USING SYSTEM DYNAMICS TO SUPPORT STRATEGIC DECISION-MAKING: THE CASE OF DIGITALIZATION IN MODULAR CONSTRUCTION COMPANY

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ABSTRACT

USING SYSTEM DYNAMICS TO SUPPORT STRATEGIC DECISION-MAKING: THE CASE OF DIGITALIZATION IN MODULAR CONSTRUCTION COMPANY

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Digital technologies have become a part of the transformative change of industries for more efficient production, business models, and value chains with the onset of Industry 4.0. The AEC business had to follow this trend due to globalization and the increasing complexity of projects, and the use of digital technologies for innovation has become increasingly common. However, it is common knowledge that the construction industry takes a long time to incorporate new technology and adapt business models to digital environments. In this regard, this research proposed that the digitalization of the construction companies and the effects of different technology integration should be analysed as a holistic approach by approaching it as an objective to create a digital ecosystem, integrating the strategic goals for both the processes and people. Hence this research proposed to utilize business process engineering and simulation with system dynamics modelling to investigate the impacts of digital technologies on project objectives and its existing management dynamics. The system dynamics model is created with the contribution of an experienced Turkish modular construction company. According to the strategic

position of the company in terms of digitalization, different strategies are considered for maturity levels of BIM, Enterprise Resource Planning systems and RFID technologies. The simulation tests conducted with the company indicated that the model enhances strategic decision-making by depicting the causalities, and feedback between the decisions and their consequences for technology integration.

Keywords: Digitalization, System Dynamics Modelling, Strategic Decision-making

ÖZ

STRATEJİK KARAR VERMEYİ DESTEKLEMEK İÇİN SİSTEM DİNAMİKLERİNİN KULLANILMASI: MODÜLER İNŞAAT FİRMALARINDA DİJİTALLEŞME ÖRNEK ÇALIŞMASI

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Dijital teknolojiler, Endüstri 4.0'ın başlamasıyla birlikte daha verimli üretim, iş modelleri ve değer zincirleri için endüstrilerin dönüştürücü değişiminin bir parçası haline geldi. İnşaat endüstrisi de küreselleşme ve projelerin artan karmaşıklığı nedeniyle bu eğilimi takip etmek zorunda kaldı ve inovasyon için dijital teknolojilerin kullanımı giderek daha yaygın hale geldi. Ancak inşaat sektörünün yeni teknolojiyi bünyesine katmasının ve iş modellerini dijital ortamlara uyarlamasının uzun zaman aldığı bilinen bir gerçek. Bu bağlamda, bu araştırma, inşaat şirketlerinin dijitalleşmesinin ve farklı teknoloji entegrasyonlarının etkilerinin hem süreçler hem de insanlar için stratejik hedefleri entegre eden, dijital ekosistem oluşturma hedefinde, bütünsel bir yaklaşımla analiz edilmesi gerektiğini önermiştir. Dolayısıyla bu araştırma, dijital teknolojilerin proje hedefleri ve mevcut yönetim dinamikleri üzerindeki etkilerini araştırmak için sistem dinamik modelleme, iş süreci mühendisliği ve simülasyonu kullanmayı öne sürmektedir. Sistem dinamikleri modeli deneyimli bir Türk modüler inşaat firmasının katkılarıyla oluşturulmuştur. Şirketin dijitalleşme konusundaki stratejik konumuna göre BIM ve farklı gelişmişlik seviyeleri, Kurumsal Kaynak Planlama sistemleri ve RFID teknolojisi farklı

stratejiler için değerlendirilmiştir. Şirketle yapılan simülasyon testleri, modelin, kararlar arasındaki nedensellikleri, geri bildirimleri ve teknoloji entegrasyonu için sonuçları göstererek stratejik karar vermeyi geliştirdiğini göstermiştir.

Anahtar Kelimeler: Dijital teknolojiler, Sistem Dinamikleri, Stratejik Karar Verme

To my beloved family

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LIST OF ABBREVIATIONS

ABBREVIATIONS

BIM	Building Information Modelling
BPR	Business Process Reengineering
BPS	Business Process Simulation
CLD	Causal Loop Diagram
ERP	Enterprise Resource Planning
GMB	Group Modelling Sessions
KPI	Key Performance Indicator
MW	Model Window
RFI	Request for Information
SD	System Dynamics
SFD	Stock Flow Diagrams
IoT	Internet of Things

CHAPTER 1

INTRODUCTION

With the advent of the Fourth Industrial Revolution and the resulting framework of Industry 4.0 (MacDougall, 2014), digital technologies have become a part of the transformational change of the industries for more efficient production, business models and value chains. In line with the globalization and complexity of the projects, the AEC industry had to follow this trend as Construction 4.0, and the utilization of digital technologies has become more widespread for innovation. The framework of Construction 4.0 combined the trends and technologies to present the idea of "digital ecosystem" (Sawhney et al., 2020). According to the report of McKinsey (2020), the next normal in the construction industry will be composed of three perspectives as industrialization (new production technologies and shift toward off-site construction), new materials (sustainable materials with improved logistics) and digitalization of products and process (smart buildings, BIM, data-driven decision making). The report stated that the construction processes would be increasingly product-based (e.g., structures are becoming products manufactured off-site), and management will majorly depend on the data and analytics. Moreover, the vision of civil engineering for the next five years is defined as stepping forward to sustainability and informed decision-making by relying on databases, sensors, living models and other digital technologies (ASCE, 2007). However, it is a well-known fact that the construction industry has a slow undertaking for implementing the technologies and transferring the business models to digital environments. The reason behind this is generally referred to by the unique characteristics and dynamics of the projects and the industry itself. Oesterreich and Teuteberg (2016) stated these structural problems as complexity (e.g., interrelated processes and parties),

uncertainty due to the unforeseeable conditions and environment, high fragmentation, focusing on temporary solutions rather than long-term innovations, and culture with siloed thinking, resistance to change.

