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DEFINING DIGITAL TRANSFORMATION INDICATORS FOR THE CONSTRUCTION PHASE BASED ON A SOCIOTECHNICAL APPROACH

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ABSTRACT

The construction industry has been facing difficulties in embracing the opportunities offered by digital technologies, advances in data management, and progress from other industrial revolutions. Furthermore, recent studies have shown that the simple adoption of digital innovations, without adequate implementation, integration into the work routine, and alignment with business strategies, has not been enough to drive an effective digital transformation (DT). Thus, achieving competitive advantages requires a comprehensive understanding of managing and measuring the transformation of the construction processes using metrics such as maturity indicators. Therefore, this work proposes a set of maturity indicators for digital transformation in the construction phase based on a sociotechnical approach. A total of 15 social, technical, and operational indicators and a method for calculating them are introduced. This work presents one of the steps of a broader doctoral thesis that employed Design Science Research as its research strategy. Theoretical contributions include a comprehensive analysis of the aspects the construction industry needs to manage to advance on the path to digital transformation. Practical contributions include a set of indicators that enable construction companies to assess their current state, identify areas needing attention, optimize resource allocation, perform benchmarking, and establish precise goals for DT.

KEYWORDS

Construction Industry. Digital Tranformation. Maturity Indicators. Sociotechnical systems. Construction phase.

INTRODUCTION

Different from other industrial sectors, the construction industry (CI) has had difficulty taking advantage of the opportunities offered by technology and advancements in data management (Sawhney et al., 2020) and progress from other industrial revolutions. Industry 4.0 is an even more significant challenge for the CI because of its low innovation culture and the demographics of its business, with few business leaders and a majority of small and medium enterprises with diverse technological maturity (Klink & Turk, 2019).

Thus, integrating resources and concepts from the latest industrial revolutions (Industries 4.0 and 5.0) is even more challenging for this sector. Moreover, the development of several studies focusing on the implementation of digital technologies in the construction phase (Melo et al., 2017; Álvares et al., 2018; Álvares et al., 2019; Pérez & Costa, 2021; Rey et al., 2021; Santos et al., 2021; Lima et al., 2023; Staffa et al., 2023; Silveira & Costa, 2023; Peinado et al., 2023; Silva et al., 2023; Araújo et al., 2024) has shown that only adopting these digital innovations, without proper implementation, inclusion in the work routine, and alignment with business strategies, is insufficient to promote effective transformations, resulting in an ineffective digital transformation (DT). Therefore, it has been identified that there is a need to determine which aspects of the construction environment, in addition to the adoption of digital technologies, need to be measured and managed to achieve a successful digital transformation based on the principles of Industries 4.0 and 5.0 (IR 4.0 and IR 5.0). These principles are Human centricity, Flexibility, Resilience, Efficient use of time and resources, Transparency, Collaboration, Decentralization, Virtualization, Horizontal and vertical integration, Timely capability, Sustainable management, Predictive capacity, and Interoperability (Fernandes &Costa, 2024).

The use of indicators that enable maturity assessments developed from a sociotechnical perspective can significantly support digital transformation in the construction phase. A sociotechnical approach in this context is recommended because it acknowledges that achieving successful technology implementation requires a comprehensive understanding of the organizational context, encompassing structure, work dynamics, and the workforce (Sackey et al., 2015). Therefore, these indicators enable construction companies to identify social, technical, and operational areas requiring specific attention (KPAs - Key Project Areas).

The main benefits of using maturity indicators include improving visibility into best and worst practices, clarifying tasks, deadlines, and responsibilities, promoting consistency in documentation and process implementation, and enabling benchmarking across projects and companies (Heller & Varney, 2013). However, the literature lacks maturity indicators specifically designed for digital transformation in the construction phase. Moreover, no indicators have been developed from a sociotechnical perspective for this purpose. Therefore, this study aims to propose a set of digital transformation maturity indicators for the construction phase based on a sociotechnical approach. This work presents part of a broader doctoral thesis that aims to propose a Maturity Measurement System (MMS) for Digital Transformation in the Constriction Phase.

