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Article

Accepted Version

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ABSTRACT

Although digitalization becomes a prospect that is counted on for many problems in the construction industry, there are limited attempts on exploring decision-making processes in construction firms about 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 BIM, ERP and RFID at different maturity levels. The simulation tests revealed that the impacts of technologies are influenced by both the internal dynamics of projects, 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.

Author keywords: Digitalization, System Dynamics Modelling, 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 2020; European Construction Sector Observatory Report 2021; RICS Report 2022). Oesterreich and Teuteberg (2016) proposed the utilisation 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 digital technologies of Industry 4.0 such as big data, cybersecurity, cloud technology, additive manufacturing, and augmented reality. Entrenching 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 prioritising sustainability for a new production model within the industry (European Commission 2021). Considering that construction industry has a slow undertaking for implementing technologies and adopting 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, BIM fills the gap of structured information exchange through digital modelling 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 IoT devices with BIM, and Li et al. (2017) integrated RFID for prefabricated construction. Using the real-time data driven from the sensors or IoT devices for BIM processes, digital twins (DT) stepped forward for the integration of the physical world with the virtual. As autonomous systems, DT paved the way for advanced project management practices by helping the data communication, better predictions, and flexibility to uncertainties for construction processes (Pan and Zhang 2021). Despite the popularity of considering BIM as a requisite for the digital transformation of the industry, scepticism still continues for the development of an integrated BIM environment, which can be observed by the prevalence of using modelling 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 towards collaborative working and change in behaviour of practitioners in the industry (Eadie et al. 2014; Hajj et. 2021).

Despite various attempts in the literature about technology adoptions, the 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 impair the current status quo of the digital transition of construction firms, the practitioners need to recognize the new opportunities of technologies together with the technical, organisational, and external factors within a strategic context. In this regard, this research primarily aims to explore the strategic decision-making process in construction companies about implementing different digital technologies and assess impact of digital technologies at the project level. A systems approach has been utilised to model the decision-making process behind the technology integration including the project processes as well as company and business level factors. The research was carried out in collaboration with a modular construction company operating in international markets. Since the research targets to understand the strategic value of technology adaptation from an inclusive systems perspective, systems dynamics (SD) was utilised to simulate decision-making processes within this company. The developed SD model assesses the impacts of several factors such as company capabilities, project and management-related aspects, benefits as well as challenges associated with digital technologies and external uncertainties on the project environment. In the forthcoming parts of this paper, first, the research background will be presented about 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 would 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 most prominent applications of smart technologies as progress tracking, real-time monitoring, and schedule estimation. Where the literature is mostly focused on the utilisation of individual technologies for different tasks, there is a need of creating a proper strategy to help construction organizations define the key goals, pertinent actions, and assessment techniques (Love and Matthews 2019; Nikmehr et al. 2021). Moreover, while these studies revealed the benefits of individual technologies, there is still lack of studies that comprehensively elaborate the impact of technologies as strategies and analyse 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 with using different perspectives and methods. Among these one of the most commonly employed methods is technology acceptance models

(TAM), with placing the individual behaviour, intention to use, at its core place. Accordingly, 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), 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 made 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 common de facto is once a construction organization invested in new technology, it becomes obligatory for operators to use it in their work processes, which are overlooked in that literature (Sepasgozar 2023). Therefore, when considering the objective of this study as understanding the strategic value of digital technologies for the construction, the focus has been shifted from the influence of individuals' behaviours 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, VR/AR, sustainability) and value-driven computational design (digital designs for simulating changes, digital twin city). 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 I4.0 technologies into production systems by evaluating the sociotechnical factors such as people, organizational structure, and external environment. For the construction industry, the socio-technical 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 multi-objective optimization of projects (Guo and Zhang 2022), there is a lack of studies that focus on the dynamics of digital technology integration decision-making process. This study attempts to fulfil 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 the decision-making for the problems exhibited in them by understanding the behaviour 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 modelling 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 the project planning, control, and strategic decision-making by system dynamics, to the best of the authors' knowledge, there are no studies that analyse the outcomes of technology integration, particularly digital technologies using this method. With the intention to fill this gap in the existing literature, this research endeavours 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 modelling dynamics of technology implementations within companies taking into account of project, company and business factors to support digitalization decisions. It has been hypothesized that systems approach, particularly SD can be used for this purpose. Case study type of research is relevant for this research objective as in SD, a specific system or a specific problem is modelled with its constituent components and interactions. Case studies are compliant with construction project management research since 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 utilising the systems thinking perspective. Systems thinking proposes comprehending how things affect each other as a whole and considers "problems" as 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 modelling were used in this study.