Moreover, from a technological point of view, until recently, the industry has lack of structured information exchange on construction products, and this situation began to reverse somewhat with the increase in Building Information Modelling (BIM) adaptations. Especially the methodology behind BIM became the central aspect which led to both different research directions and sectoral applications (Eastman et al., 2011; Cheng & Lu, 2015). Nevertheless, the recent attempts for digitalization of the construction industry either focused on individual technologies or analysis of future scenarios that are not specifically technology related (Ernstsen et al., 2021). Therefore, the digitalization of the construction companies and the effects of different technology integration should be analysed as a holistic approach by approaching it as an objective to create a digital ecosystem, integrating the strategic goals for both the processes and people. The related idea is adapted as the socio-technical perspective for different technologies in the literature. For instance, Li et al., (2019) proposed other use cases for distributed ledger technology and utilized the socio-technical systems theory for four dimensions technical, social, process and policy. Accordingly, the approach suggests that technological advancements must be addressed by considering organizational and technical factors.

In this regard, this research aims to analyse the technological integrations with a holistic approach to unfold different dynamics of processes and integrate people into the picture by conducting a case study to understand the insights of sector partners. For the system modelling and simulation technique, systems dynamics is used to discuss the contribution of different technologies to the project objectives and integration into the existing managerial actions. The research evaluated the existing dynamics at the project level and captured the impact of different Construction 4.0 technologies such as BIM, Enterprise Resource Planning (ERP) systems and RFID.

Similar to many construction management-related problems, the strategic analysis of technology adaptation involves different interdependences and non-linear relationships with several feedback loops that change over time. Hence further causalities exist among the project attributes. Nevertheless, these aspects of system dynamics make it an appropriate approach since the digitalization problem needs a detailed, holistic method that features both involving quantitative and qualitative data (Alzraiee et al., 2015). Moreover, system dynamics is widely used for complex and dynamic problems and enhance strategic decision-making to examine different strategies and policy formulations (Yildiz et al., 2020).

The research proposed that from conceptualization to simulation, the system development can support strategic decision-making for technology integration. Developing a system dynamics model for strategic analysis necessitates considering system boundary and dynamic environment in terms of strategic goals. Since this research aims to configure the impact of digitalization goals on project-level attributes, the internal capabilities and external uncertainties of the projects are considered. The developed model can simulate the effects of technologies for different scenarios and performance indicators (project objectives). To reveal the simulation of the model under different scenarios, a demonstrative case study is conducted with an experienced Turkish construction company. The opinions of the experts are used for evaluating different strategic goals for the company, understanding the project uncertainties, and comparing the behaviour of the model with the real project. As the company is particularly active in modular/industrialized construction, it has enabled production-related technologies and methodology to be analysed in the research. The case study enables to capture the uniqueness of projects and create a bridge between the practical and theoretical orientations for the digitalization topic.

Although the system development and simulation are shaped according to the opinions of the case company experts, the presented model may be used as a roadmap for similar companies since it encompasses generic project-related assumptions. For

a different company, the strategic goals and project environment may be reconsidered.

Moreover, the created model is constituted to evaluate the impacts of technologies on project process improvement, with the business process engineering method. Hence from the literature review to system dynamics modelling, the proposed outline of the research may guide similar attempts for both academicians and practitioners who want to investigate the strategic value of technologies for "project success".

Accordingly, the research is structured as follows. Firstly, the research background is presented to get an in-depth understanding of Construction 4.0, digital technologies, and system dynamics literature. Then, the details of the research methodology including objectives, approach and steps are set out in detail in chapter three. In the fourth and fifth chapters of the research, two steps of system dynamics modelling are presented as Conceptual and Computerized Modelling, respectively. For the conceptual model, the strategic position of the case company is depicted, the technology integration goals are identified, and causal loops are created accordingly. Then these conceptual models are transferred to computerized models and validated in the next chapter in different iterative steps. In the final step, the finalized models are simulated by the company data and scenarios are tested with various discussions.

It is expected that this study facilitates the group strategic decision-making and evaluates the benefits of digital technologies from the "system" perspective.

CHAPTER 2

RESEARCH BACKGROUND

This section reviews the literature that composes the background for this research. Firstly, the digitalization concepts and technologies are presented under the framework of Construction 4.0. Then, since the main idea of the research is to create a system dynamics model for the strategic decision-making of technologies, the terminology of the method is presented. Additionally, the literature on system dynamics in the project and construction management is mentioned to give the utilized aspects for model development.

2.1 Key Concepts of Construction 4.0

The concept of Construction 4.0 was first mentioned by Roland Berger (2016), and it encompasses four perspectives: digital data, automation, connectivity, and digital access. From these perspectives, firstly, digital data refers to the electronic collecting and analysis of data to obtain new insights for decision-making and enhancing the value chain. Second, automation is a term that refers to the collection of new technologies that enable autonomous, self-organizing systems. Third, the possibility of mobile connectivity to the internet and internal networks is referred to as digital access. Finally, digital access investigates the potential of connecting and synchronizing previously disparate activities by integrating different technologies. The definitions and related concepts have evolved tremendously in recent years. Still, the key understandings that the report proposed remain valuable for the literature and construction companies that want to make a difference.