DIGITAL TRANSFORMATION IN CONSTRUCTION

Vial (2019) defines digital transformation as "a process that aims to improve an entity by triggering significant changes to its properties through the combination of information, computing, communication, and connectivity technologies." It is guided by Industry 4.0 principles across several industrial sectors. According to Rosin et al. (2019), IR 4.0 technologies facilitate the implementation of communication, flexibility, and real-time capabilities. The emergence of IR 4.0 in the construction industry (Construction 4.0) encompasses several interdisciplinary technologies and concepts that enable digitization, digitization, automation, and integration of the construction process in different phases (Oesterreich & Teuteberg, 2016).

According to Sawhney, Riley, and Irizarry (2020), Construction 4.0 is a framework that is a confluence and convergence of the following areas:

• Industrial production – prefabrication, 3D printing and assembly, offsite manufacture.

• 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.

However, according to Sony and Naik (2020), effective collaborations between humans and machines require a sociotechnical approach. The environment allows specific roles for organizations, people, and technical artifacts, and a sociotechnical approach provides the basis for determining the appropriate limits for these elements and their joint optimization (Sackey et al., 2015). Trist (1981) originally defined sociotechnical systems as a combination of social and technical subsystems, while Vlachos et al. (2021) expanded this concept to include the operational system, which is more appropriate for construction environments (Fernandes & Costa, 2024).

Fernandes and Costa (2024) emphasize that digital transformation in construction must integrate Industry 4.0 and Industry 5.0 as complementary concepts, with their respective principles driving this transformation. According to these authors, embracing Industry 5.0 principles can assist construction practitioners, and academics in discerning which Industry 4.0 features could prove valuable and effective in construction rather than merely replicating practices from manufacturing, automotive, and other sectors (Fernandes & Costa, 2024).

INDICATORS AND BENCHMARKING

Prior to a measurement process, it is crucial to determine what aspects to measure, how to analyze them, and how to quantify these measurements, and indicators play a pivotal role in this regard (Sanches, 2010). The term "indicator" derives from the Latin word "indicare," meaning to disclose, point out, or estimate something (Hammond et al., 1995). The OECD (2003) defines an indicator as a parameter or value derived from parameters that provide information about, describe the state of, or indicate a phenomenon, environment, or area with implications beyond the parameter itself. Heink and Kowarik (2009) describe an indicator as a measure or component from which conclusions about a phenomenon of interest can be inferred. For Hammond et al. (1995), an indicator provides information for a matter of greater significance or makes visible a trend or phenomenon that is not immediately noticeable. For example, a drop in the barometric pressure (indicator) may indicate a storm (Hammond et al., 1995). It also has the visibility function, showing the current performance of an organization or environment, indicating its strengths or weaknesses, or emphasizing its dysfunctions (Costa, 2003). This type of evaluation enables the establishment of priorities in quality improvement programs by identifying the company sectors where interventions are most crucial or feasible (Costa, 2003).

According to Silva (2007), an indicator is not a number but a variable to which quantitative or qualitative value can be measured or assigned. Joung et al. (2012) characterize an indicator by the following attributes: • Identification (ID): a unique alphanumeric identifier; • Name: The word for a distinct designation of the indicator; • Definition: the statement that expresses the essential characteristics and function of an indicator • Type of measurement: type of indicator (quantitative or qualitative) • Unit of measurement: the unit of the indicator value • References: cited documents of existing indicators or set of specific indicators; • Level of application: the level in the hierarchical organization at which the indicator is applied. The primary benefits of using indicators are reducing the number of measures needed to describe a situation and simplifying the information process, ensuring that the measure effectively reaches the end user (Silva, 2007).

Another significant benefit of using indicators is their role in enabling benchmarking (Fernandes & Costa, 2021). Benchmarking is a vital practice for continuous improvement, allowing companies to enhance their performance by identifying, adapting, and implementing best practices observed in a group of participating companies (Ramírez et al., 2004). It facilitates performance comparisons between different organizations, helping them to recognize their weaknesses and strengths by using industry standards as a reference (El-Mashaleh et al., 2007). Benchmarking can be classified into external and internal. External benchmarking involves learning from competitors' best practices (Luu et al., 2008), while internal benchmarking uses references within the company itself, such as comparisons between different construction projects, departments, or teams (Fernandes & Costa, 2021).

