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Using System Dynamics to Support Strategic Digitalization Decisions

Hazal Deniz Kaya[1] and Irem Dikmen[2]

Abstract: Although digitalization has become a prospect that is counted on for many problems in the construction industry, there have been limited attempts at exploring decision-making processes in construction firms concerning the integration of digital technologies and impacts beyond the projects. In this research, the system dynamics (SD) approach was proposed to investigate digitalization as a strategic decision considering the inherent relationships between project company and business levels. The SD model was conceptualized, formulated, and tested by conducting a demonstrative case study within a modular construction company. Conforming to the strategic priorities of the case company, business process engineering principles were adopted to model the existing practices and assess the impacts of implementing digital technologies such as building information modeling (BIM), enterprise resource planning (ERP), and radio frequency identification (RFID) at different maturity levels. The simulation tests revealed that the impacts of technologies are influenced by the internal dynamics of projects and company competencies as well as external uncertainties. The SD model has the potential to improve strategic decision-making by anticipating the causalities and feedback between the decisions and consequences of technology integration. The findings and model development steps proposed in this paper can be used by other companies that aim to make process improvements with digital technologies as well as researchers exploring the implications of digitalization in construction considering competencies and uncertainties. **DOI: 10.1061/JCEMD4.COENG-14112.**

Author keywords: Digitalization; System dynamics modeling; Strategic decision-making.

Introduction

Digitalization has been conceived as the panacea for poor productivity in construction, and there is a strong interest among policymakers to support digitalization within the industry (McKinsey Company 2020; European Construction Sector Observatory Report 2021; RICS 2022). Oesterreich and Teuteberg (2016) proposed the use of Industry 4.0 technologies within the construction value chain from different perspectives of adoption such as economic, social, and environmental. Similarly, Wang et al. (2020) stated that the industry is on the edge of a major revolution thanks to the digital technologies of Industry 4.0 such as big data, cybersecurity, cloud technology, additive manufacturing, and augmented reality. Expanding upon these, Sawhney et al. (2020) framed Construction 4.0 as encompassing the trends and technologies that will change the way of design and construction in the built environment. Industry 5.0 iterates on the technological advancement of Industry 4.0 by integrating humans within the paradigm and prioritizing sustainability for a new production model within the industry (European Commission 2021). Considering that the construction industry is slow to implement technologies and adopt business models to digital environments, it is still not clear how the industry will embrace the changes brought by narrowly conceptualized Construction 5.0. The reason behind this can be linked to the unique characteristics of construction, such as the existence of many parties within the value chain, project complexity, and uncertainty (Oesterreich and Teuteberg 2016). Nevertheless, contributing to the competitive landscape of the industry, building information modeling (BIM) fills the gap of structured information exchange through digital modeling and simulation, especially for design, and enables the overall integration of construction processes with other technologies. For example, Tang et al. (2019) demonstrated the integration of real-time data from internet of things (IoT) devices with BIM, and Li et al. (2017) integrated radio frequency identification (RFID) for prefabricated construction. Using real-time data driven from sensors or IoT devices for BIM processes, digital twins (DTs) stepped forward for the integration of the physical world with the virtual. As autonomous systems, DTs paved the way for advanced project management practices by helping data communication, better predictions, and flexibility to uncertainties for construction processes (Pan and Zhang 2021). Despite the popularity of considering BIM a prerequisite for the digital transformation of the industry, skepticism still continues for the development of an integrated BIM environment, which can be observed by the prevalence of using modeling tools only for internal development and design stages. Challenges of implementing BIM have been listed as technical difficulties such as inadequate experience, incompatibility of software and interoperability issues (Abd Jamil and Fathi 2020), legal concerns (Arensman and Ozbek 2012) and the need for a paradigm shift toward collaborative working and change in behavior of practitioners in the industry (Eadie et al. 2014; Hajj et al. 2021).

Despite various attempts in the literature to consider technology adoptions, construction industry professionals still have unclarity in their minds about which technologies need to be integrated, for which purposes, and how to implement them in practice (Lavikka et al. 2018; Wang et al. 2022). Hence, to improve the current status quo of the digital transition of construction firms, practitioners need to recognize the new opportunities of technologies together with the technical, organizational, and external factors within a strategic

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context. In this regard, this research primarily aimed to explore the strategic decision-making process in construction companies concerning implementing different digital technologies and assess the impact of digital technologies at the project level. A systems approach has been used to model the decision-making process behind the technology integration, including the project processes as well as company-level and business-level factors. The research was carried out in collaboration with a modular construction company operating in international markets. Because the research aims to understand the strategic value of technology adaptation from an inclusive systems perspective, systems dynamics (SD) was used to simulate decision-making processes within this company. The developed SD model assessed the impacts of several factors such as company capabilities, project and management-related aspects, and benefits, as well as challenges associated with digital technologies and external uncertainties in the project environment. In the forthcoming parts of this paper, first, the research background will be presented on decision-making for digitalization. Then, the research methodology will be presented, followed by the developed SD model and demonstration of the case application. Simulation results from the demonstrative case study will be discussed, as well as general research findings, contributions, limitations, and recommendations for future studies.

Digitalization in Construction

Digitalization is a strategic decision that can enable companies to reach their long-term objectives. Nevertheless, digitalization as a research topic in construction has generally been limited to the demonstration of digital technologies as promoters of project performance, especially in terms of cost and schedule. For example, Bryde et al. (2013) focused on the benefits of BIM in project management and revealed the major benefits as cost reduction and control. Kang et al. (2008) and O'Connor and Yang (2003) stated technologies have a strong positive correlation with schedule performance; Hwang et al. (2019) investigated the effect of BIM on rework during design and construction; and Zhu et al. (2022) proposed the most prominent applications of smart technologies as progress tracking, real-time monitoring, and schedule estimation. Where the literature is mostly focused on the use of individual technologies for different tasks, there is a need to create a proper strategy to help construction organizations define key goals, pertinent actions, and assessment techniques (Love and Matthews 2019; Nikmehr et al. 2021). Moreover, although these studies revealed the benefits of individual technologies, there is still a lack of studies that comprehensively elaborate upon the impact of technologies as strategies and analyze this under the circumstances of project conditions, current company competencies, and external conditions.

On the other hand, prior to discussing the effects of technologies on the process, the acceptance and use of different technologies have also been addressed in the literature using different perspectives and methods. Among these, one of the most commonly employed methods is technology acceptance models (TAMs), which place individual behavior, intention to use, at its core place. Accordingly, the TAM posits that users' intention to adopt technology is shaped by two key beliefs: perceived usefulness and perceived ease of use. These beliefs, in turn, can be influenced by external factors like system characteristics, development processes, and training (Xu and Lu 2022). In the construction industry, the model is widely used to understand the acceptance of different technologies such as BIM (Lee et al. 2015), enterprise resource planning (ERP) (Chung et al. 2009), and smart construction systems (Liu et al. 2018) based on cognitive constructs of individuals. Therefore, in most of these studies, tactical conclusions have been drawn for the success of technology implementation in organizations. Although these studies elaborate on the reasons behind the mindset of technology users, a widely held viewpoint is that the TAM is insufficient in predicting technology adoption at the organizational level, and a commonly observed phenomenon is that once a construction organization invests in new technology, it tends to become a de facto obligation for operators to incorporate it into their work processes, which is overlooked in the existing literature (Sepasgozar 2023). Therefore, when considering the objective of this study as understanding the strategic value of digital technologies for construction, the focus has shifted from the influence of individual behaviors in the technology acceptance process to the potential visionary achievements that can be attained upon technology implementation and its subsequent effects on processes using a systems approach.

Ernstsen et al. (2021) indicated the three visions of the construction companies for digitalization as efficient construction (modularization), user-data–driven built environment [real-time data of IoT, virtual reality/ augmented reality (VR/AR), sustainability] and value-driven computational design (digital designs for simulating changes, digital twin cities). The authors stated that the innovation and digitalization visions of the industry should be approached by combining different discourses such as technology, business, and policy rather than focusing on the benefits of individual technologies. Similarly, Almeida et al. (2022) proposed assessing the integration of industry 4.0 (I4.0) technologies into production systems by evaluating sociotechnical factors such as people, organizational structure, and external environment. For the construction industry, the sociotechnical perspective used by several authors (Li et al. 2019; Lavikka et al. 2018) suggests that digital technology integration must be investigated by considering both organizational and technical factors.Rather than just the evaluation criteria, the interrelations between these criteria and how the dynamics behind that influence the digitalization decision is another missing part of the current body of construction management knowledge. Although there have been several studies that model the dynamics of decision-making for construction projects such as discrete even process simulation (Doloi and Jaafari 2002), dynamic risk management systems (Zhou and Zhang 2010), and dynamic multiobjective optimization of projects (Guo and Zhang 022), there is a lack of studies that focus on the dynamics of the digital technology integration decision-making process. This study attempts to fill the research gap using SD as a tool to simulate and explore the considerations that companies need to take into account when making decisions about digitalization by combining both organizational and technical factors as well as multiple technologies.

The main purposes of SD are understanding complex systems and improving decision-making for the problems exhibited in them by understanding the behavior of different components over time (dynamism) and with feedback effects (Forrester 1997). SD has been widely used in the strategic management literature to model different systems and support various decisions. Applications include modeling of project success (Lyneis et al. 2001; Lyneis and Ford 2007), sustainability assessment (Yao et al. 2011; Zhang et al. 2014), analysis of the competitiveness of construction firms (Ogunlana et al. 2003; Dangerfield et al. 2010; Barnabè 2011), performance management Yildiz et al. (2020), and selecting the best approach for delivering projects (Nouh et al. 2023). Although there is much research in the existing literature regarding project planning, control, and strategic decision-making by system dynamics, to the best of the authors' knowledge, there are no studies that analyze the outcomes of technology integration, particularly digital technologies, using this method. With the intention to fill this gap in the existing literature, this research endeavors to demonstrate how SD can be used for simulating the impacts of different technologies on processes and influence the decision-making process itself with a demonstration in a modular construction company.