Oesterreich and Teuteberg (2016) explored the current state of the art of utilization of different Industry 4.0 technologies in the built environment and proposed the implications of digital adaptation from several perspectives, economic, social,

technological etc. The authors revealed that the technologies could provide automation, digitization, and integration of different construction processes in the construction value chain. The central technologies for the transformation are revealed as Building Information Modelling (BIM), Cloud Computing and the Internet of Things (IoT). These technologies' main benefits are improved productivity, efficiency, quality, and collaboration. Hence, the authors stated that different technologies of the Industry 4.0 paradigm should be explored for more effective production and business models. Based on these findings, Sawhney et al. (2020) defined Construction 4.0 as a combination of trends and technologies that change the built environment's design and construction. The authors described Construction 4.0 as the convergence of Cyber-physical systems (CPS) and the Digital Ecosystem. CPS are enabling technologies that create a connection between "physical" and "virtual" (Griffor et al., 2017). The digital ecosystem in this framework means a group of organizations, people, and/or things that use standardized digital platforms for a mutually beneficial purpose, such as innovation or common interest. Hence, rather than focusing on the individual benefits of technologies, combining a range of them (such as the Internet of Things (IoT), BIM, big data, and automation) for different trends has become more critical for reaching the full potential of digital transformation of the construction industry (Ernstsen et al., 2021). Thus, other emerging technologies and trends are presented in the following subsection to understand their potential.

2.2 Technologies of Digital Ecosystem

Construction 4.0 concepts encompass several technologies and explore the benefits of these by the corresponding trends. Based on this, Oesterreich and Teuteberg (2016) defined three clusters for the movements of integrating the Industry 4.0 perspective to the construction industry: smart factory, simulation and modelling, and digitization and virtualization. The first cluster consists of trends such as the creation of virtual networks, real-time tracking, and complete automation of

construction processes. Similarly, the report of McKinsey (2020) shows that soon, the construction industry will draw into the product-based approach, as the projects will be delivered as "standardized" products, and modular construction will become widespread. Furthermore, the shift towards the controlled environment of factories from the construction site enhances the implementation of lean principles (Innella et al., 2019). Moreover, the modularization and standardization of the processes improve productivity and quality. The simulation and modelling cluster considers collaboration through models and real-time information sharing. Especially, combining BIM with IoT sensor networks established information "integration" and value-chain control. According to the Industry 4.0 framework proposed by Kagermann et al. (2013), the digital value chain is composed of end-to-end engineering through the value chain and horizontal integration (i.e., the combination of same level value chains of business in a digital platform). Third cluster trends encompass concepts such as digitization with Big Data (i.e., data-driven decision-making and risk management), virtualization (VR/AR) technologies and access to construction documents from common space by Cloud computing.

According to the given trends, different technologies are considered in this research to create an outline for the case study. For selecting emerging technologies and matching them with the trends, the frameworks of Ernstsen et al. (2021) and Sawhney et al. (2020) are referred to and presented in Table 2.1.

Although the technologies are selected according to their recent popularity in academic studies and sectorial applications, the concept of Construction 4.0 is not limited to these technologies. The idea also adapts different technologies, such as Blockchain, Unmanned Aerial Systems, Robotics, and Laser Scanning, which have skills such as decentralized management, image processing/collection, automation, and point-cloud data collection (Sawhney et al., 2020). However, considering both the characteristics and capabilities of the case company and the intention to make project-level modelling, these technologies are ignored in the scope of this study.

Table 2.1: Considered Construction 4.0 trends and technologies

Technology	Trends	Functions
Design Automation (Modelling)	Automation	Modelling and simulation of different design processes (Bryde et al., 2013; Abrishami et al., 2020)
BIM	Integration	Integration of BIM with other technologies such as IoT (Tang et al., 2019), Enterprise Resource Planning (Sarkar et al., 2021), Big Data and Digital Twins (Pan & Zhang, 2021)
Artificial Intelligence (AI)	Digitization	Data-driven decision making (predicting, optimizing and problem-solving), especially for management processes (Elghaish et al., 2022).
Virtual Reality/Augmented Reality (VR/AR)	Virtualization	Creating effective visualization of different end-users (Song et al., 2021), virtualization of complex workplaces enabling accident-preventive behaviour for employees (Li et al., 2018)
Common Data Environment (Cloud Computing)	Integration	Effective communication by linking different stakeholders for supporting business processes (Du et al., 2018), integrating real-time data with cloud-BIM for effective management (Matthews et al., 2015)
RFID	Productivity Modularization	Providing location information for products or parts (Kereri & Adamtey, 2019), integration with BIM (smart construction objects and physical internet-enabled models) for prefabricated construction (Chen et al., 2017; Li et al., 2017), connection with IoT services for intelligent factory (Oesterreich & Teuteberg, 2016)

In addition to the Construction 4.0 technologies in Table 2.1, especially for the industrialized construction environment, enterprise resource planning (ERP) information systems become critical for effective supply chain management (Babič et al., 2010). However, the implementation of ERP systems still faces hesitation in the sector due to the high implementation costs and uncertainties (Yang et al., 2007). Nevertheless, in line with the need for agility in the sector's supply chain, especially the procurement, logistics, and inventory control modules of ERP systems are becoming increasingly common.