The research used the two-step modelling methodology of SD, as proposed by several authors (Sterman 2000; Forrester 1997; Senge 1990). The first step is the conceptualization and qualitative modelling, which comprise causal loop diagramming (CLD). Then causalities are converted into level and rate variables to imitate the behaviour 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 utilizing stock-flow diagrams (SFD). Levels are represented by the stock variables whereas rates are variables of flow.

The two-stage model of the SD process is comprised of four consequential steps (1) conceptualization, (2) formulation, (3) testing, and (4) simulation (Sterman 2000). The conceptualization step encompasses the problem articulation and defining the system parameters and interrelations. For problem articulation, the strategic positioning of the case company in terms of digitalization was investigated, which includes describing the internal (resource-based) and external environment of companies for both current and future scenarios (Price and Newson 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-size 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.

<Insert Fig. 1 here>

THE CASE COMPANY

The research was carried out in collaboration with an international construction company which 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. Since the company emphasized globalization as a strategic goal in recent years, they complete many projects worldwide and have a presence in more than 60 countries. Moreover, the company is one of the biggest 250 contracting companies in the world, which appeared in the ENR (Engineering News-Record) list for the last ten years (ENR, 2018). The company is experienced in BIM, emphasized modern methods of construction 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 of analysing the effects of technologies on both controlled (fabrication/production process) and uncontrolled (assembly on site) environments.

The case company contributed to the SD model development with the involvement of staff in different modelling sessions, which are structured according to the framework proposed by Vennix (1995) as explained in the next section. The framework was comprised of creating models by brainstorming with the experts having diverse industrial knowledge and background. 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 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 MODELLING SESSIONS (GMS)

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

<Insert Table 1 here>

Firstly, 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 was configured. For that session, the contribution of the Chief Technology Officer (CTO) of the company was essential to ascertain the initial requirement to utilize SD modelling for strategic analysis. Then the system boundary was defined in the second session as the problem articulation step. For that step, the methodology of the SD modelling 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**.

<Insert Table 2 here>

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 utilised, the reasons behind the decision of digitalization, digital technologies that were aimed to be implemented and related key performance criteria were evaluated together with experts. The company was currently utilizing BIM as a modelling 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 improving the BIM coordination among different departments and different processes of the projects. Moreover, the company was experienced with the ERP system that has been used for the last 5 years for controlling the 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 which could be compensated with process improvements by digital technologies. Another reason for seeking technological solutions was identified as decreasing the rework. Considering the necessity of material supply for the entire process chain, the accuracy problem of the existing material lists was emphasized. For the 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. The 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 the modular construction has differences than 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 modelling 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 are embracing 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 as (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 referred to the communication of models or part of models using both proprietary and non-proprietary formats (e.g., IFC). It can take place within a single project lifecycle phase or between two phases, such as the architectural and structural model exchange during design, and the steel model exchange during production. In 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 the smart gateways in the front of factories. In the factory and construction site, tracking building components with RFID was identified as a priority. Despite having a competitive advantage through modularization, the experts noted that the company has to follow certain strategies and procedures to minimize the risk of accidents. One of these is 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**.