Research Objective and Methodology

The objective of this research has been identified as modeling dynamics of technology implementations within companies taking into account project, company, and business factors to support digitalization decisions. It has been hypothesized that a systems approach, particularly SD, can be used for this purpose. The case study type of research is relevant for this research objective because in SD, a specific system or problem is modeled with its constituent components and interactions. Case studies are compliant with construction project management research because each project is a case with specific physical requirements and unique control as well as management methods (Gomes Araújo and Lucko 2022). The case study was designed using the systems thinking perspective. Systems thinking proposes comprehending how things affect each other as a whole and considers problems part of the system rather than isolating them from other constituents (Sterman 2001). Based on the idea that the strategic value of technology adaptation cannot be fully understood without an understanding of the system (the processes, actors, and their interrelationships), internal dynamics as well as the external environment, systems thinking, and SD modeling were used in this study.

The research used the two-step modeling methodology of SD, as proposed by several authors (Sterman 2000; Forrester 1997; Senge 1990). The first step is conceptualization and qualitative modeling, which comprise causal loop diagramming (CLD). Then causalities are converted into level and rate variables to imitate the behavior of the system by different numerical calculations as quantitative models. The term “level” refers to anything that builds up or diminishes over a certain period, whereas the rate displays how much the level has changed over time. The level and rate are formulated in SD using stock-flow diagrams (SFDs). Levels are represented by the stock variables, whereas rates are variables of flow.

The two-stage model of the SD process is composed of four sequential steps: (1) conceptualization, (2) formulation, (3) testing, and (4) simulation (Sterman 2000). The conceptualization step encompasses problem articulation and defining system parameters and interrelations. For problem articulation, the strategic positioning of the case company in terms of digitalization was investigated, which included describing the internal (resource-based) and external environment of companies for both current and future scenarios (Price et al. 2003). The system parameters and interrelations were described for both current and future strategies in the project process chain by evaluating different digital technologies. Then, the parameters were converted into formulations, transferred into a computerized environment, and tested with initial parameters for validity iteratively. In the final step, different scenarios in the project environment and strategic goals for digitalization were simulated in Stella Architect version 2.3.1. For the sampling part of the SD model, typical inputs were used for a medium-sized modular construction project of the case company. This typicality also encompasses the extreme conditions of the projects, which improve the reliability of the case study application. As the data source, interviews and oral feedback were used, which were depicted as group model-building (GMB) sessions. The research steps are illustrated in Fig. 1. The selection process of the case company and model development steps will be explained in the next section.

The Case Company

The research was carried out in collaboration with an international construction company that was exploring digital transformation possibilities and was willing to collaborate with researchers. The company is one of the earliest established firms in Turkey for prefabricated modular steel structure production, export, and international contracting services, with more than 40 years of experience. Because the company emphasized globalization as a strategic goal in recent years, it completed many projects worldwide and has a presence in more than 60 countries. Moreover, the company is one of the 250 biggest contracting companies in the world and has appeared in the *Engineering News-Record* (ENR) list for the last 10 years (ENR 2018). The company is experienced in BIM, emphasizing modern methods of construction such as design for manufacturing and assembly (DfMA) and designing for industrialized methods of construction (DIMC) over traditional methods of construction. With its experience in the industry as well as the willingness to collaborate, the company was found to be a good partner in this research. A modular construction company was also considered a good research partner due to the opportunity to analyze the effects of technologies on both controlled (fabrication and production process) and uncontrolled (assembly on site) environments.

The case company contributed to the SD model development with the involvement of staff in different modeling sessions, which were structured according to the framework proposed by Vennix (1995), as explained in the next section. The framework was composed of creating models by brainstorming, with the experts having diverse industrial knowledge and backgrounds. Considering the disconnection between the cognitive models of C-level executives and the management and digitalization team in the company, the integration of experts from both groups was found to be crucial for model development. The process was structured and conducted in 1–2.5-h sessions where three experts participated in seven sessions in the case company. The group discussions during the sessions were recorded and transcribed.

Group Modeling Sessions

In the SD development process, knowledge elicitation from the company experts involved five main steps. The background of the experts is given in Table 1.

First, a preliminary study was conducted as the initial GMB session where the aim of the study and the need of the case company in terms of digitalization were configured. For that session, the contribution of the chief technology officer (CTO) of the company was essential to ascertain the initial requirement to use SD modeling for strategic analysis. Then, the system boundary was defined in the second session as the problem articulation step. For that step, the methodology of SD modeling was introduced to the experts, and the predeveloped basic Stella model was created as an example of the process chain of similar modular construction projects. Then, experts provided feedback on the existing project processes and future digital technology integrations. Model formulations and parameters were transferred into the computerized model iteratively by the contributions of experts. After clarifying the parameters and interrelations with the mathematical formulations, the baseline scenarios were tested for different external conditions and evaluated. The GMB sessions are summarized in Table 2.

Development of the SD Model for the Case Company

Initial Session: Strategic Positioning and Technological Improvements

In the initial session, the current situation of the company, technologies currently used, reasons behind the decision to digitalize,

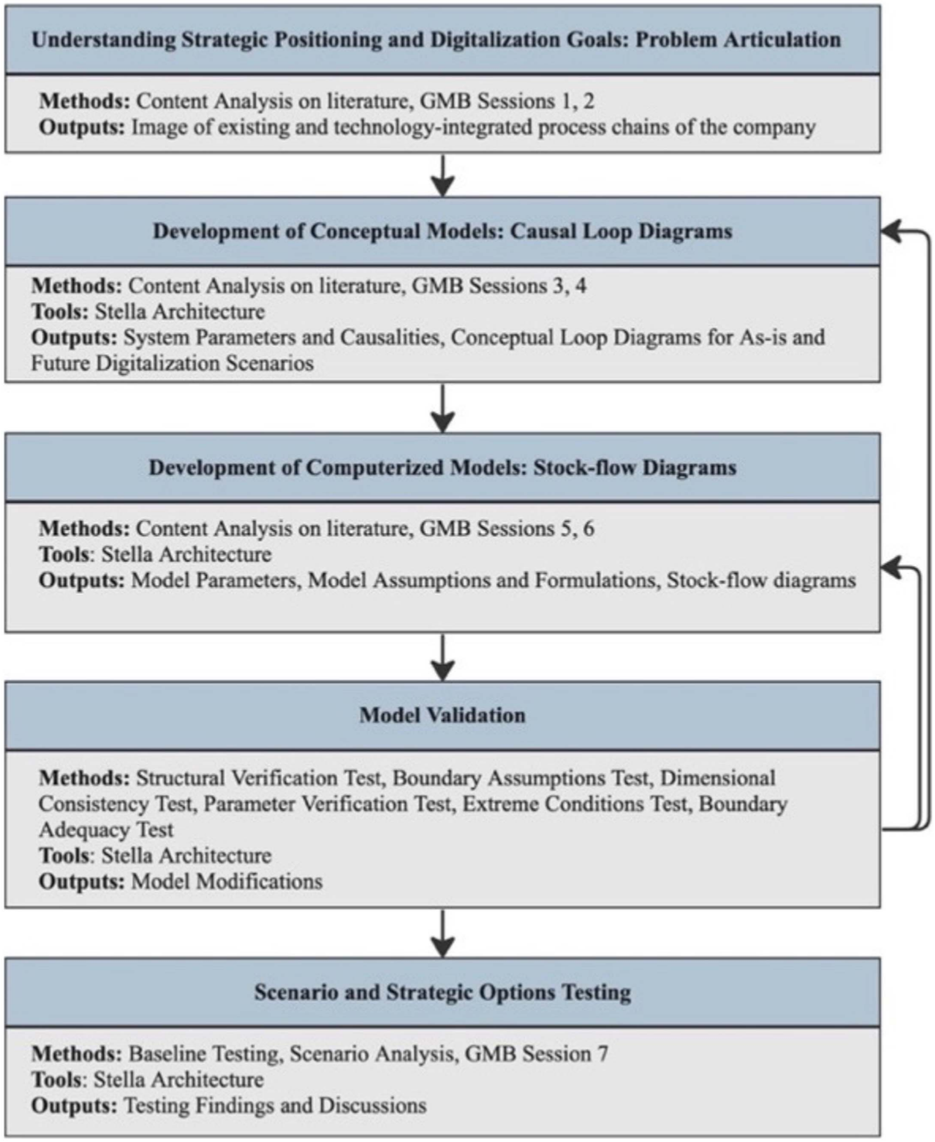

Fig. 1. Research steps.