After clarifying the technologies through literature review under Construction 4.0 concepts, the second part of the research background is focused on the system dynamics.

2.3 System Dynamics

"Computer-aided modelling technology for policy and strategy design", system dynamics (SD) was developed by Jay Forrester as an MIT professor in the mid-1950s. The primary purpose of SD is to understand the complex dynamic systems and reinforce the decision-making for the problems exhibited in them (Forrester, 1961). Since then, it has been applied to several areas such as economics, health care, education, social sciences, and engineering. As a simulation and modelling technique, SD provides detailed insights about the system and related problems by the behaviour of different components over time (dynamism). SD has four elements as a system, feedback, levels, and rates. In the following section, the logic behind SD and the terminology of the system are presented.

2.3.1 Systems Thinking Approach

The modelling technique is based on the methodology of "Systems Thinking". The approach proposes comprehending how things affect each other within a whole and considers "problems" as part of the system rather than isolating them with other constituents (Sterman, 2001). Anderson and Johnson (2007) characterized the methodology by five principles.

i. It is thinking of a "big picture", taking a step back to broaden the perspective for the root cause of the problems
ii. Creating a balance between the long-term and short-term perspectives (e.g., rather than searching for the solution in the nearest causality, focusing on the other elements and their interrelationships as well)

iii. Understanding the dynamic, complex and interrelated nature of different systems
iv. Involving both measurable and immeasurable elements of the system in analysis
v. Always consider the perspective of the modeler and its position in the system and its surrounding environment

These "Systems Thinking" philosophies were incorporated into the SD and further investigated as a simulation technique. Sterman (2000) stated that the primary step of SD modelling is to understand the "system" according to the problem statement and decide on the boundary. Despite the diversity of system definitions, it is widely accepted that a system consists of a collection of parts (components, elements) that are connected in an organized way inside a defined boundary under a shared purpose, which can be a physical process, an organization or even a country. (Waring, 1996; Yim et al., 2004). There is a synergy between system elements that are dynamically changed over time. Hence, it is crucial to correctly define the "closed boundary" of the systems. The interactions of components in the system boundary specified the system structure (Yim et al., 2004). Similarly, its components and interactions must be examined and modelled to comprehend a system. The following section will further explore the concept of feedback and causal loop diagrams.

2.3.2 Causality and Feedback

The causal relationship means one element affects another element in the system boundary, which is modelled by the causal loop diagramming (CLD). The CLD encompass the qualitative/conceptual step of SD models, enables the representation of experts' mental models, and delineates critical feedback loops within the system. Strategic decision-making is a process affected by interpersonal relationships and biases. Hence, it is necessary to develop causal/cognitive maps to further understand the environment and mentality of actors. The method was first developed to navigate psychological behaviour by Tolman (1948), and then it started to be used in

management studies to develop thinking models (Eden, 1992). Causal mapping is a method for uncovering and actively shaping mental models or belief systems used to perceive, contextualize, simplify, and make sense of complex problems. The causal maps are directed graphs in which perceptions of the situation are described as statements (nodes/concepts), and causal links connect these statements. These causal links represent either positive or negative relations (Eden, 1992; Ackermann & Eden 2011). The feedback of elements depicts additional positive (+) or negative (-) polarity to the CLDs, which means it reflects the circular chain of causality that "feeds back" to itself. In a feedback system, the change in the environment causes a "decision", which then leads to an "action" that influences the environment and future decisions (Forrester, 1997). The logic stated by Sterman (2000) as a feedback view is a contradiction to conventional open-loop, event-oriented, sequential problem-solving. The idea is based on the logic that the actions may have side effects and short-term solutions may create future problems, called "policy resistance". Consequently, it is essential to understand the causalities and feedback to interpret the issues of uncontrollable and unpredictable complex environments.

In the CLDs, the positive relationship means one element positively influences the other; the increase in this element induces the other to increase. For the negative relation, it is the opposite. These two causalities result in two types of feedback loops: reinforcing (R) and balancing (B). The popular explanation of feedback loops is for population growth modelling, as in Figure 2.1. In that, the "reinforcing loop" is often exemplified as follows: as the population grows, so does the birth rate, which leads to an increase in the overall population. On the contrary, the "balancing loop" is demonstrated; as the population grows, so does the number of deaths, resulting in population declines (Yim et al., 2004).

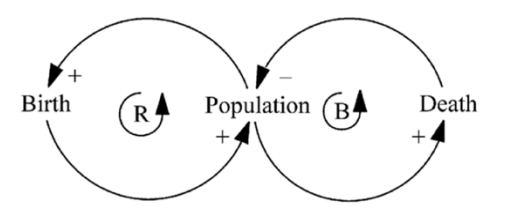

Figure 2.1: The causal loop diagram of the population growth model (Yim et al., 2004)

2.3.3 Level and Rate

Although the CLD ensure simple representation for users and enhance communication, there is a lack of sensitivity analysis among variables and calculation of all elements' overall influences on the target system (Yim et al., 2004). Hence, the computer simulation part of SD behaves as an imitation of system behaviour by different numerical calculations that are implemented into the framework of mental models that are covered in the previous section. For this purpose, the quantitative modelling part of SD utilizes 'levels' and 'rates', which will also be incorporated into the stock-flow diagrams (SFD) in the computer models. The level refers to anything that accumulates or depletes within a specific time interval (Forrester, 1997). For instance, the amount of water in the bathtub, inventory amount, total number of employees etc. The rate reflects the extent of the change in level over time. As a result, whether the element has a time factor impacts the difference between the level and the rate. An element's level indicates its accumulated rate over time, which calculates the rate by averaging the accumulated levels throughout the overall time taken. For modelling and simulation purposes, the level and rate are formulated in SD using SFD. 'Levels' are represented by the 'stock' variable in SFD, whereas 'rates' are variables on 'flow'. As a result, the value of a stock at time t is calculated as the below equation.