RESEARCH METHOD

This paper presents part of a PhD work developed using the Design Science Research (DSR) strategy. DSR focuses on relevant real-world problems to be solved in practice and is based on the perception (brought from the pragmatist philosophy of science) that a deep analysis of what works or does not work in practice can enable a significant contribution to the theory (Lukka, 2003). The research design is presented in Figure 1.

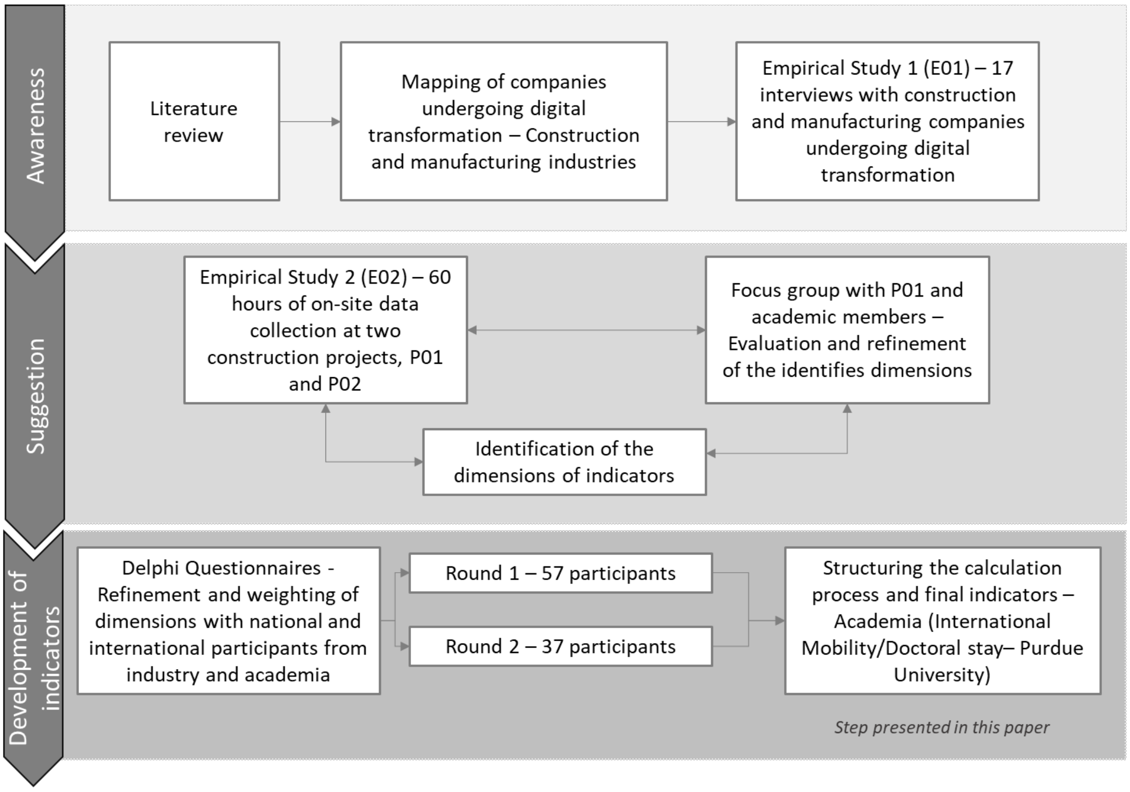

Figure 1. Research Design

The data were collected first through two empirical studies, E01 and E02. E01 involved 17 interviews with companies undergoing digital transformation in the construction and manufacturing sectors. E02 comprised approximately 60 hours of on-site data collection at two construction sites, P01 and P02, located in northeast Brazil. P01 is a low-income residential project with a site area of 18,756.35 m², featuring four ten-story buildings and a total of 320 units. P02 is a mid-range residential development with a site area of 7,514.84 m², comprising two fourteen-story buildings and a total of 160 units. In the empirical studies, 24 indicators of aspects that influence digital transformation in construction were identified and categorized into social, technical, and operational indicators, presented as follows.

- Social indicators: Coordination, Sustainability, Innovation, Training, Participative decision-making, Communication, Occupational health and safety, and Promotion of formal education.
- Technical indicators: 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 indicators: Complexity management, Production planning and control, Storage and logistics management, Timely prediction, Supply chain management, Quality management, Performance management, Cost reduction, and Timely action.

The outcomes of these steps are presented in detail by Fernandes and Costa (2024).