Table 1. Expert profiles

Expert ID	Education level	Years of experience in industry	Industry	Current title	Experience in digital transformation
1	MSc	10	Building/residential	BIM/digitalization expert	High
2	MSc	10	Building/residential	BIM/digitalization expert	High
3	PhD	15	Building/residential	Chief transformation officer	High

Table 2. Summary of group modeling sessions

ID	SD step	Session aim	Session duration (h)	Experts	Session output
1	Conceptualization	Understanding the strategic position and goals for digitalization	2	C-level executive, two digitalization experts	Existing and redrawn business process chain
2	Conceptualization	Defining system parameters	1	Two digitalization experts	As-is causal loop diagrams
3	Conceptualization	Finalizing conceptual maps	1.5	C-level executive	Reconfigured (digitalization options) causal loop diagrams
4	Formulation	Model assumptions	2.5	Project manager, two digitalization experts	Computerized models
5	Testing	Baseline testing	1	Project manager, two digitalization experts	Finalized stock flow diagram, findings and discussions
6	Simulation	Scenario analysis	2	C-level executive	Findings and discussions

digital technologies intended to be implemented, and related key performance criteria were evaluated together with experts. The company was using BIM as a modeling and simulation tool, especially for design automation. The technology development process was managed by a technology team, which is responsible especially from the design stage and in improving BIM coordination among different departments and processes of the projects. Moreover, the company was experienced with the ERP system that had been used for the last 5 years for controlling inventory, creating material lists, and overall planning of logistics and production. The main reasons behind the digitalization strategies were expressed as increasing productivity and responding quickly to the changing environment. Due to the frequent changes in market conditions, immediate remedies such as procuring materials, hiring people, and doing overtime became more difficult, and there were considerable cost overruns that could be compensated for with process improvements by digital technologies. Another reason for seeking technological solutions was identified as decreasing rework. Considering the necessity of material supply for the entire process chain, the accuracy problem of the existing material lists was emphasized. For exploration of the general and digitalized process chain of the case company, the concept of business process reengineering (BPR) was used, as proposed by Hammer and Champy (1993). As previously stated, the scope of the model is configured in accordance with the strategic objectives and pertinent project processes concerning the digital technologies employed within the context of the modular case company. Modular construction projects involve creating building sections or complete units off-site in factories, which are then transported to the designated location for assembly. Because modular construction has differences from the traditional construction process, such as production of repetitive units with multiple intended uses and standardization (Innella et al. 2019), in this research, the main processes of modular projects were considered. The initial group modeling sessions underscored the case company's primary focus on specific processes, including design, supply, production, and construction. The BRP and SD model development would be similar in traditional construction but might have included different processes, resulting in different findings.

The company was expecting to further implement BIM in different processes. That statement of the experts merged with the literature of BIM to define the parameters as maturity levels that embrace integration from different perspectives. In this research, the proposed model of Succar (2010) was used, which encloses both the technological and policy aspects, depicting three maturity levels: (1) object-based models, (2) model-based collaboration, and (3) network-based integration, which is supported and extended by other research in the literature (Yilmaz et al. 2019; Khosrowshahi and Arayici 2012). Model-based collaboration refers to the communication of models or parts of models using both proprietary and nonproprietary formats [e.g., issue for construction (IFC)]. It can take place within a single project lifecycle phase or between two phases, such as architectural and structural model exchange during design and steel model exchange during production. At the network-based integration level, integrated models that are rich in semantics are developed, exchanged, and maintained cooperatively throughout the project lifecycle phases. For the supply process, the company was seeking to enhance the integration of ERP systems for inventory management. Additionally, the RFID technology was selected by the case company to enhance material tracking by smart gateways in front of factories. At the factory and construction sites, tracking building components with RFID was identified as a priority. Despite having a competitive advantage through modularization, the experts noted that the company had to follow certain strategies and procedures to minimize the risk of accidents. One of these was adopting new technologies, such as safety tools (wearable devices, sensors) for construction sites. The related digital technologies identified as a result of the initial session are represented in Fig. 2.

At the end of the initial session, the company experts prioritized the digitalization strategies for the current inefficiencies and mentioned possible technology integrations within the processes. First, the C-level executive of the company underlined the acceptance of BIM as an automation tool from the design departments and the interoperability problems between BIM models for processes. Therefore, the priority was identified as increasing automation of design by improving the level of details of object-based models and competency of the technology team of the company. The second priority was stated as improving the time and cost of data integration to BIM models for better project management. The third priority encompassed the second level of BIM, model-based collaboration, defined as improving the level of interoperability between different models and processes. The fourth priority was determined as updating the ERP module with material lists from the BIM. Experts identified implementing RFID for element tracking during supply and production as the fifth priority. The sixth priority was to improve BIM as a network-based integrated tool with other technologies. Considering the importance of keeping down the uncontrolled working environment, the final priority was defined as the implementation of safety tools. Subsequently, the strategies and technologies derived from company experts were translated into system dynamics model parameters. The aforementioned technologies and process-based improvement strategies were contingent upon the company's engagement in the modular construction domain. For instance, the integration of ERP technology into the model was prompted by the company's inbound logistics operations and uncertainties within material supply, thereby necessitating the inclusion of relevant parameters in the simulation process. How the priorities and technologies were modeled in SD will be explained further in the following sections.

Conceptual Modeling

As the first step of SD development, for conceptual modeling, the system parameters and causalities were determined by causal loop diagramming. Considering the time-dependent simulation feature of SD modeling, conceptual models were created for schedule performance, which was then used for analyzing cost performance indicators in computerized modeling. First, as-is CLD was drawn for the current project management process, which was configured according to model structures in the construction management literature and feedback from the company experts. The basic feedback structure of the project management system was composed of essential elements such as (1) project progress, (2) errors and reworks, (3) project planned schedule, and (4) management strategies and consequences of these actions. Because the experts mentioned different remedial actions for different project processes, model parameters were changed for each process in the computerized modeling section. For project progress, the commonly adopted logic is that the required work finishes with a completion rate that depends on the productivity and number of resources (Lyneis et al. 2001). Productivity was defined as the work done for a unit of time per resource in this research. The resource represents the expanded definition of sources used for the specific task (e.g., production and construction labor or design teams). Nonetheless, the project almost always flows less than perfectly, encountering some errors and thereby rework. Errors have different representations in the literature of SD, such as error fraction (Lyneis et al. 2001; Love et al. 1999), positive denotation as acceptance rate of completed tasks (Wang and

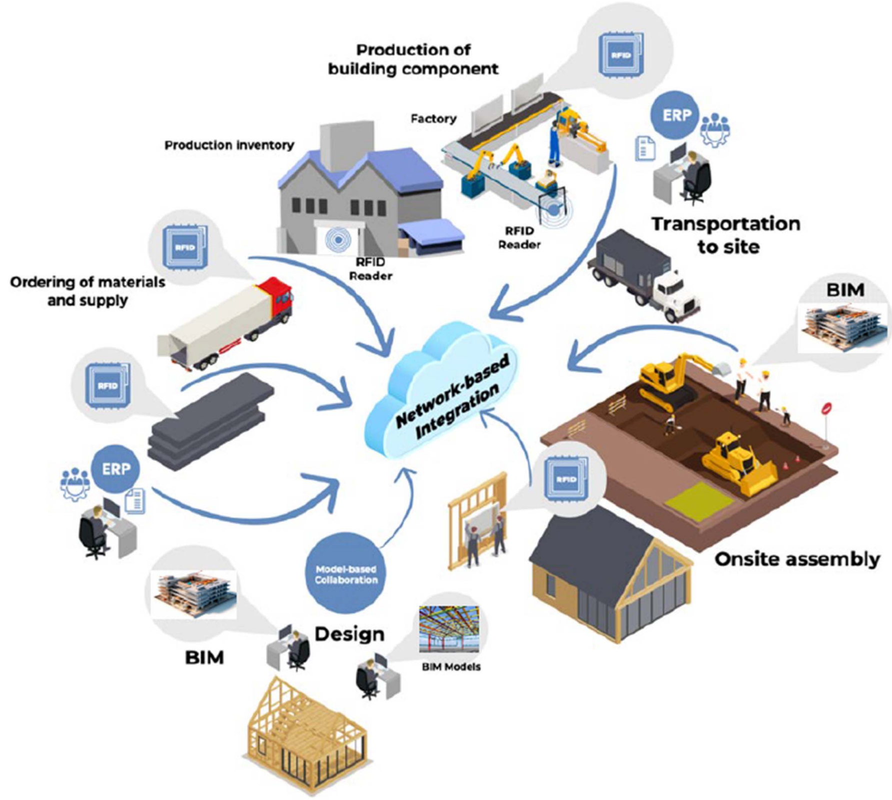

Fig. 2. Digitalized business process chain.

Yuan 2017), and quality (Pargar and Kujala 2021). Considering the expressions of the experts, the error ratio was found more convenient to define the erroneous portion of the work and predicted as a percentage for each project process in the quantitative model. As the third aspect, the project planned schedule and requirements were configured. The schedule pressure defines the ratio of actual completion time (required time to correctly complete the work) to planned completion time. When a project falls behind the planned schedule there are general remedies such as overtime and resource allocation, which originate in different balancing (B) and reinforcing (R) loops, as can be seen in Fig. 3.

For instance, from Fig. 3, B1 represents that as the actual completion time increases, so does the schedule pressure, which increases the actual error ratio and therefore the rate of task completion and time again. Accordingly, management strategies like overtime for releasing schedule pressure and increasing the resource level for reducing remaining work were modeled with its consequences such as employee fatigue and congestion on the work site that result in lowering productivity and increasing errors (Lyneis and Ford 2007). Therefore, the system parameters and feedback loops were constituted based on the methods proposed and widely used in the SD literature, such as Lyneis et al. (2001) and Lyneis and Ford (2007).

The rationale behind the stated feedback loops constitutes a basis for strategically redrawn conceptual models for digitalization strategies. Therefore, after configuring the existing management strategies and project dynamics, digital technology parameters were added according to the experts' feedback from the previous session. The mentioned technologies and their strategically directed impacts were added to the CLD of each project process in accordance with the group modeling sessions conducted with the experts and were therefore in line with their anticipations of technology influence on processes. Additionally, the study also consulted the existing literature on digitalization in construction management to validate the rationality of stated causalities.