Equation 1:Stock value calculation for system dynamics

$$Stock_t = Stock_{t-dt} + (Inflow_{t-dt} - Outflow_{t-dt}) * dt$$

The SFD of the population growth model can be depicted in Figure 2.2. The "stock" variable is represented as a rectangle; in this model, population increases or decreases by the birth and death rates/flows. The flow variables units are always proportional to time (e.g., for the sample model, the birth unit can be person/year). As depicted in Figure 2.2, other variables may be added to the SFDs by causal logic. For instance, fractional birth rate defines the birth rate per person (the number of children one person has in a lifetime), and the multiplication of the population calculates the birth rate with this value. In similar logic, the yearly birth inflow can be defined by the division of birth rate with average lifetime. The reasoning behind stock flows and other 'converter' variables explained in this section will be further examined and adapted for the details of SD modelling.

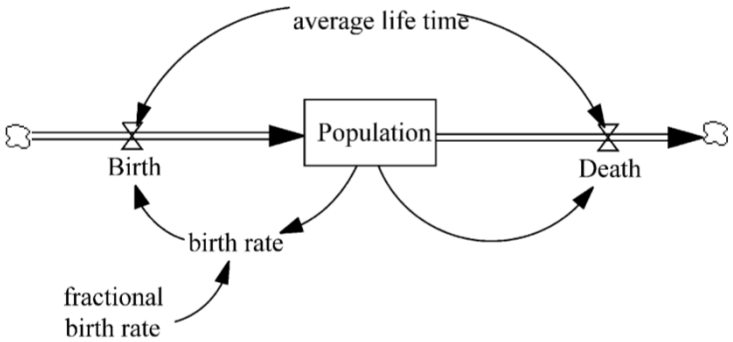

Figure 2.2: Stock-flow diagram of the population model (Yim et al., 2004)

2.3.4 Time Delays

The logic of systems thinking, in general, is based on the effects of the decisions on the system. Nevertheless, in some situations, the actions may take time, and the time delays between the decisions and their impact on the system can be problematic. Hence, the decision may have side effects, delayed reactions from the system, and even changes in the goals in the first place. SD modelling enables the analysis of time delays between parameters as well. The delays are modelled as it divides the

flow into two parts, which divide the accumulation of inflow and outflow. In other words, according to the delay time, the inflow is collected till the discharge (Forrester, 1961). The delays are generally presented with two parallel lines above the causal connectors between two nodes/parameters.

After briefly explaining the theory behind the SD and related features, the literature review for the application of SD in project and construction management is presented in the next section.

2.4 System Dynamics in Project and Construction Management

In the literature, one of the most significant application areas of system dynamics in project management. As an outstanding resource in this domain, Lyneis and Ford (2007) investigated the project dynamics and their relations with the system dynamics methodology. The authors stated that project features could be simulated by representing the realistic project dynamics and involving the project managers in the modelling practice. The controlling feedback can be reflected in the models focusing on the information processing of project managers and performance management. Conducting project performance metrics such as time, cost, quality, and scope are modelled into the SD models to implement different strategies and close the gap between the target and actual performance. The management strategies such as overtime, slipping the deadline etc. have feedback mechanisms that SD offers and causality examination of different project features has a significant influence on the project's success (Rodrigues & Bowers, 1996; Lyneis et al., 2001; Lyneis & Ford, 2007).

The benefits/limitations of digitalization are also investigated in the current literature for different projects and processes such as production projects and supply chains. For instance, Ghadge et al. (2020) proposed the SD modelling for integrating Industry 4.0 technologies such as RFID and cloud technology into the supply chains. The research investigated the drivers and barriers of different technologies from the simulation analysis. It provided a conceptual framework for an effective transition

to digital supply chains by comparing the traditional and technology-driven feedback loops.

In addition, SD modelling has gained popularity in the construction engineering and management field. Sterman (1992) stated the justification for the utilization of SD in the construction industry as follows.

- The construction projects have complex nature and mostly interdependent components.
- The projects have highly dynamic systems and environment
- The processes are composed of different feedbacks and nonlinear relations
- The projects comprise both qualitative and quantitative data

Hence, SD has become an effective methodology for investigating the complicated dynamics and relationships of different management processes because of these features of the construction projects, especially in line with the increase in the complexities of the construction industry in recent years. According to the study by Liu et al. (2019), SD adaptation in construction management mainly focuses on (1) project planning and control, (2) performance and effectiveness (3) Strategic decision-making/policy analysis. Since the modelling efforts for this research will comprise these topics, a brief literature review from the construction management area will be presented.

2.4.1 Project Planning and Control

The implementation of SD into the project planning and control of the construction industry is mainly associated with the dynamic planning and change management in the literature. As one of the first attempts at this, Ford and Sterman (1998) explored the interrelations of project features such as error and rework loops. The authors modelled the processes, resources, scope, and targets. Change management is also analysed through the sub-systems. Hence, SD modelling enables the examination of complex relationships between internal project activities and the problems' feedback.