The indicators identified in the empirical studies were assessed and assigned weights using Delphi questionnaires. This technique collects expert opinions to achieve a reliable consensus (Cantrill et al., 1996). Participants were instructed to assign a weight from 1 to 10 to each indicator, reflecting its significance as follows: 1-4 for Low Importance, 5-7 for High Importance, and 8-10 for Essential. They were also invited to propose any additions or removals of indicators and to provide feedback or comments through open-ended questions. The aim was to establish an agreement among respondents regarding the importance level of the proposed indicators. The adopted consensus criterion was to achieve 67% (2/3) of the responses with the same level of importance in each indicator.

In the first stage, responses were collected from 54 experts in Construction Management from both industry and academia. The second stage involved 37 respondents. Participants were from Brazil, Chile, Colombia, Denmark, India, Portugal, South Africa, and the United States. The characterization of the sample is presented in Figure 2. A detailed analysis of the findings of the first round is presented in Fernandes et al. (2024).

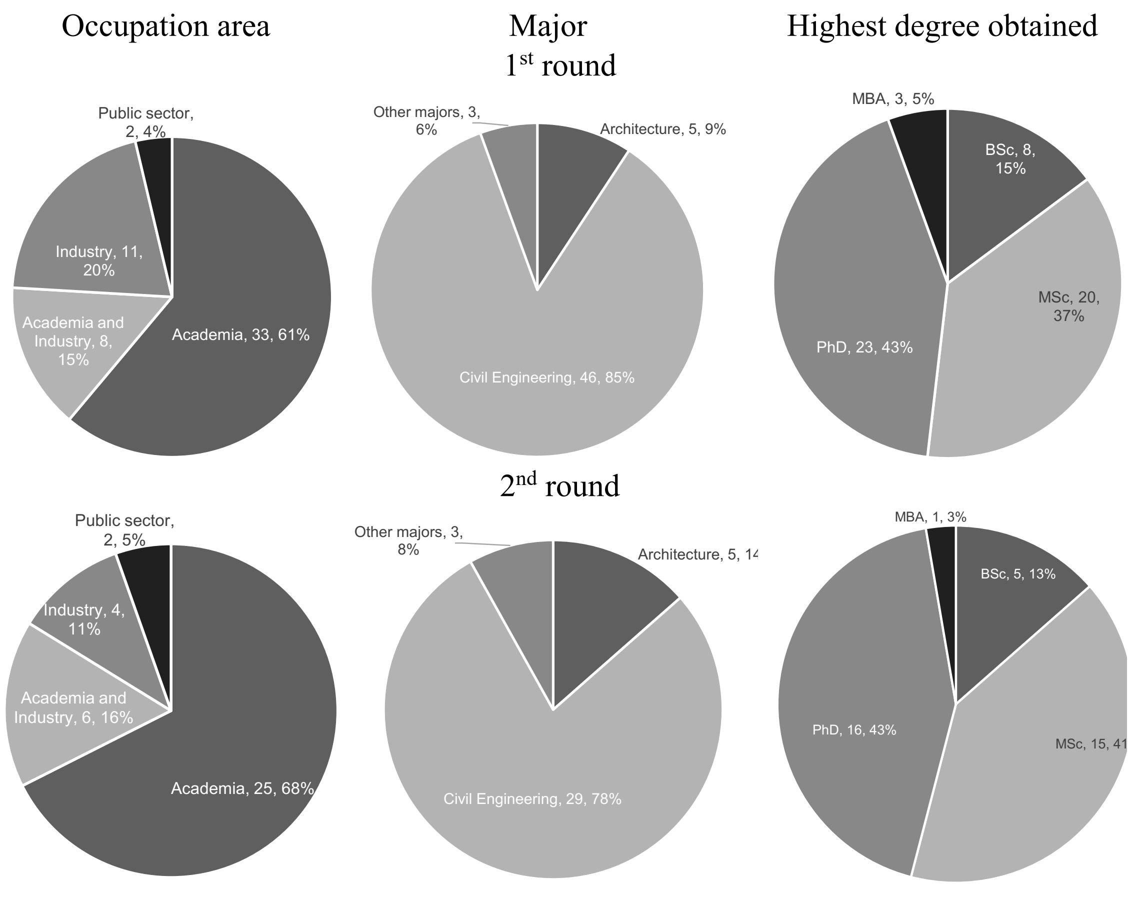

Figure 2. Characterization of the Delphi respondents' sample

Following the Delphi application, the process of structuring the calculation and final indicators was conducted in collaboration with academic members. Part of this process occurred during a doctoral stay at Purdue University in the United States. During the international mobility period, several meetings with international academic members enabled detailed discussions and multiple cycles of analysis and refinement of the indicators' scope. The outputs of these last two stages are summarized in the next section.

