (Figure 1) into a practical tool—the Maturity Measurement System (MMS). Future steps involve (a) the proposition and validation of assessment criteria and equations to measure the maturity in each dimension, subsystem, and overall environment and (b) the application, test, and validation of the MMS, with subsequent guidelines for implementation.

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