<Insert Fig. 2 here>

At the end of the initial session, the company experts prioritised the digitalization strategies for the current inefficiencies and mentioned possible technology integrations within the processes. Firstly, 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 the 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 encompasses 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 (SD) model parameters. It should be noted that the aforementioned technologies and process-based improvement strategies are 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 are modelled in SD will be explained further in the following sections.

Conceptual Modelling

As the first step of SD development, for conceptual modelling, the system parameters and the causalities were determined by Causal Loop Diagramming (CLD). Considering the time-dependent simulation feature of SD modelling, conceptual models were created for schedule performance, which was then used for analysing cost performance indicators in computerized modelling. Firstly, 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 is 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. Since the experts mentioned different remedial actions for different project processes, model parameters were changed for each process in the computerized modelling section. For the project progress, the adopted common logic is that the required work finishes with 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 used sources for the specific task (e.g., production and construction labours or design teams). Nonetheless, the project flows less than perfectly almost always, encounter some errors and hereby reworks. 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 Yuan 2017), 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.**

<Insert Fig. 3 here>

For instance, from Fig.3, B1 represents that as the actual completion time increases, so as the schedule pressure, which increase the actual error ratio and therefore rate of task completion and time again. Accordingly, the management strategies like overtime for releasing schedule pressure, and increasing the resource level for reducing remaining work were modelled 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.2011; Lyneis and Ford 2007.

The rationale behind the stated feedback loops comprises a basis for strategically re-drawn 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 modelling sessions conducted with the experts, 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 the strategic objectives related to BIM, the automation capabilities, interoperability between different models and the level of integration 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 4D and 5D models related as a strategy and relevant technology parameter defined as the *effectiveness of project management.* The experts mentioned that the 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 decided as another technology parameter as the depiction of interoperability between models. The last maturity level, *network-based integration* was considered as a system parameter that was connected with the error ratios of production and construction processes regarding its benefits for close-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 *missing materials* system parameter, that implements tags to material packages and trucks to read the 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 is increasing the resources (e.g., hiring labour, upscaling the number of equipment), which provides backup for the other projects in the portfolio. Since the 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/units. Therefore, *RFID* technology was connected with efficiency parameters and error detection parameters (the time of rework detection on the production site) of the production process. Besides, the additional effort/time required due to the two separate modelling of the design and production process was observed as a process inefficiency. Thus, the modeller added an interconnection between *model-based collaboration* and the *production modelling* system parameters. The related operational parameters and causalities can be observed from the finalized CLD of production process as an example in **Fig. 4.**

<Insert Fig. 4 here>

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 managemen*t to release schedule pressure. The technology-related system parameters and their linked model parameters are given in **Fig.5.**

<Insert Fig. 5 here>

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 supply chain (Tambovcevs and Merkuryev 2009; Powell 2013), RFID influence on missing materials (Demiralp et al. 2012). Although the technologies and causalities may differ in another company, the objective of the paper is to demonstrate the influence of SD on decision-making of technology integration. Hence, SD is proposed as a generic method and how it can be developed and implemented in practice to test impacts of digital technology is demonstrated by a case company. Based on the conceptual model, each process is drawn in the Stella Architect CLD window and transferred into stock-flow diagrams as will be explained in the next section.

Computerized Modelling

The CLD for each project process was converted into SFD in Stella to test and simulate the system. Firstly, 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 (6) formulations. Accordingly, the endogenous (internal) factors encompass 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 the 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 the market were defined together with management strategies. The formulation parameters were added to the model as converters aiming to transfer information to variables and ensure dimensional consistency.

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

For instance, *automation of design* parameter was calculated in percentage according to the rating of the level of details (LOD) in object-based models, level of interoperability and competency of the technology team. LOD of object-based models referred to parametric modelling as the preparation and modularization of 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 decided 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, modelled as binary digits in the model, as given in Supplementary Data, Table S1.