As strategic objectives related to BIM, the automation capabilities, interoperability between different models, and level of integration were aimed to be improved in the company. Considering the maturity levels of Succar (2010), the first maturity level is object-based models related to the *automation of design* parameter. It is stated that the parameter majorly affects the productivity of the design team, which was reflected in the efficiency parameter. Then, increasing the level of four-dimensional (4D) and five-dimensional (5D) models is related as a strategy and relevant technology parameter defined as the *effectiveness of project management.* The experts mentioned that schedule pressure due to any changes in the planned durations can be managed effectively by this parameter. As the second maturity level, *model-based collaboration* was chosen as another technology parameter as the depiction of interoperability between models. The last maturity level, *network-based integration*, was considered a system parameter that was connected with the error ratios of production and construction processes regarding its benefits for closed-loop visibility and traceability of progress through real-time status. Considering the stated strategic goals of the company for the supply process, the *accuracy of material quantities* was stated as a system parameter connected with the order contingency, which refers to inventory and overall material management through the ERP systems. Considering the importance of availability of supply in avoiding material discrepancies for modular construction companies, RFID technology was linked with the *missing materials* system parameter, which implements tags to material packages and trucks to read management information for supply (Demiralp et al. 2012). For the production process, the case company experts stated their existing management strategy for possible delays or external requests increased resources (e.g., hiring labor, upscaling the amount of equipment),

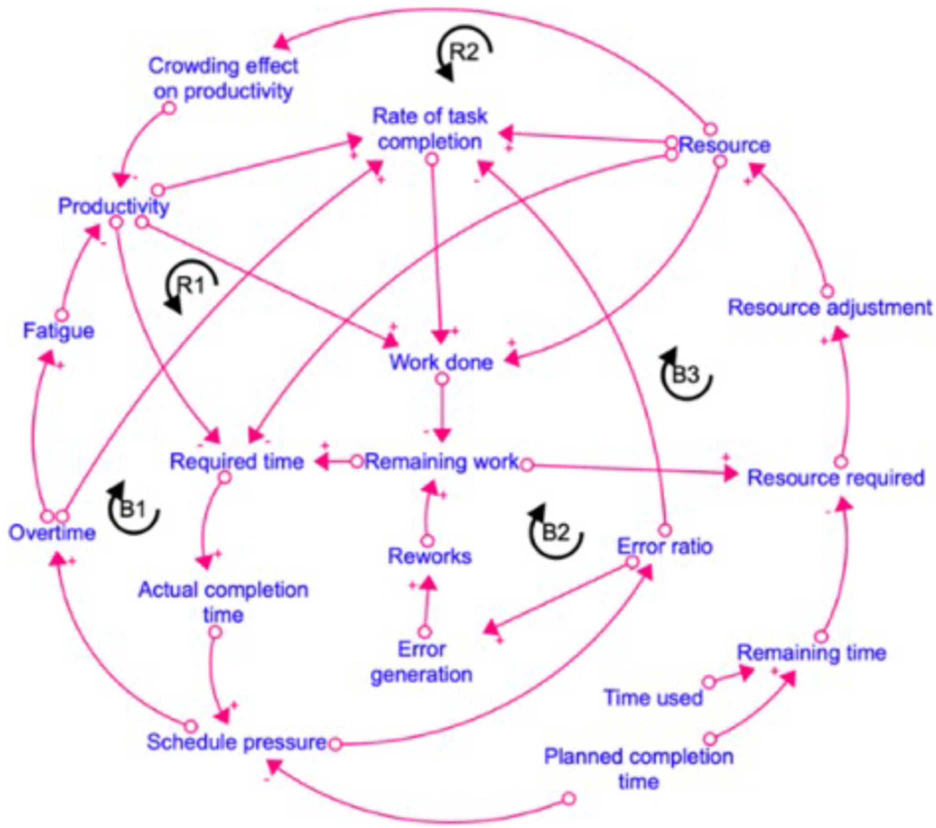

Fig. 3. As-is CLD of project management.

which provides backup for other projects in the portfolio. Because factories generally work for the maximum hours, there was no overtime option. Increasing productivity as the main objective of production, RFID technology was considered by the experts of the digitalization team in the factory, and real-time information on production positioning can decrease time-consuming identification of the location of materials or units. Therefore, *RFID* technology was connected with the efficiency and error detection parameters (time of rework detection on the production site) of the production process. Also, the additional effort and time required due to the separate modeling of the design and production process was observed as a process inefficiency. Thus, the modeler added an interconnection between *model-based collaboration* and the *production modeling* system parameters. The related operational parameters and causalities can be observed from the finalized CLD of production process as an example in Fig. 4.

Considering the uncontrolled environment of construction sites and the strategic goal of decreasing errors, *health and safety management* was added as a system parameter and connected with the *safety tools* parameter. BIM maturity levels were linked with strategically relevant parameters such as *communication on site* to increase productivity or the *effectiveness of project management* to release schedule pressure. The technology-related system parameters and their linked model parameters are given in Fig. 5.

Consequently, the mentioned system parameters and causalities were decided together with the company experts according to the case company's inefficiencies, strategies, and expected benefits from digital technologies as well as previous research findings reported in the literature, such as for the maturity levels of BIM (Succar 2010), impact of ERP on the supply chain (Tambovcevs and Merkuryev 2009; Powell 2013), and RFID influence on missing materials (Demiralp et al. 2012). Although the technologies and causalities may differ in another company, the objective of this paper was to demonstrate the influence of SD on decision-making in technology integration. Hence, SD was proposed as a generic method, and how it can be developed and implemented in practice to test impacts of digital technology was demonstrated by the case company. Based on the conceptual model, each process was drawn in the Stella Architect CLD window and transferred into stock-flow diagrams, as will be explained in the next section.

Computerized Modeling

The CLD for each project process was converted into SFD in Stella to test and simulate the system. First, different boundary conditions and model assumptions were defined for adapting real-time settings. The model comprised endogenous and exogenous factors, which were categorized into six groups: (1) initial (2) project objectives (performance indicators), (3) resource and capability, (4) external factors, (5) managerial actions, and (6) formulations. Accordingly, the endogenous (internal) factors encompassed parameters such as the project's initial values (e.g., project scope, anticipated durations, material inventory). For the second group, the actual completion time of the processes and total project duration were considered. Then, the final resource and material levels, overtime factors, and contract conditions (e.g., liquated damages) were equated with unit prices for project cost analysis. The factors under the third category indicate project resources (human, equipment), planned productivities, and technology integration capabilities, which are exogenous project and company-specific system parameters that have undergone internal changes for different simulations. The external uncertainties from the client and market were defined together with management strategies. The formulation

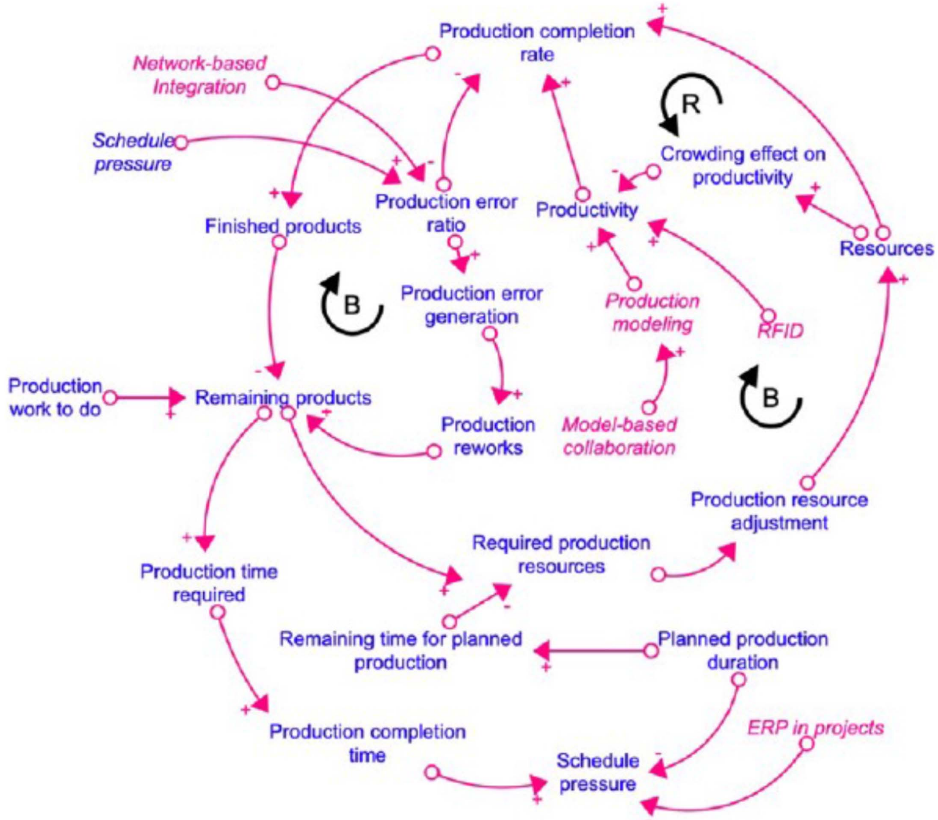

Fig. 4. Production process conceptual loop diagram with technology strategies.