For instance, Peña-Mora and Li (2001) utilized SD for dynamic planning and control of fast-track construction projects; likewise, Sing et al. (2016) created a dynamic model to enhance the workforce planning of infrastructure projects.

Errors in construction that result in reworks and adjustments frequently have a cascading effect on various project performance metrics (e.g., schedule, cost, quality). SD research is a good choice for controlling rework and change because of the dynamic interaction between planned activities and reasons for reworks or changes (e.g., unforeseen events, errors, design revisions, omissions). More research in the domain of dynamic planning and construction rework has been incited by the significance of examining causal linkages between rework/change and other variables within the construction system (e.g., activity, project, organizational, human, and environmental factors). For the determination of reworks in the project management domain, Lyneis et al. (2001) developed the rework cycle structure as in Figure 2.3. The model consists of four stocks of work, at the start of the project, there is the "Work that needs to be done", according to the "People" (staff) and their "Productivity" (work/time/person); the work is accomplished with a rate. However, work is executed at varying, less than perfect, which is represented as Errors that affect the quality (e.g., the fraction of work being done at any time point to work really/correctly done). The rest of the work that needs rework flows to the stock of "Undiscovered rework", which depicts the work that has flaws, yet is undetected. "Rework discovery" may occur weeks or even months after the error has happened, during which time-dependent work has included these faults or technical derivations thereof. Once identified, the stock "Known rework" necessitates the use of resources in addition to those required to complete the remaining work to be done. As it can be understood, some of the rework items flow through the cycle one or more times, increasing the reworks in the middle and at the end of the project, which has a logical structure.

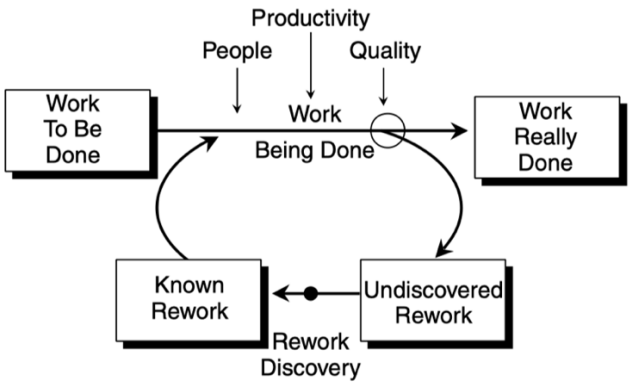

Figure 2.3: Work accomplishment/rework cycle structure (Lyneis et al., 2001)

Although the rationality of Figure 2.3 has been used widely, the construction projects need more extensive analysis due to the characteristics and behaviour patterns such as physical constraints (e.g., rework generally means demolition of what has been built), involvement of many activities/organizations and precedence relationships between them. The construction changes may result in unintended changes (e.g., because of low work quality, poor work conditions etc.) or intentional changes (managerial actions). Moreover, the unintended changes may be caused by the hidden errors (undiscovered reworks) in the upstream activities, such as the design of Park and Peña-Mora (2003).

In addition to classifying construction changes by intention, the change management models in the literature also encompass the precedence between activities (e.g., linking design with construction), quality management process and request for information (RFI) (Lee et al., 2005; Lee, 2017). These models define two critical parameters: Scope Management (SM) and Claim and Change Management (CCM). SM represents the review phase, and CCM is identifying changes and approving/rejecting these changes. The main logic behind these models is that the work needs to be done, and related rates specify the upstream work and work that is correctly done block depicts the downstream (e.g., for concrete pouring, the floor slab work is upstream and pouring the concrete into the correct slabs is downstream). If there is a need to correct upstream at the beginning of activities, it is represented

as RFI. Then, according to the response to the requested information, the process is somewhat changed or reprocessed and, in the end, comes back to the Work to Do stock. After that, the Work Rate represents the work that is assumed to be correct and flows to Quality Management. Consequently, whether the errors, RFIs or managerial changes are founded upstream or downstream, there is a delay in correcting the processes, and the delay may result in schedule pressure, which again influences the quality and creates and feedback loop (Park & Peña-Mora, 2003; Motawa et al., 2007).

In the model for this research, the error generation (for the construction phase, it can be assumed as RFIs) and quality check of processes will be examined similarly to the rework structure of Lyneis et al. (2001) and feedback logic of Lee et al. (2005) as explained above. However, to simplify the model, the unintentional and managerial changes are not separated and assumed together as "error generation". Moreover, since the project processes are separated from each other, the errors that are noticed downstream are supposed to induce errors in the following process; hence there are no additional causal factors for that. Nevertheless, the feedback rationale of schedule pressure affecting a decrease in initial quality and correcting errors again cause schedule pressure added into the model similar to the existing literature.

2.4.2 Project Performance and Effectiveness

Performance in the construction industry is a controversial topic regarding the different criteria. In recent years, rather than only focusing on the financial measures, the competencies and skills of the companies have become more critical primarily due to the demand for sustainability and innovation. One of the most up-to-date definitions of performance is the accomplishment of efficiency and effectiveness of both qualitative and quantitative goals for overall project success (Nassar & AbouRizk, 2014). Hence project performance should be evaluated by combining both the hard (e.g., cost, schedule) and soft (e.g., safety, client satisfaction) measures. In the literature, SD modelling contributes to making optimizations of management

plan changes and policy analysis for project performance. At the organizational level, SD enables the modelling of different policies and simulates the extensive models to compare different scenarios (Ogunlana et al., 2003).