Considering the supply process, IF THEN rule was defined to link accuracy of material quantities with the implementation level of ERP. The experts assumed full/perfect accuracy (1) if ERP level is 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 3-5), efficiency will increase with 25%. The exemplified model equations are given in Table S2 in Supplementary 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/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 exemplified from the finalized SFD of the design process as given in **Fig.6.**

<Insert Fig. 6 here>

The quantified technology parameters were used in the equations of the connected system parameters as stated in conceptual modelling. 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.

$$\text{Design efficiency} = \text{IF } (\text{Automation of design} \geq 0.6 \text{ AND Automation of design} < 1) \\ \text{THEN } (1.20 * \text{Fatigue}) \text{ ELSE IF Automation of design} = 1 \text{ THEN } (1.5 * \text{Fatigue}) \text{ ELSE Fatigue} \quad (1)$$

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 influence on the level of construction errors, however considering the human influence on errors, as experts stated, even with the full technological maturity, there can be a minimum level of errors assumed as %5. The errors create reworks, but with a delay as rework discovery takes some time. where rework detection can be reduced by technology utilisation (e.g., with RFID for production). These assumptions were incorporated in equations, as given in detail in Supplementary Data Table S3.

While this aspect may not be subject to empirical validation, it is important to emphasize that the central aim of the 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, the assumptions were made related to (1) the flow of project processes and (2) external factors. The project process was initially modelled from the time perspective and its unit was selected as a week for a medium-size modular project. The project flow was modelled according to the task dependencies and logical relationships between the processes.

Secondly, modular construction company was encountering uncertainties due to additional work requests by the clients. The change 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 the 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 requirement 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, redound on as another company-specific capability parameter. The finalized SFD of the production and construction processes can be found in **Fig. 7** and **8**, respectively.

<Insert Fig. 7 here>

<Insert Fig. 8 here>

After deciding on the model parameters, interactions and assumptions that embrace 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 Supplementary 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, the 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 with unit cost percentages for 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, Supplementary Data.

<Insert Fig. 9 here>

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 (i) by validating the structure and assumptions and (ii) 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 behaviour may be tested regarding the observed real-system behaviour. 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 encompasses the continuous discussions with the partners during the group modelling sessions which shaped the conceptual models of each process. The model parameters including the project, digitalization and extreme conditions 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 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 modeller used the 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 the discussions with the experts for each process. At the end of the conceptual models of each process, during the GMB-3 and 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 the Computerized Modelling, 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 modelling sessions and the Computerized Model passed the test since 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 behaviour of the system under sudden shocks, by evaluating different imaginary maximum and minimum values. Firstly, the test was applied for the technology-related input parameters and then the sudden shocks, such as change orders. According to data of baseline project, both groups of parameters were tested for worst scenarios and modified according to the behaviour 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 Supplementary 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 behaviour of the model under various future situations, scenario testing was carried out and the impacts of technologies were analysed. The inputs for the baseline testing are given in **Table 3**.

<Insert Table 3 here>

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-weeks project duration, with 5 weeks of delay from the planned duration. During the 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.

<Insert Table 4 here>

A total of seven priorities, as previously discussed in the paper, were operationalised as strategies in the existing model by changing the level/maturity of technology parameters. The strategies were selected and implemented in order of importance as stated in the initial session and conceptual modelling. Moreover, for specific technologies, the external conditions were altered (as scenario 1 and 2) and results were evaluated. The changes from the base case in each simulation is given in **Table 5**.

<Insert Table 5 here>

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

<Insert Table 6 here>

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 with 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 influences the effectiveness of project management for design and construction processes as given in **Fig 10.**

<Insert Fig 10 here>

Accordingly, it was observed that the reason behind decreasing cost and design errors was releasing the schedule pressure and hereof 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 with one level. The simulation results for that strategy indicated the major influence on cost, by increasing the production and construction efficiency, which eliminates the demand for resource allocation and thus decreases resource cost. The conceptually linked aspects of model-based collaboration for production modelling and communication on-site generated a significant resource level decrease for the existing dynamics of the project, as given in **Fig.11**.