	Priorities	Model Parameters	Linked Model Parameters			
			Design	Supply	Production	Construction
1	Increasing the level of details and interoperability of BIM models for automation (BIM Level-1)	Automation of design	Design efficiency Design error ratio			
2	Increasing the integration of time and cost data to BIM models (BIM Level-1.2)	Effectiveness of project management	Schedule pressure of design			Schedule pressure of construction
3	Increasing the interoperability between design models and process models (BIM Level-2)	Model-based collaboration	Design rework discovery		Production modelling	Communication on site
4	Reinforcing the accuracy of material lists from ERP modules	ERP		Accuracy of material quantities	Schedule pressure of production	
5	Implementing RFID technology (tags and receivers) for tracking	RFID		Missing material	Production efficiency Production rework discovery	Construction rework discovery
6	Network-based integration	Network-based integration			Production error ratio	Construction error ratio
7	Using safety tools in construction site	Safety tools				Health and safety management

Fig. 5. Technology model parameters.

parameters were added to the model as converters aiming to transfer information to variables and ensure dimensional consistency.

Accordingly, the determined technology parameters and their causalities were reflected in the computerized model with 5-point Likert scale ratings and formulations.

For instance, the *automation of design* parameter was calculated as a percentage according to the rating of the level of detail (LOD) in object-based models, level of interoperability, and competency of the technology team. The LOD of object-based models refers to parametric modeling as the preparation and modularization of

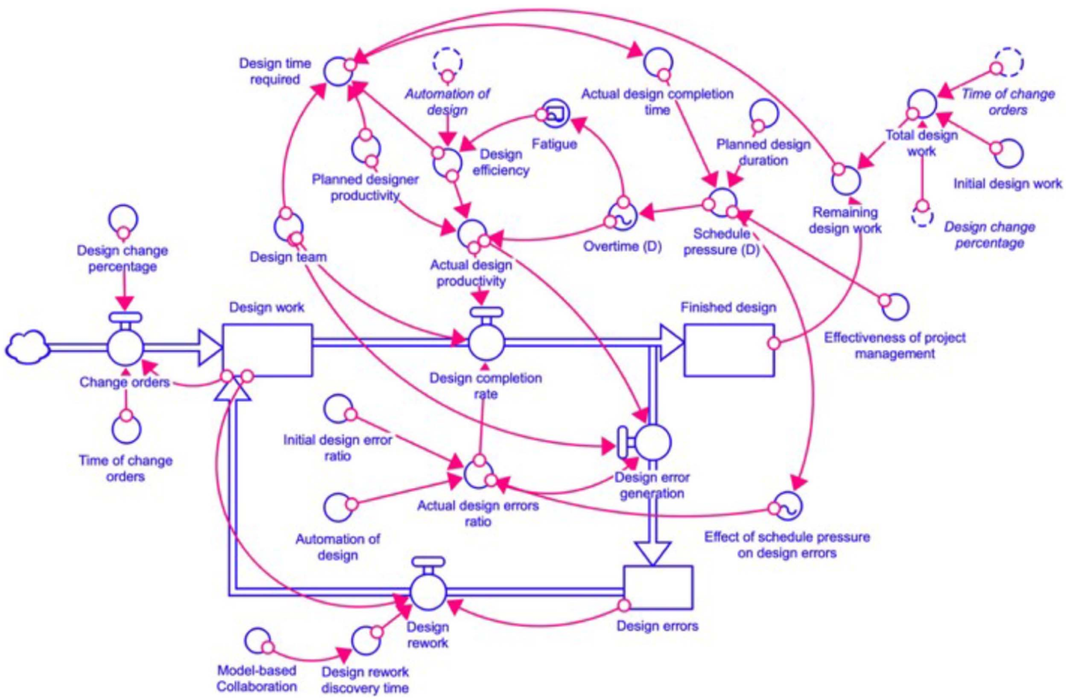

Fig. 6. Stock flow diagram of the design process.

as-built models for optimization and informed iterations of design (Sharma et al. 2017). Moreover, for that equation, the capability of the digitalization team was chosen as a limiting factor for automation through BIM. Similarly, the effectiveness of project management parameters was rated in the Likert scale considering the level of time and cost data integration in BIM. The technology parameter of RFID was rated as yes or no and modeled as binary digits in the model, as given in Supplemental Data, Table S1.

Considering the supply process, the IF THEN rule was defined to link the accuracy of material quantities with the implementation level of ERP. The experts assumed full or perfect accuracy (1) if ERP level were high, and for the current ERP level, (moderate) accuracy was stated as 0.7. Similarly, it was assumed that for the increase in level of interoperability (from moderate to high [between 3 and 5]), efficiency would increase by 25%. The exemplified model equations are given in Table S2 in Supplemental Data.

Although productivity was defined as the unit of work that is done in a week by one resource (units/weeks/resource), these parameters reflect the planned or initial estimations of the company. Due to the changes in circumstances in the project dynamics, inherent consequences of managerial actions (e.g., fatigue), or technology integration, it can change positively or negatively. In this context, the efficiency parameters were added to the model as converters collected these impacts and transferred them to actual productivities, as can be seen from the finalized SFD of the design process, as given in Fig. 6.

The quantified technology parameters were used in the equations of the connected system parameters, as stated in conceptual modeling. To quantify the impact of technology parameters on productivity and error variables in the computerized model, GMB-4 was conducted, and the expected impacts of the future scenarios were reflected in the model formulations as IF ELSE statements. For example, for the design process, the impacts of automation were reflected in the design efficiency equation with different constants, as given in Eq. (1)

$$\begin{aligned}\text{Design efficiency} = {} & \text{IF}\,(\text{Automation of design} \\ & \geq 0.6 \text{ AND Automation of design} < 1) \\ & \times \text{THEN}\,(1.20 \times \text{Fatigue}) \\ & \times \text{ELSE IF Automation of design} \\ = {} & 1 \text{ THEN}\,(1.5\times)\,\text{ELSE Fatigue} \qquad (1)\end{aligned}$$

The actual error ratios were quantified considering endogenous (e.g., the effect of schedule pressure on errors) and exogenous variables (technology parameters). For instance, BIM maturity level 3 and network-based integration have an influence on the level of construction errors; however, considering the human influence on errors, as experts stated, even with flull technological maturity, there can be a minimum level of errors assumed to be 5%. Errors create rework, but with a delay because rework discovery takes some time, where rework detection can be reduced by technology use (e.g., with RFID for production). These assumptions were incorporated in equations, as given in detail in Supplemental Data Table S3.

Although this aspect may not be subject to empirical validation, it is important to emphasize that the central aim of this paper is not to posit correlations between an advancement in technology and an equivalent upsurge in productivity or decrease in time. The main argument behind the model is that impacts of technology should be concurrently evaluated with internal factors (such as mitigation strategies, external and internal capabilities, etc.) and considering dynamic processes.

In addition to model parameters, assumptions were made related to (1) the flow of project processes and (2) external factors. The project process was initially modeled from the time perspective, and its unit was selected as a week for a medium-sized modular project. The project flow was modeled according to the task dependencies and logical relationships between the processes.

Second, the modular construction company was encountering uncertainties due to additional work requests by clients. Change

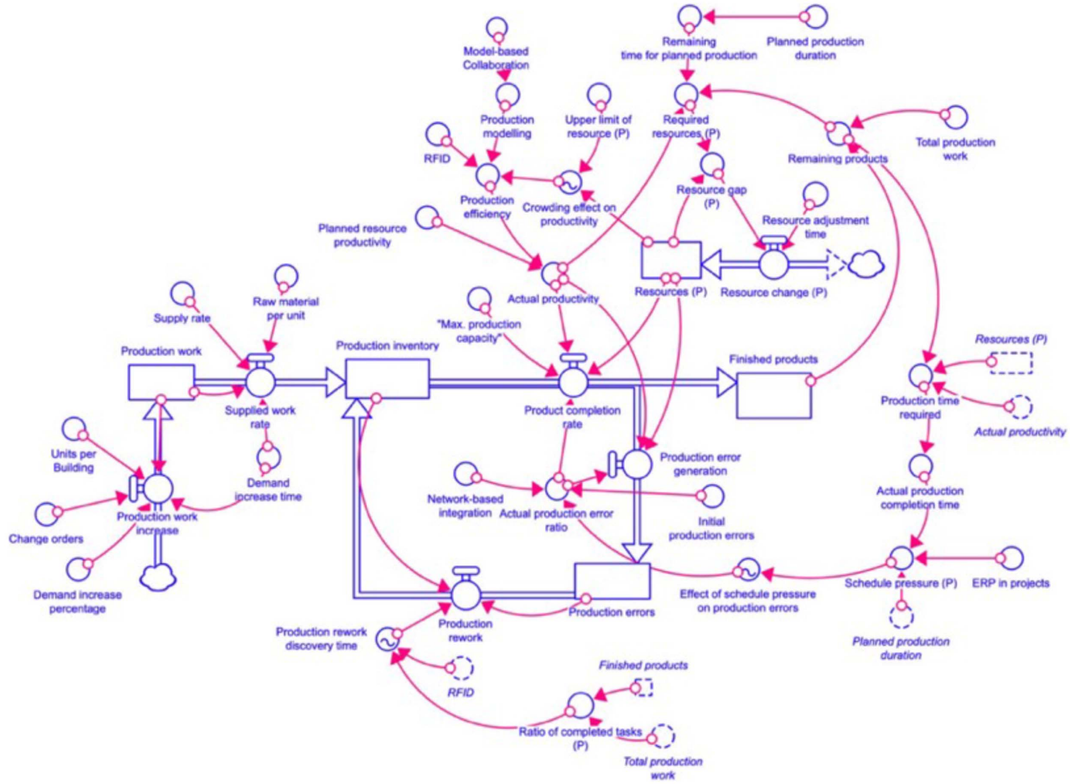

Fig. 7. Stock flow diagram of the production process.

orders at the design stage may result in additional work, or there may be additional production units (panels, modules) requested with the same design. To reflect these aspects, two exogenous model parameters were implemented as *change orders* and *production work increase* as additional flows to initial stocks with STEP built-in software. Considering the timing of change orders is uncertain in projects, it was randomly simulated for different scenarios. On the side of material supply, the third external parameter *order increase* was configured to model the amount of additional material required in case of insufficient supply.