At the project level, SD has been utilized to analyse performance criteria such as cost, time, quality, skilfulness, and other soft skills. For the schedule performance, most of the research in the literature has benefited from the work of Lyneis and Ford (2007) and the proposed feedback loop for achieving the target schedule is depicted in Figure 2.4. Since SD modelling is based on the logic of time-dependency, the model that the authors proposed mainly creates feedback loops for the remaining work and time. As it can be seen from the figure, according to the remaining work, which is the summation of work left to do and reworks, the expected completion delay is calculated with the causalities between the deadline and time required. Subsequently, the actions such as overtime, slack off, or hiring are evaluated by considering the results of these actions (e.g., fatigue, too big to manage, errors and experience dilution). The trade-off between the actions and consequences of these remedies is the main feature of system dynamic models that investigate the schedule performance. The logic behind this model will also be incorporated into this research which will further be explained in the following chapters.

Moreover, the schedule performance and overall performance of the projects are affected by productivity, one of the factors that digitalization impacts. As it can be seen from Figure 2.4, the productivity can be influenced by the management decisions (e.g., increasing the number of resources may cause communication difficulties and decrease productivity) and project characteristic itself (relation between system and environment). In this context, Nasirzadeh and Nojedehi (2013) focused on finding the root causes of decreased labour productivity through system dynamics modelling. Rather than creating a generic workflow sector, the research also utilized the outputs of the time sector to evaluate total project cost and overrun, which will be utilized for the model development of different project objectives in this research.

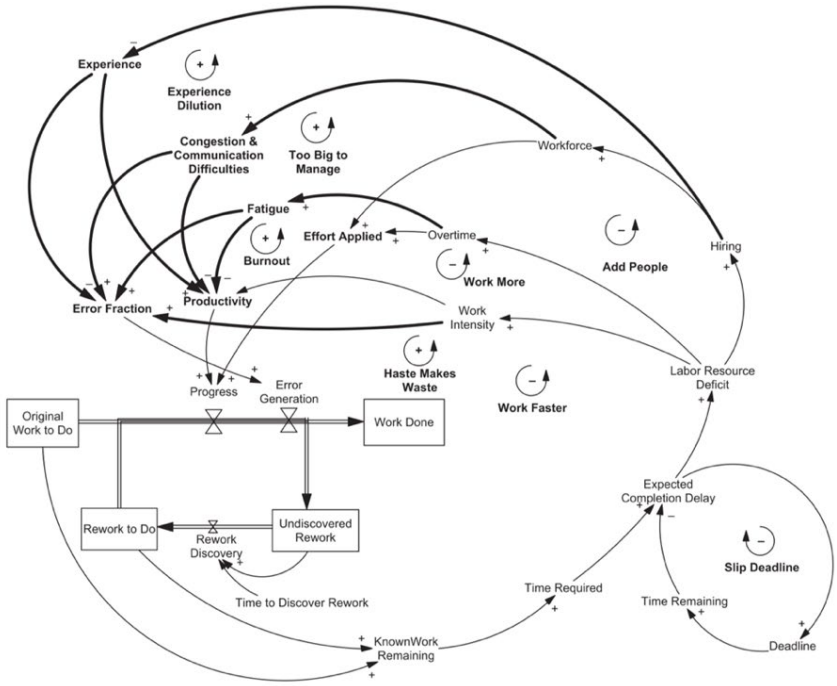

Figure 2.4: Controlling feedback loops for schedule performance (Lyneis & Ford, 2007)

2.4.3 System Dynamics in Strategic Decision-making

Rather than modelling the feedback mechanisms and causalities between different project features, SD also can assess different scenarios for the system and investigate the adaptability of the strategies. In this regard, there is an interest from researchers and stakeholders in using the method for evaluating different solutions for different problems.

Project management involves the strategic planning for making optimizations for project decisions considering the external and internal uncertainties and re-engineering processes with innovative decisions to achieve more effective and productive way for businesses. In this regard, Doloi and Jaafari (2002) proposed tool that utilizes dynamic simulation modelling system for proactive and optimal strategic decision-making in the project life cycle. The corresponding methodology in that

research is similar to the SD since it makes simulation of dynamics systems according to the different conditions.

Having mentioned on the project-level strategic decision-making, as the strategic policy evaluation, the sustainability assessment has been made for different construction industry strategies by utilizing the SD (Yao et al., 2011; Zhang et al., 2014). Moreover, as the company-level attempts, SD has been utilized to understand the competitiveness of construction firms (Dangerfield et al., 2010). Similarly, Barnabè (2011) proposed a system-dynamics based balance score charts that investigated the organization's performance in four aspects: financial, customer, internal business processes and learning and growth, and developed a dynamic mapping tool enhancing the organizational learning.

Additionally, especially for the top-level strategy concerns, Yildiz et al. (2020) demonstrated how strategy maps can improve strategic decision-making by assessing the impact of different performance criteria under different scenarios. The research utilized the SD models' balanced scorecards and PESTBEL framework to investigate a construction company's internal and external conditions.

2.5 Point of Departure and Aim of the Study

From the first part of the literature review, it is understood that the Construction 4.0 concept is a holistic picture for the future of the industry, and it cannot be applicable without considering the key characteristics and dynamics of the industry with strategic decisions. As a result of the fact that, as previously presented, each digital technology benefits different trends for the processes and companies. Moreover, most of the technologies mentioned in the literature individually or there are few attempts to connect them. However, the main aim of the digital transformation is the creation of digital ecosystem rather than focusing on short-term benefits. These aspects make the digitalization problem a strategic decision-making problem that should be investigated at both project and company levels. Hence, research that

investigates the benefits of technologies to the existing project dynamics needs to take it forward to portfolio-level and company-level in the future.