<Insert Fig 11 here>

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 influences mainly the material cost improving inventory levels. Nevertheless, during the GMB-6, with the experts, it was observed that since the determined order contingency for the project was not sufficient for the external change requests, the impact of ERP cannot 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.

<Insert Fig. 12 here>

The next strategy of the company is implementing RFID technology which drastically improved workforce productivity by decreasing the amount of time needed to track the 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. Since the simulations revealed that the RFID technology significantly increased productivity and speed up the detection of reworks at the construction site, during GMB-6 another scenario was tested with the experts, as an extreme situation, which is requests from the client at Week 12. In the extreme scenario, RFID was not adequate to manage the delays since there was a need for additional material and resource allocation strategy at the end of the planned project duration.

<Insert Fig.13 here>

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 the 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 was 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 as the most potent factor in lowering the cost increase due to the change requests, by accelerating the 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 are 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 is influenced by how reliable contingencies are 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 digitalisation strategy by considering the company capabilities as well as 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 the the company actions/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 need of high resource reallocation under extreme external conditions. Therefore the maximum production capacity of the companies is decisive in this context and limits the expected performance. Therefore, the benefits of a digital technology is contingent on dynamic conditions and reactive actions to be taken by the company.

3. About 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. The technologies like BIM and RFID mainly reduce 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 cloud (maturity level 3) is expected to decrease human-related errors as also highlighted by Tang et al. (2019). 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 the decision-makers about 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 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 behavioural validation tests. The simulation results led to the conclusion that, when taking into account of 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/conditions. It has been found that technologies can help coping with the 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 assist 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 digitalisation strategy by considering the company capabilities as well as alternative scenarios that could impact consequences of technology implementation. Although the findings are case specific, since 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 modelling 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, 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 every system development research, some limitations exist. Firstly, 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. Secondly, 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 the 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 supported the findings of this study are available from the corresponding author upon reasonable request.

ACKNOWLEDGEMENTS

The authors represent sincere thanks to the Turkish construction company which supported this research as the case company and participated in the group modelling sessions.

SUPPLEMENTARY MATERIALS

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

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Table 1: The 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 modelling 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 re-drawn 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

Table 3: Data of major variables for the baseline scenario

	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	1000	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	%

Table 4: Comparison of model with project data

	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					
	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

Strategy 1: Improving LOD in object-based modelling 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, **Strategy 7**: Implementing safety tool