For the production process, the initial level of resources was iteratively altered by the simulation itself to finish the project in the expected duration by increasing the resource gap in hiring time. However, similar to many workplaces, there is a capacity, an upper limit of resources. For that, the crowding effect on productivity was reflected in the efficiency equations. Although production and construction processes have a similar pattern for model development, the main difference is the parameter of maximum production capacity, added as another company-specific capability parameter. The finalized SFD of the production and construction processes can be found in Figs. 7 and 8, respectively.

After deciding on the model parameters, interactions, and assumptions that include both the resources and capabilities of the case company and external market-related uncertainties, the SFDs for each process were created by the conceptual causalities and mathematical equations, as summarized in Supplemental Data, Table S3, and presented in detail in Kaya (2022).

The finalized SFD of each process is dependent on not only technical factors of projects but also human factors (e.g., initial productivity and error parameters) and company capabilities such as the competency of the technology team, existing level of technology integrations, and consequences of selected managerial actions. Consequently, the duration of each process and project, final resource and material levels, overtime factors and liquidated damages multiplied by unit cost percentages for the SFD of the project cost are given in Fig. 9. The details of the time and cost sector equations are also given in Table S4, Supplemental Data.

Model Validation and Verification

As the third step of the SD development, the system parameters and defined equations were iteratively validated with different tests from the literature. Coyle (1977) defined SD validation as examining the purpose and confidence of a model for real-world reflection. In the construction management literature, model validation has been usually conducted by case studies and compared with real-world data by consulting with industry experts (Dangerfield et al. 2010; Ogunlana et al. 2003). Within the scope of this study, the model validation was conducted in two ways: (1) by validating the structure and assumptions and (2) by verifying the technical correctness of equations and implementation. Forrester and Senge (1980) stated that for structural validity, the model can be compared with the descriptive knowledge of the real system, and behavior may be tested regarding the observed real-system behavior. Thus, a structural verification test was conducted to compare with the real world. In this research, the group model-building sessions provided empirical validation, as guided by the experience of the participants and descriptive knowledge. This empirical validation encompassed the continuous discussions with the partners during the group modeling sessions, which shaped the conceptual models of each process. The model parameters, including the project, digitalization, and extreme conditions, were defined together with the company experts and iteratively validated throughout the sessions. Structure verification entails a direct comparison between the model's structure and the actual system it represents, in this case the real modular construction project processes. Verification may involve experts

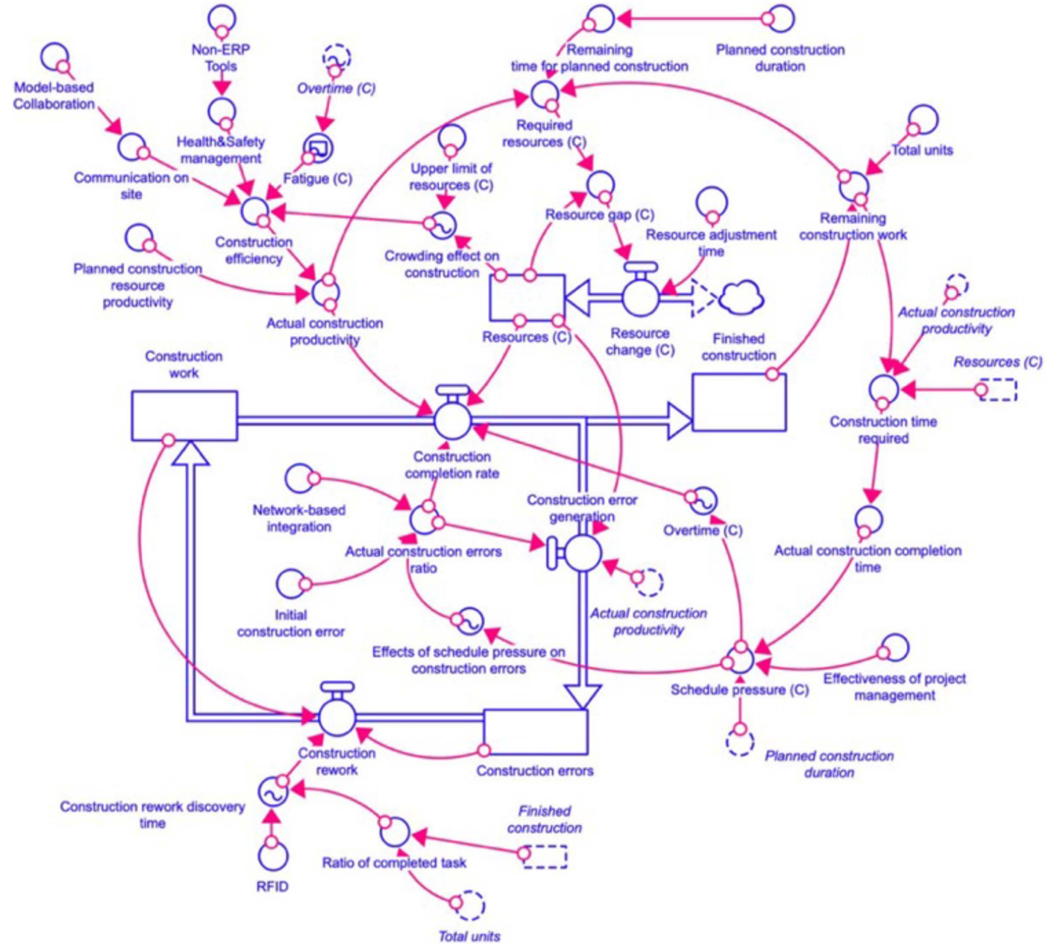

Fig. 8. Stock flow diagram of the construction process.

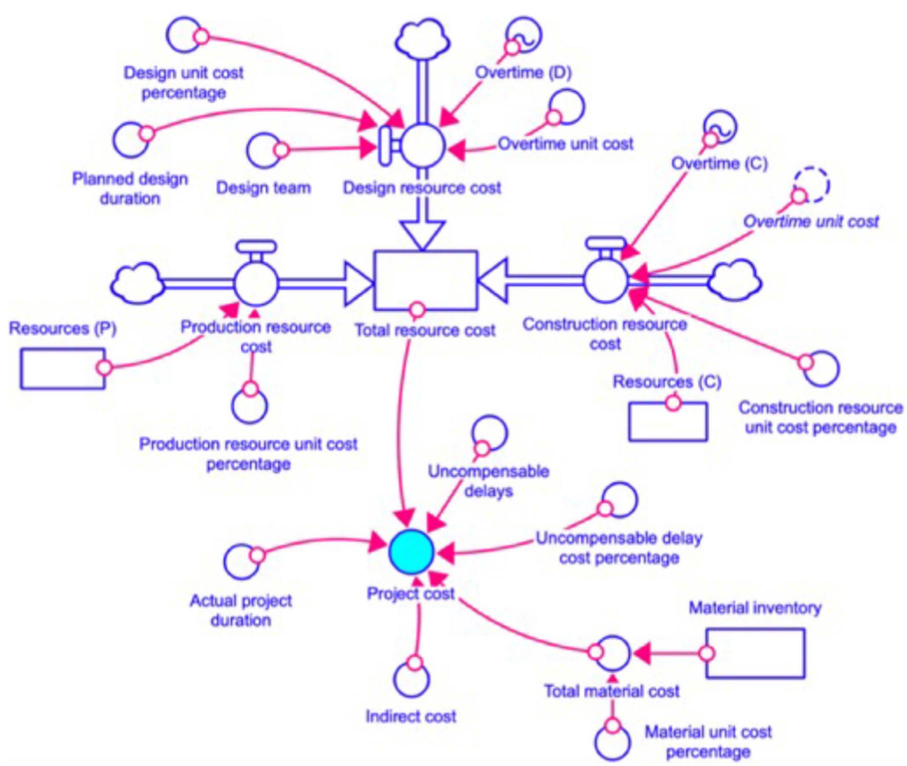

Fig. 9. Stock flow diagram of project cost.

reviewing the model's assumptions in relation to relevant aspects of the real system and examining how these assumptions align with existing literature on decision-making and organizational relationships. Initially, the modeler used similar system dynamics models from the literature as a basis for the project process, such as error generation and rework structures, productivity, and schedule pressure equations (Lyneis et al. 2001; Lyneis and Ford 2007); then, the technology-related strategy parameters and external conditions of the projects were added to the model according to discussions with the experts for each process. At the end of the conceptual models of each process, during GMB-3 and GMB-4, both the opinions of C-level executives (verifying the strategy parameters) and project managers (verifying the logic of sequence of processes and managerial action parameters) were used for validating the structural relevance of the model.