RESULTS

DELPHI

FIRST ROUND

As previously stated, in the scope of the Delphi application, the consensus was defined as achieving, within each indicator, a minimum of 67% (2/3) of responses with the same level of importance assigned. As noted during the relevance evaluation in the previous phase (Fernandes, 2024), the operational indicators demonstrated a higher level of consensus regarding their importance, with only one indicator, “Complexity management,” lacking agreement. Consensus was reached for 50% and 57% of the social and technical indicators, respectively. Table 1 shows the metrics with and without consensus in the first round.

Table 1. Indicators with and without consensus achieved in the first round

Subsystem	Indicators with consensus attained		Indicators without consensus attained	
Social	4	Innovation, Training, Communication, and Occupational health and safety.	4	Coordination, Sustainability, Participative decision-making, and Promotion of formal education.
Technical	4	Digital technologies implementation and management, Collection, storage, processing, analysis, and management of massive and complex data, Data security, and Workspace.	3	Development and maintenance of digital solutions, Robots and cobots, and Construction site layout.
Operational	8	Production planning and control, Storage and logistics management, Timely prediction, Supply chain management, Quality management, Performance management, Cost reduction, and Timely action.	1	Complexity management.

Table 2 summarizes the indicators list, their respective subsystems, and the percentage of responses at each level of importance. It also indicates whether each indicator reached a consensus, highlighting indicators that required further assessment and discussion in the following round.

Table 2. Delphi’s 1st round results

Indicator	Subsystem	% of answers in each level of importance			Consensus achieved?
		(1-4)	(5-7)	(8-10)	
Communication	Social	0.00%	1.85%	98.15%	Yes
Training	Social	0.00%	9.26%	90.74%	Yes

Production planning and control	Operational	0.00%	14.81%	85.19%	Yes
Digital technology implementation and management	Technical	0.00%	16.67%	83.33%	Yes
Data Security	Technical	1.85%	20.37%	77.78%	Yes
Quality management	Operational	0.00%	16.67%	83.33%	Yes
Workspace	Technical	3.70%	22.22%	74.07%	Yes
Performance management	Operational	1.85%	16.67%	81.48%	Yes
Innovation	Social	0.00%	24.07%	75.93%	Yes
Timely action	Operational	1.85%	18.52%	79.63%	Yes
Supply chain management	Operational	5.56%	14.81%	79.63%	Yes
Development and maintenance of digital solutions	Technical	0.00%	37.04%	62.96%	No
Storage and logistics management	Operational	3.70%	22.22%	74.07%	Yes
Timely prediction	Operational	3.70%	27.78%	68.52%	Yes
Occupational health and safety	Social	3.70%	27.78%	68.52%	Yes
Collection, storage, processing, analysis, and management of massive and complex data	Technical	1.85%	29.63%	68.52%	Yes
Cost reduction	Operational	3.70%	27.78%	68.52%	Yes
Coordination	Social	3.70%	33.33%	62.96%	No
Construction site layout	Technical	3.70%	38.89%	57.41%	No
Participative decision-making	Social	5.56%	33.33%	61.11%	No
Sustainability	Social	5.56%	29.63%	64.81%	No
Complexity management	Operational	7.41%	40.74%	51.85%	No
Promotion of formal education	Social	11.11%	42.59%	46.30%	No
Robots and cobots	Technical	20.37%	57.41%	22.22%	No

SECOND ROUND

Table 3 presents the indicators with and without consensus in the second round.

Table 3. Indicators with and without consensus attained in the second round

Subsystem	Indicators with consensus attained		Indicators without consensus attained	
Social	4	Coordination, Sustainability, and Participative decision-making,	4	Promotion of formal education.