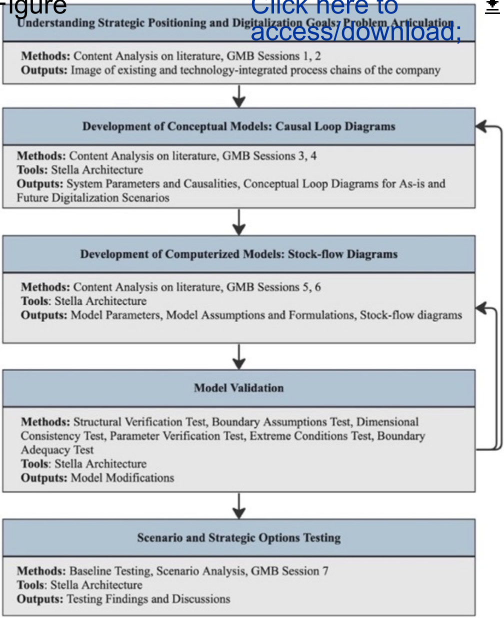
List of Figures

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


Understanding Strategic Positioning and Digitalization Goals: Problem Articulation
Methods: Content Analysis on literature, GMB Sessions 1, 2
Outputs: Image of existing and technology-integrated process chains of the company
Development of Conceptual Models: Causal Loop Diagrams
Methods: Content Analysis on literature, GMB Sessions 3, 4
Tools: Stella Architecture
Outputs: System Parameters and Causalities, Conceptual Loop Diagrams for As-is and Future Digitalization Scenarios
Development of Computerized Models: Stock-flow Diagrams
Methods: Content Analysis on literature, GMB Sessions 5, 6
Tools: Stella Architecture
Outputs: Model Parameters, Model Assumptions and Formulations, Stock-flow diagrams
Model Validation
Methods: Structural Verification Test, Boundary Assumptions Test, Dimensional Consistency Test, Parameter Verification Test, Extreme Conditions Test, Boundary Adequacy Test
Tools: Stella Architecture
Outputs: Model Modifications
Scenario and Strategic Options Testing
Methods: Baseline Testing, Scenario Analysis, GMB Session 7
Tools: Stella Architecture
Outputs: Testing Findings and Discussions

Figure

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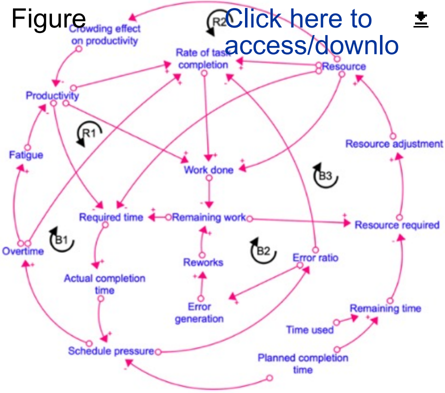

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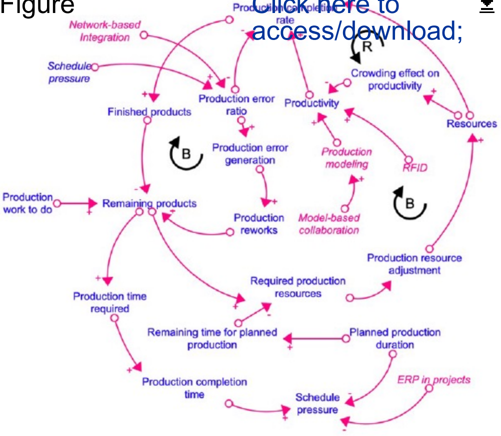
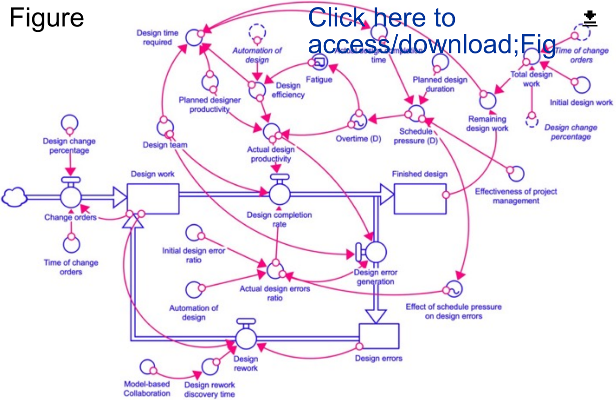


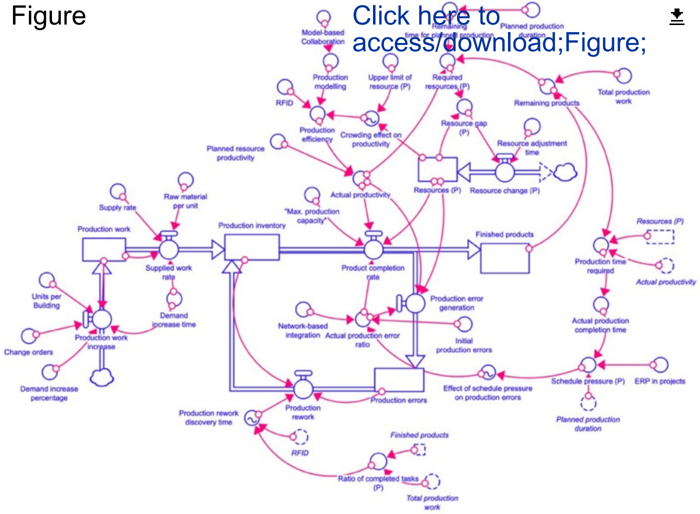
	Priorities	Model Parameters	Linked Model Parameters			
			Design	Supply	Production	Construction
1	Increasing the level of details and interoperability of BIM models for automation (BIM Level-1)	Automation of design	Design efficiency Design error ratio			
2	Increasing the integration of time and cost 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