As one of the key validation steps for computerized modeling, a dimensional consistency test was conducted with the unit checker of Stella Architect. Initially, when transferring conceptual models to stock flows, it was noted that the model had over 50 unit warnings. To ensure consistency, adjustments were made to the units. With experts, the main units for each process were established, such as production "units" and supply in "tonnes." To rectify errors, different conversion factors were implemented in the model; for instance, errors arose in the Stella software due to the discrepancy between the unit of design completion rate ("Buildings/Weeks") and the order ("Tonnes"). To address this issue, the model was modified by introducing the parameter "Units per Building" to represent the units required for producing and installing one building. These units were then converted into material units using the "Raw Material per Unit" factor. However, it is important for these unit conversion parameters to align with the real system. Hence, a parameter verification test was conducted in collaboration with the experts from the case company. Ultimately, after clarifications and adjustments to the units, the dimensional consistency was verified using Stella Architecture. The parameter verification test was conducted, which examines whether the parameters are relevant to the system's descriptive and numerical knowledge. Necessary changes were done iteratively during the group modeling sessions, and the computerized model passed the test because the company experts set the values for each parameter comfortably for simulation. As another critical test, the extreme conditions test was applied to understand the behavior of the system under sudden shocks by evaluating different imaginary maximum and minimum values. First, the test was applied for technology-related input parameters and then sudden shocks, such as change orders. According to the data of the baseline project, both groups of parameters were tested for worst scenarios and modified according to the behavior of real projects under these circumstances. The necessary changes made for these two tests are summarized in Table S5 and Table S6, respectively, in the Supplemental Data. As a result of 61 tests in Stella (Kaya 2022), the developed model was finalized. Thereafter, as the most important part of the validation step, the model was tested with the inputs of the experts and compared with the actual project data. The conducted baseline testing and results of the scenarios simulations are presented in the following section.

Simulation: Scenario Analysis and Testing of Strategies

The simulation included two one-off tests with the company. To uncover the dynamic behavior of the model under various future situations, scenario testing was carried out, and the impacts of technologies were analyzed. The inputs for the baseline testing are given in Table 3.

Table 3. Data of major variables for the baseline scenario

Category	Parameter	Input	Units
Design	Initial design work	4	Buildings
	Initial designer productivity	1.3	Buildings/week/team
	Design team	1	Team
	Planned design duration	3	Weeks
	Design error ratio	30	%
Supply	Units per building	250	Units/buildings
	Planned supply duration	5	Weeks
	Missing material	20	%
Production	Initial production work	1,000	Units
	Planned production duration	12	Weeks
	Resource Productivity	1	Units/week/resource
	Max. production capacity	130	Units/weeks
	Initial resource	80	Resource
	Production error percentage	20	%
Construction	Planned construction duration	8	Weeks
	Resource productivity	5	Units/week/resource
	Initial resource	30	Resource
	Construction error percentage	10	%
	The upper limit of resources	40	Resource
External	Change order	15	%
	Production work increase	30	%
	Material order contingency	15	%
Technology	LOD in object-based models	4	(1-5)
	Level of integration of time and cost data	2	(1-5)
	Level of interoperability (model-based collaboration)	3	(1-5)
	Level of integration of processes (network-based integration	2	(1-5)
	Competency of the technology team	4	(1-5)
	RFID	0	(0 or 1)
	ERP	2	(1–3)
	Safety tools	0	(0 or 1)
Cost	Design team cost	5	%
	Production resource cost	20	%
	Construction resource cost	7.5	%
	Material cost	50	%
	Indirect cost	15	%
	Uncompensable delay cost	2.5	%

For simulation purposes, random numbers were generated for the timing of change orders and production work increases. A baseline scenario was tested with the given inputs of the case project, which encountered change orders during the design stage (Week 2) and additional unit requests during production (Week 7). According to the simulation, for a 45% work increase, the project cost increased by nearly 50% with a 30-week project duration, with 5 weeks of delay from the planned duration. During GMB-5, the project manager and digitalization experts compared the results with real project data and stated that the results were reasonable for the baseline scenario, so the final SFDs were set for scenario testing. The comparison of the performance indicators of the model and real project can be seen in Table 4.

A total of seven priorities, as previously discussed, were operationalized as strategies in the existing model by changing the level/maturity of technology parameters. The strategies were selected

Table 4. Comparison of model with project data

Category	Cost increase (%)	Actual design duration (weeks)	Actual supply duration (weeks)	Actual production duration (weeks)	Actual construction duration (weeks)	Project duration (weeks)	Uncompensable delays (weeks)
Baseline	52.73	4.24	9	18.06	8.11	30.41	4.17
Project data	53	4	9	18	8	31	5

Table 5. Changes in the base scenario for simulations

Simulation	Related technology parameter	Baseline rating (i)	With improvement ($i+1$)
Strategy 1	LOD in object-based models	4	5
Strategy 2	Level of integration of time and cost data	2	3
Strategy 3	Level of interoperability	3	4
Strategy 4	ERP	2	3
Strategy 5	RFID	0	1
Strategy 6	Level of integration of processes	2	3
Strategy 7	Safety tools	0	1
Scenario 1	Production work increase	30%	10%
Scenario 2	Time of change orders	Week 2	Week 12

Table 6. Key findings of strategies

	Key outputs					
Category	Cost increase (%)	Project duration (weeks)	Uncompensable delays (weeks)	Actual design error (%)	Actual production error (%)	Actual construction error (%)
Baseline	52.73	30.41	4.17	34.7	23.1	10.0
Strategy 1	52.59	30.36	4.17	27.5	23.1	10.0
Strategy 2	51.42	30.35	4.17	24.0	23.1	10.0
Strategy 3	34.15	28.3	2.18	24.0	22.6	10.0
Strategy 4	33.98	28.3	2.18	24.0	20.0	10.0
Strategy 5	26.98	27.5	1.47	24.0	20.0	10.0
Strategy 6	23.7	27.45	1.34	24.0	8.0	4.0
Strategy 7	20.9	27.45	1.34	24.0	8.0	4.0

Note: Strategy 1: Improving LOD in object-based modeling for BIM, Strategy 2: Improving time and cost data integration for BIM, Strategy 3: Improving level of interoperability, Strategy 4: Improving ERP with BIM, Strategy 5: Implementing RFID, Strategy 6: Improving the level of integration for BIM, and Strategy 7: Implementing safety tools.

and implemented in order of importance, as stated in the initial session and conceptual modeling. Moreover, for specific technologies, the external conditions were altered (as Scenarios 1 and 2), and results were evaluated. The changes from the base case in each simulation are given in Table 5.

Finally, the results of each strategy are given in Table 6, along with the baseline.

Testing the Impacts of Alternative Digitalization Strategies by Simulation

The first strategy was determined as increasing the automation of design by increasing the level of details in the object-based parametric models that provide further coordination and facilitate change management. The parameter increased by one level under the same circumstances as the baseline scenario. Accordingly, the automation of design improved from 64% to 80% for the same competency of the technology team. Considering the external change requests from the client for the case project, the strategy was not entirely sufficient to decrease cost increases and delays. The major impact of the strategy was observed in decreasing design errors. The second strategy was determined as improving the integration of time and cost data, which influenced the effectiveness of project management for design and construction processes, as given in Fig. 10.

Accordingly, it was observed that the reason behind decreasing cost and design errors was releasing the schedule pressure and therefore the requirement of overtime and its negative impact on design errors. Therefore, the overtime cost for design was impeded by this strategy. The third strategy of the company was to improve the interoperability for different models; therefore, the related parameter increased by one level. The simulation results for that strategy indicated the major influence on cost by increasing the production and construction efficiency, which eliminated the demand for resource allocation and thus decreased resource cost. The conceptually linked aspects of model-based collaboration for production modeling and communication on-site generated a significant resource level decrease for the existing dynamics of the project, as given in Fig. 11.

As the fourth strategic priority, ERP system integration was improved, and current material lists was coordinated with BIM. The results of the simulation indicated that this strategy mainly influenced the material cost, improving inventory levels. Nevertheless, during GMB-6, with the experts, it was observed that because the

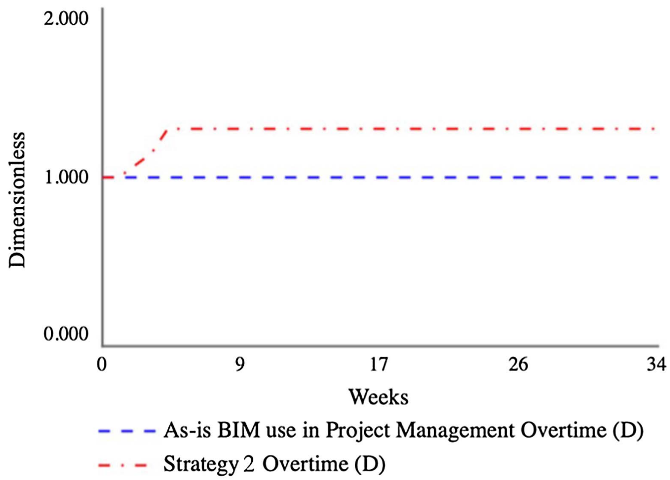

Fig. 10. Strategy 2 and design overtime.

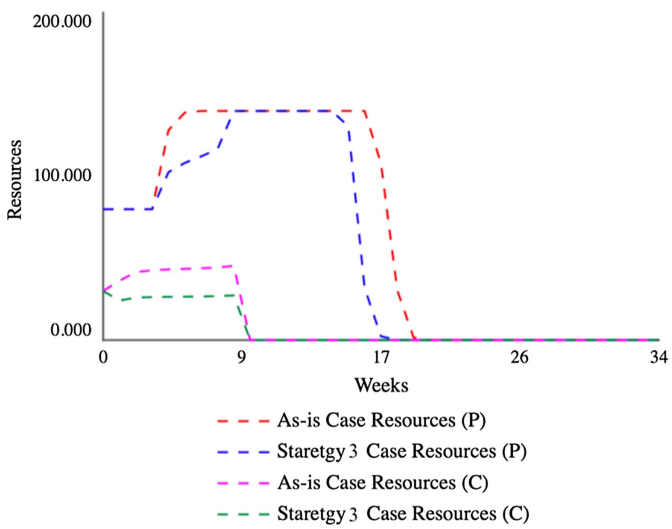

Fig. 11. Strategy 3 and resource levels of production and construction.