Technical	4	Development and maintenance of digital solutions and Construction site layout.	3	Robots and cobots,
Operational	8	Complexity management.	1	-

Table 4 summarizes the outcomes of the second round. Out of the eight indicators evaluated, the consensus was not achieved in two, "Robots and Cobots" and "Promotion of Formal Education." It is important to note that “Robots and Cobots” was the only indicator rated as Low Importance (1-4) by some respondents in this round. As participants in the first round also raised doubts regarding the criticality or relevance of these two metrics for digital transformation in the construction phase, they were subsequently removed from the set and integrated into the scope of other indicators, resulting in a total of 22 metrics.

Table 4. Delphi's 2nd round results

Indicator	**Subsystem**	**% of answers in each level of importance**			**Consensus achieved?**
		(1-4)	**(5-7)**	**(8-10)**	
Coordination	Social	-	16%	84%	Yes
Sustainability	Social	-	24%	76%	Yes
Participative decision-making	Social	-	22%	78%	Yes
Promotion of formal education	Social	-	35%	65%	No
Development and maintenance of digital solutions	Technical	-	19%	81%	Yes
Robots and cobots	Technical	19%	65%	16%	No
Construction site layout	Technical	-	19%	81%	Yes
Complexity management	Operational	-	22%	78%	Yes

After the second round, based on the comments and outcomes obtained in this step, another round of refinement was performed, resulting in a total of 19 indicators in the MMS. The main adjustments were:

- “Cost reduction” was rescoped as “**Cost management.**”
- “Timely prediction” and “Participative decision-making” were incorporated into “Timely action.” The indicator was renamed to **“Timely decision-making.”**
- "Supply chain management" was integrated into a narrower scope within **"Storage and logistics management."**
- “Performance measurement” was incorporated into **“Performance management.”**

FINAL REFINEMENT

After further analysis of the data from previous stages and the suggestions and comments provided during all evaluation steps, a final refinement of the indicators was performed. This involved reanalyzing patterns and relationships among the data and refining the indicators through several discussions, including during the doctoral stay at Purdue University. One of the main concerns raised by researchers was the number of indicators, which posed challenges in terms of application, evaluation, and implementation. During these discussions, overlaps in the indicators' dimensions were identified, and suggestions were made to remove certain elements to streamline the scope without compromising the overall purpose. Based on these discussions, the comments and contributions of international researchers, and all previously collected and analyzed data, a total of 15 indicators were defined. The main revisions were:

- "Cost management" was incorporated into the context of "**Performance management.**"
- "Data security" was integrated into the context of "**Collection, storage, processing, analysis, and management of massive and complex data.**"
- "Development of digital solutions" was rescoped to "**Development of innovative solutions**," incorporating the indicator "Innovation."
- "Storage and logistics management" were integrated into "Construction site layout." The indicator was renamed to "**Layout and Logistics Management.**"

DIGITAL TRANSFORMATION INDICATORS

Table 5 presents the proposed digital transformation indicators for the construction phase and their IDs and purposes. All indicators are quantitative, unitless, and designed for application at the operational level (construction site).

Table 5. Maturity Indicators and their respective purposes

Subsystem	Indicator	ID	Purpose
Social indicators	**Coordination**	**S1**	Measure the maturity of the Coordination aspect, including team, budget, strategy, and integration of DT into the strategic planning.
	Sustainability	**S2**	Measure the maturity of the Sustainability aspect in the construction phase across social, economic, and environmental pillars.
	Training	**S3**	Measure the maturity of the Training aspect by evaluating elements such as planning, budgeting, inclusivity (involvement of diverse hierarchical levels), and monitoring.
	Communication	**S4**	Measure the maturity of the Communication aspect by examining the processes for transmitting and exchanging information with all stakeholders to achieve normative, formative, participative, and integrative transparency.
	Occupational health and safety	**S5**	Measure the maturity of the Occupational Health and Safety aspect, including inspection routines, safety instructions, information sharing, and activities to promote workers' mental health and well-being.