Figure



Design time required
Automation of design
time
Time of change orders
Total design work
Initial design work
Planned design duration
Design efficiency
Fatigue
Planned designer productivity
Remaining design work
Design change percentage
Design team
Actual design productivity
Overtime (D)
Schedule pressure (D)
Design change percentage
Design work
Finished design
Effectiveness of project management
Change orders
Design completion rate
Time of change orders
Initial design error ratio
Design error generation
Actual design errors ratio
Automation of design
Effect of schedule pressure on design errors
Design rework
Design errors
Model-based Collaboration
Design rework discovery time

Figure



Remaining time for planned production
Planned production duration
Model-based Collaboration
Production modelling
Upper limit of resource (P)
Required resources (P)
Remaining products
Total production work
RFID
Production efficiency
Crowding effect on productivity
Resource gap (P)
Resource adjustment time
Planned resource productivity
Actual productivity
Resources (P)
Resource change (P)
Supply rate
Raw material per unit
"Max. production capacity"
Production work
Production inventory
Finished products
Resources (P)
Supplied work rate
Product completion rate
Production time required
Actual productivity
Units per Building
Demand increase time
Production error generation
Network-based integration
Actual production error ratio
Initial production errors
Actual production completion time
Change orders
Production work increase
Demand increase percentage
Effect of schedule pressure on production errors
Schedule pressure (P)
ERP in projects
Production errors
Production rework discovery time
Production rework
Planned production duration
RFID
Finished products
Ratio of completed tasks (P)
Total production work

Figure

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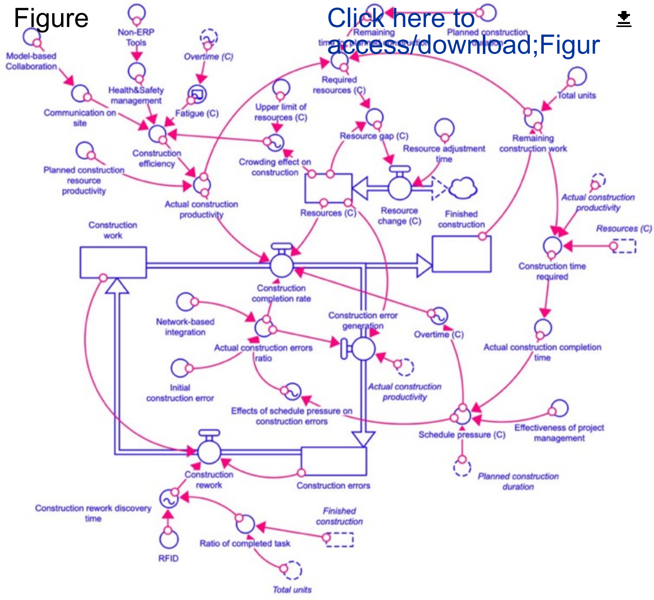

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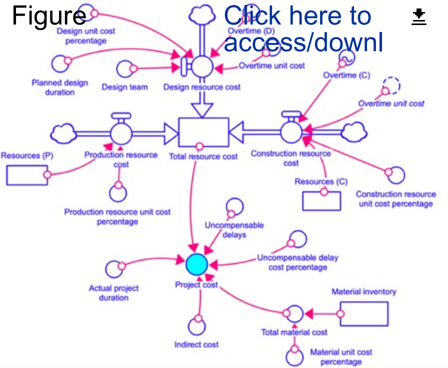