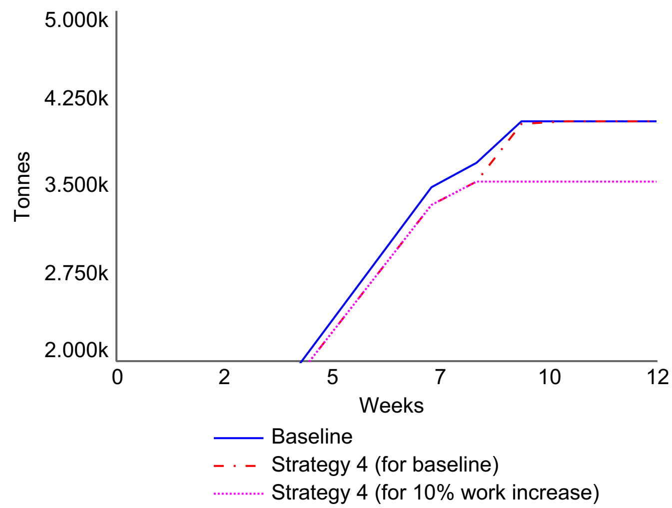

Fig. 12. Strategy 4 results and material inventory.

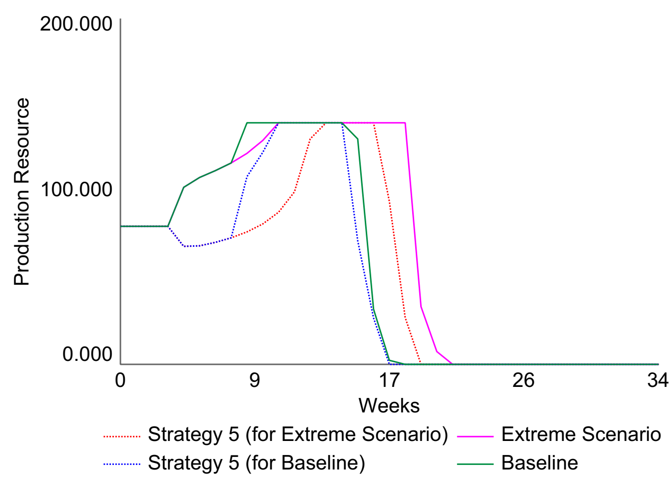

Fig. 13. Strategy 5 results for production resource levels.

determined order contingency for the project was not sufficient for the external change requests, the impact of ERP could not be fully understood for inventory management. Therefore, another scenario was tested, with a 10% production work increase, as given in Fig. 12. Accordingly, the strategy enabled decreasing the excessive material ordering with more accurate and updated material lists, which resulted in a 9% decrease in material costs.

The next strategy of the company was implementing RFID technology, which drastically improved workforce productivity by decreasing the amount of time needed to track production units. As a result, there was less demand for extra resources in the case of change orders and material discrepancies in supply, which resulted in a cost decrease. Because the simulations revealed that the RFID technology significantly increased productivity and sped up the detection of reworks at the construction site, during GMB-6, another scenario was tested with the experts as an extreme situation: requests from the client at Week 12. In the extreme scenario, RFID was not adequate to manage the delays because there was a need for an additional material and resource allocation strategy at the end of the planned project duration, as depicted in Fig. 13.

As the sixth strategy related to BIM maturity, the level of network-based process integration reduced the production and construction error ratio, which increased the overall schedule performance. The last strategy, implementing safety tools for construction sites, increased the existing construction efficiency by 89%, which also reduced construction cost, as also given in Table 6.

Discussion of Findings

After the simulations were complete, in GMB-6, company experts were questioned regarding whether the simulation assisted them in understanding the advantages of digitalization considering the company and project dynamics. It was revealed that SD was particularly useful for analyzing the impacts and interactions between technologies, project and company factors, and external factors under different scenarios. Some of the findings that may affect decisions on digital technology adoptions can be listed as follows:

1. About the impacts of capabilities and external factors: It was revealed that, even if Strategy 1, which was increasing the level of detail of the object-based models, were implemented, full automation to manage change orders during design would not be possible if the competency of the technology team, interface management process, and collaborative design practices were not improved. On the other hand, the third strategy,

increasing the level of interoperability (model-based collaboration), was discovered to be the most potent factor in lowering the cost increase due to change requests by accelerating rework detection for design, increasing productivity by eliminating the necessity of two separate production and design models, and enhancing communication on the construction site. SD findings showed that both the impacts of ERP and RFID-related strategies were dependent on external conditions such as supplier performance and internal factors such as management competency of the company. For instance, the benefit of the ERP strategy was influenced by how reliably contingencies were estimated by the company. There is a need for better planning and accurate contingency estimations to maximize the benefits of ERP and RFID. This finding highlights that companies should evaluate the potential benefits of a new digital technology or feasibility of a digitalization strategy by considering the company capabilities as well as the occurrence of alternative scenarios that may happen as a result of changes in the external environment (Love and Matthews 2019; Nikmehr et al. 2021).
2. About the impact of dynamic external factors and reactive strategies: The model represented a trade-off between company actions or resources and the impacts of technology-related strategies. In that regard, implementing RFID was identified as a viable digital technology due to its potential to increase productivity in the factory, but the simulation results pointed out the incompetency of technology if there is a need for high resource reallocation under extreme external conditions. Therefore, the maximum production capacity of companies is decisive in this context and limits the expected performance. Therefore, the benefits of digital technology are contingent on dynamic conditions and reactive actions to be taken by the company.
3. About the impact of digital strategies on managing risks: The company was operating in an uncertain environment, where the one of the expectations from technologies was about decreasing the risk. Technologies like BIM and RFID mainly reduced the requirement of overtime and additional resource allocation in case of any delays by increasing automation and productivity. By looking at the model outputs, the experts became aware that using these technologies would decrease vulnerability to external uncertainties and delays. Moreover, increasing the maturity of BIM with process integration and combining it with other technologies like IoT and the cloud (maturity level 3) is expected to decrease human-related errors, as also highlighted by Tang et al. (2019). The findings demonstrate that one of the major benefits of digital technologies is to increase resilience under uncertain operating conditions.

It is apparent that the most feasible strategy also depends on the costs. The SD model gave useful insights to decision-makers about the potential benefits of alternative strategies, but the costs should be estimated to find the most feasible strategic option(s).

Conclusions

This research proposed that digitalization decisions should be considered as strategic decision-making problems, and there is a need for a systems thinking approach to improve understanding of the existing and future dynamics of business processes as well as project-related factors. A demonstrative case study was conducted with an experienced international modular construction company to reveal how SD models can support decision-making about digital technologies. For this purpose, the business process engineering approach was used to model the company's current and prospective processes, and different technologies were configured as strategic options for possible process improvements. The chosen digital technologies, such as BIM, RFID, and ERP, and their various levels of maturity were then taken into consideration during the conceptualization stage to identify which processes and performance indicators may be influenced along with the project characteristics, managerial decisions, and their consequences (feedback). The computerized model was built for four processes: design, supply, production, and construction, using Stella Architect software and iteratively evaluated using structural and behavioral validation tests. The simulation results led to the conclusion that when taking into account advantages of different technology improvements, project-specific conditions (e.g., productivity and errors), the internal capabilities of the company (e.g., competency of the technology team, management strategies), and external uncertainties (e.g., change orders) have a significant impact on the effectiveness of digitalization choices. For instance, the impact of ERP depends on both internal factors (such as contingency estimation) and market conditions (such as supply); thus, the overall impact of ERP can not be assessed without considering any one of these factors or conditions. It has been found that technologies can help cope with changes in the environment, but their impacts are pursuant to the inherent dynamics of projects and the current technological and managerial abilities of the company.

The case study demonstrated how SD models can help company professionals to understand causalities and feedback between their actions, internal factors, uncertainty, and impacts of digital technology. Findings pinpoint that companies should evaluate the potential benefits of a new digital technology and feasibility of a digitalization strategy by considering the company capabilities as well as alternative scenarios that could impact the consequences of technology implementation. Although the findings are case specific, because the SD model involves general strategic parameters such as internal capabilities, external uncertainties, and maturity levels of different technologies, it can be accommodated for different projects and companies using the proposed modeling approach, contributing to SD literature in construction management domain. Another theoretical contribution of this paper lies in demonstrating the potential use of SD for strategic decision-making in construction companies, highlighting benefits and limitations of digital technologies in a case company. It is believed that this study contributes to the digital transformation research agenda from the perspective that digitalization strategies should be formulated considering several company and project-level parameters as well as external factors that tend to change over time rather than taking the benefits of technology for granted. The advantages anticipated from technology deployments are constrained by company skills and resources and vary depending on external circumstances and the firm's responses, and SD can be used to examine these dynamics at play during decision-making.

As in all system development research, some limitations exist. First, because the SD models only take into account a part of the system and environment, it is not possible to fully validate and generalize the models. Second, although the constructed model accurately captures the system and its environment by structuring it to serve the intended purpose, its operational validity remains to be tested in the future. Moreover, this research did not take into account factors such usability or perception; instead, technologies were seen as tools that simply enable efficient running of processes, disregarding the factors that could reduce the impact of technologies, such as individuals behaviors. In future studies, different technologies (e.g., blockchain, robotics) and business processes can be integrated into the proposed model, considering different performance criteria as well as technology acceptance of the organizations.

Data Availability Statement

Some or all data or code that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

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Supplemental Data

Tables S1–S6 are available online in the ASCE Library (www.ascelibrary.org).

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