Sub system	Indicator	ID	Purpose
Technical indicators	**Digital technologies implementation and management**	**T1**	Measure the maturity of the Digital Technologies' implementation and management aspect, including interoperability, budget, digitization and digitalization actions, and requirements for technology use, such as internet connectivity availability.
	Development and maintenance of innovative solutions	**T2**	Measure the maturity of the Development of innovative solutions aspect, encompassing collaborative engagement among the Research and Development (R&D) and Information Technology (IT) departments with production workers to gather their demands and feedback, aiming to deliver practical and efficient solutions.
	Collection, storage, processing, analysis, and management of massive and complex data	**T3**	Measure the maturity of the Management of massive data aspect, including actions needed to ensure a proper process of collecting, storing, processing, and analyzing the project data, giving visibility and accessibility to it. It also concerns ensuring data privacy security.
	Layout and logistics management	**T4**	Measure the maturity of the Layout and Logistics aspect, including material flow management at the construction site, inventory control, tracking services, and efforts to reduce non-value-added activities.
	Workspace	**T5**	Measure the maturity of the Workspace aspect, with a specific emphasis on prioritizing the well-being of workers, including assigned spaces to foster integration, collaboration, and self-development, as well as actions to increase their sense of belonging and importance.
Operational indicators	**Complexity management**	**O1**	Measure the maturity of the Complexity Management aspect, including direct strategies to address complexity, such as strategic redundancies, fostering a culture of learning, encouraging diverse perspectives, supporting resilience, giving visibility to processes and outcomes, and monitoring WAI[1] and WAD[2]. This indicator complements others in this set that support the effectiveness of this aspect.
	Production planning and control	**O2**	Measure the maturity of the Planning and Control processes aspect, focusing on ensuring workers' participation from different hierarchical levels and

[1] WAI – Work-as-imagined
[2] WAD – Work-as-done

Sub syst em	Indicator	ID	Purpose
			aiming for more efficient, sustainable, safe, and productive activities.
	Timely decision-making	**O3**	Measure the maturity of the Timely decision-making aspect, encompassing the process of collecting information and responding to demands and unexpected situations timely, i.e., a period enough to avoid unsafe conditions and waste.
	Quality management	**O4**	Measure the maturity of the Quality Management aspect, focusing on timely information flow, reducing rework, and targeting standardized and efficient procedures to deliver a product with higher added value.
	Performance management	**O5**	Measure the maturity of the Performance Management aspect in this new digital transformation context, from defining indicators through data collection and processing to information management.

INDICATORS – METHOD OF CALCULATION

Another contribution of this work is the proposal of a method for calculating the indicators through the establishment of assessment criteria developed according to each indicator's purpose. For example, the operational indicator "Timely Decision-Making" requires assessment criteria to "measure the maturity of the timely decision-making aspect, including the process of collecting information and responding to demands and unexpected situations in a timely manner to avoid unsafe conditions and waste." The recommended number of assessment criteria ranges from 5 to 7 for each indicator, which is optimal for streamlining the application and ensuring comprehensive evaluation without overwhelming complexity.

The proposed evaluation method acknowledges that a criterion may still be in the intermediate stages of achievement. An assessment that prompts a simple "yes" or "no" response fails to account for the inherent progress stages of any transformation process. This fact can potentially result in incorrect assessments and a non-representative indicator value. Therefore, the criteria assessment will be performed on a scale from 0 to 4, where (0) indicates that the criterion was not met, (1) denotes the Early Stages, (2) represents the Intermediate stages, (3) signifies Further stages, (4) indicates Full achievement. The assessment criteria for this set of indicators were outlined in the subsequent phase of this work; however, due to space constraints, their development will be presented in a future paper.

Finally, the indicators will be calculated using the equation below.

$$Id = \frac{NC4 * 1 + NC3 * 0{,}75 + NC2 * 0{,}5 + NC1 * 0{,}25 + NC0 * 0}{NC} \qquad \textbf{Formula 1}$$

Where:

I= Indicator

d = Dimension

NC4 = Number of criteria fully achieved

NC3 = Number of criteria in further stages

NC2 = Number of criteria in intermediate stages

NC1 = Number of criteria in early stages

NC0 = Number of criteria not achieved

NC = Number of criteria

DISCUSSION

This work introduces a comprehensive set of indicators for digital transformation during the construction phase, along with a method for their calculation. By employing several data collection methods —such as literature reviews, interviews with professionals from the manufacturing and construction sectors, onsite data collection, and Delphi questionnaires——the research team has established 15 social, technical, and operational indicators to measure the key aspects that influence digital transformation in the construction phase. The study also proposes a method for calculating indicators by defining specific assessment criteria for each indicator based on its purpose. Unlike traditional maturity assessments, which typically rely on binary yes-or-no measures, the proposed indicators are measured on a scale from 0 to 4, based on the level of achievement of each criterion. This approach enables a more precise calculation of each indicator.