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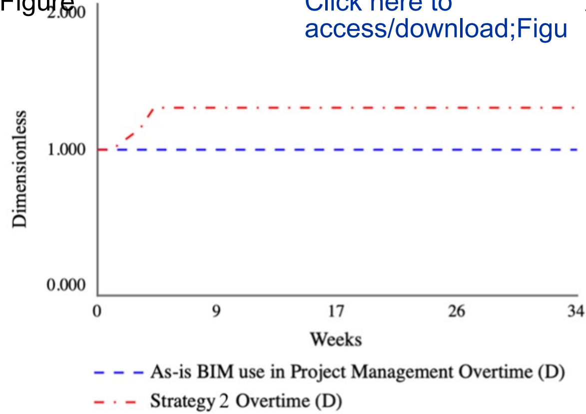

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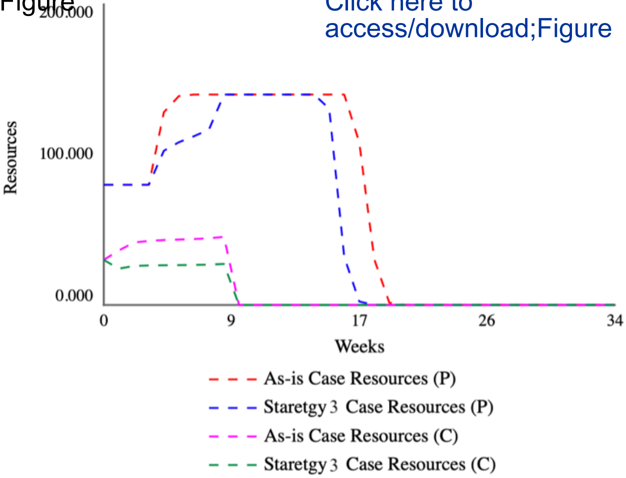
200.000
100.000
0.000
Resources
0
9
17
26
34
Weeks
As-is Case Resources (P)
Staretgy 3 Case Resources (P)
As-is Case Resources (C)
Staretgy 3 Case Resources (C)

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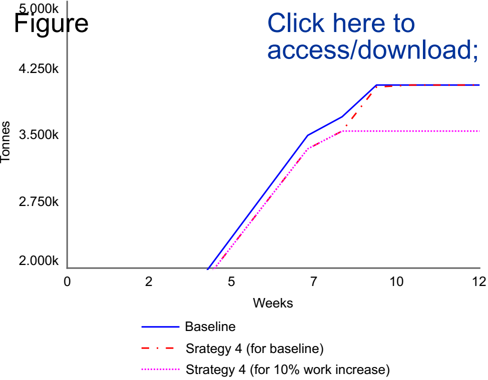

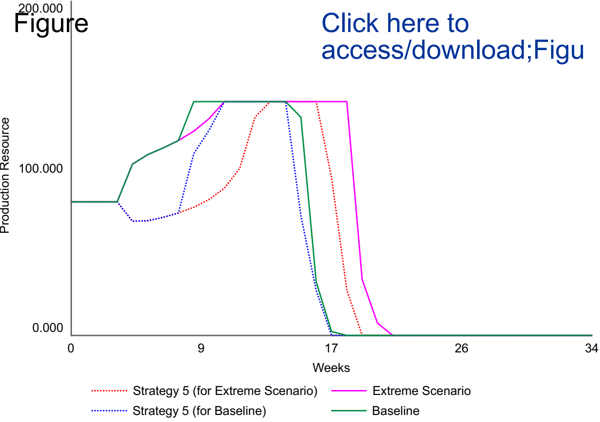
200.000
100.000
0.000
Production Resource
0
9
17
26
34
Weeks
Strategy 5 (for Extreme Scenario)
Extreme Scenario
Strategy 5 (for Baseline)
Baseline