Beyond evaluating individual companies, the value of standardized indicators lies in their ability to enable benchmarking, which is crucial for continuous improvement. Companies using the same metrics can compare results, identify best practices, and set improvement goals based on these benchmarks. Moreover, standardized measures enable the establishment of reference value databases for digital transformation. These reference values help companies enhance their own performance by allowing managers to reset targets and implement effective action. Moreover, sectoral and governmental entities can use an established database to analyze the evolution of digital transformation in the construction industry during the construction phase and identify emerging trends. Standardized metrics, therefore, support a systematic approach to performance enhancement and encourage ongoing development within the industry.

Furthermore, this calculation method, based on assessment criteria, enables the indicators to be updated over time and adjusted for context-specific situations. One issue with indicators designed to measure digital transformation processes is their tendency to become obsolete quickly due to the rapid emergence of new technologies, industrial revolutions altering the environment, and changing customer needs. This work explores the key aspects that need to be managed during a digital transformation process, ensuring that future assessment criteria can be designed to adapt to ongoing industrial revolutions and transformations within the construction sector.

In addition, this calculation method allows the indicators to be adjusted to fit a company's or country's context, aligning with management needs and objectives. While it is recommended to design assessment criteria as a core, which was addressed in the following phase of this work, organizations have the flexibility to integrate additional criteria tailored to their unique context for supporting the implementation of their own digital transformation strategy. This approach enhances the model's utility for internal benchmarking purposes, supporting the standardization of digital transformation efforts across an organization's projects.

It is noteworthy that the proposed indicators can function as either lagging or leading indicators, depending on the user's objectives. Leading indicators are measured during the execution process, allowing for anticipating and resolving problems and enabling necessary interventions for improvement and control (Fernandes & Costa, 2021; Hronec, 1994 apud Lantelme, 1994). Lagging indicators, on the other hand, assess whether the defined goals were met (Costa et al., 2005). Maturity evolvement leads, indirectly or directly, to performance improvement, so a maturity indicator indicates that aspect's (dimension) readiness to deliver continuous performance improvement (Fernandes & Costa, 2024). Thus, when measured throughout the construction phase, the proposed indicators can serve as leading metrics, helping managers understand and refine their digital transformation process. These indicators can be measured multiple times throughout the construction phase, providing data to track and delineate the evolution process. Moreover, they can function as lagging indicators by providing post-project results and, thus, generating data for the company's evolution process and future projects.

The subsequent phase of this work involved proposing a set of assessment criteria for each introduced indicator. This enabled the design of a Maturity Measurement System for digital transformation in the construction phase, which is the primary objective of the PhD thesis associated with this paper.

CONCLUSION

This study proposed a set of indicators for digital transformation in the construction phase based on a sociotechnical approach. The theoretical contributions of this paper include a comprehensive analysis of the aspects the construction industry needs to manage to advance on the path to digital transformation. The practical contributions encompass a set of indicators that enable construction companies to assess their current state, identify areas needing attention, optimize resource allocation, perform benchmarking, and establish precise goals for DT. In addition, this work also proposes a method for calculating these indicators.

The indicators proposed in this study were specifically developed for the construction industry, focusing on projects in the construction phase. Therefore, these indicators may not be suitable for measuring digital transformation maturity in broader contexts beyond this phase.

This work presents part of a broader doctoral thesis that aims to propose a Maturity Measurement System (MMS) for Digital Transformation in the Constriction Phase. The following phases of the study encompassed outlining a set of assessment criteria for each introduced indicator and proposing the MMS. The MMS is now in the implementation phase.

The future goal is to make the Maturity Measurement System available on a web platform free of charge, with the condition that data provided by companies for evaluation can be used anonymously for sectoral benchmarking and academic research. The next stage involves publicizing the platform nationally and internationally to facilitate broader data collection. This aims to create a comprehensive database of digital transformation indicators in the construction phase, enabling benchmarking among projects, organizations, regions, and countries. Expected outcomes and impacts include increased visibility of best practices for digital transformation in the construction phase and the ability to compare indicators across the sector in different localities.

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