As the system dynamics literature revealed, the method comprised of "systems thinking" and "simulation of complex systems". The modelling approach can be used to understand the causalities between interrelated systems, model the flow of processes with different objectives and analyse strategies with simulation and scenario analysis. Hence, these aspects of the method make it beneficial to propose a holistic approach for strategic decision-making on integrating digital technologies. Moreover, although there is much research in the existing literature regarding the project planning, control, and strategic decision-making of construction project by system dynamics, there are no studies that analyse the results of innovations with this method that combines digital technologies with specific project management parameters and simulates strategic analysis.

Therefore, this research focuses on the project-level strategic analysis of different Construction 4.0 technologies by system dynamics modelling and aims to understand how the existing project management dynamics affected from digitalization with a case study.

CHAPTER 3

RESEARCH METHODOLOGY

This section explains the methodology of the research by firstly giving the objectives. Then, in the forthcoming section, the overall research approach is introduced, and the reasons behind the utilization of specific methods are presented as business process engineering, system dynamics modelling and demonstrative case study. In this section, the case company that is collaborated for model development is introduced as well. Since the case company is strategically analysed for digital technologies, the existing competitive advantages of the company and the main roles in this research are also presented. The final section of this chapter demonstrates the research framework to show a clear roadmap for the rest of the chapters.

3.1 Research Objectives

The research aims to find the answers to the below two questions:

Research Question 1: Which technologies can be integrated into the business processes to create value and reach project-level objectives?

For this question, firstly a literature review is conducted to explore the digital technologies, Construction 4.0, and related trends in the AEC industry. Then the research benefits from conducting a case study and describing the case company's system and environment to evaluate different technologies. Moreover, a process-based approach is utilized for the project-level objectives to enhance efficiency and effectiveness by considering different technologies. For that purpose, it has been decided to use the business process engineering method.

Research Question 2: How do the project and management dynamics influence the impacts of technology adaptations?

Mainly, this research proposes that without understanding the system (the processes, actors, and their interrelationships), the dynamics and related environment, the strategic value of the technology adaptation cannot be completely revealed. Hence for this research question, the system dynamics modelling method is applied. By creating this generic system dynamics model, the effects of improvements of different digital technologies are observed in the extent of the existing project management dynamics, internal capabilities, and external uncertainties of companies. Moreover, a demonstrative case study is conducted with the case company for both system development and simulation.

3.2 Research Approach

According to the proposed research aims, the questions need to be addressed by a case study since there is a need to understand the unique dynamics of technology adaptations with the technical and managerial aspects.

3.2.1 Methodology for the Case Study

The case studies are adaptable to the construction research since each project is a case with specific physical requirements and unique control and management methods (Gomes Araújo & Lucko, 2022). Moreover, in line with the increase in the needs of the industry, the methods that better connect the theory and practice have become more substantial (AlSehaimi et al., 2013). Since digitalization is one of these needs of the industry, conducting a case study is relevant to the problem itself. The steps of performing case studies can be summarized as follows according to the framework of Gomes Araújo and Lucko (2022):

1. The research questions are decided, and the question/problem is a challenge.

2. The current state of the art is reviewed to understand the gaps and limitations.
3. The strategic outcome of the study should be understood, and tactical objectives should be defined. The authors proposed this step as designating the descriptive criteria of the case study.
4. The data is collected by sampling/observations.
5. The results are validated.
6. The generalizability of the case study is addressed.

Accordingly, in this research, the above steps are followed. Firstly, the research questions are analysed. Since the research aims to understand the benefits of technologies for existing project management dynamics, a "single case" study is conducted. The single case studies exploit the entire data source to understand the established criteria of research (Yin, 2014). For that, the case company's perspective is used for the problem articulation, conceptualization, and validation of the computerized model.

Moreover, the case study for this research has both descriptive and evaluative nature. Because the research firstly creates a holistic image of the proposed digital transformation of the case company as the characteristic of descriptive (illustrative) case studies. The company's existing processes and strategic positioning are "described" for the evaluation in second stage. In the literature, similar research has been conducted by Ghosh and Robson (2015) to investigate the existing project delivery system and processes of the Empire State Building and compare it with the lean principles. As an evaluative case study, the company's existing systems and strategic goals regarding digitalization are "evaluated". Moreover, to exemplify the technological integration, the qualitative and quantitative data of the case company were used as the comprehensive information sharing and data of the example project, respectively.

In the third step, the descriptive criteria of this case study, the context, system, and environment are described in detail regarding the technologic integration. This enables realism for the study (Gomes Araújo & Lucko, 2022). In this research, the

case study mainly demonstrated how the system dynamics can be used for strategic decision-making of technology integration into existing project and management dynamics. Hence this enabled generalizability for the case study and opened the way for utilizing the model for similar companies.

For the sampling part of the case study, "typical" inputs are used for the case company's medium-size modular construction project. However, 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 are used, which are depicted as "group modelling sessions". The last step of the validation is conducted according to the specific requirements and tests of the system dynamics modelling approach.

3.3 Case Company

This research is carried out with the collaboration of an international Turkish construction company. The company is one of the earliest established firms for prefabricated modular steel structure production, export, and international contracting services. In general, the company has a role in modular construction projects that use the off-site prefabrication of building modules in the controlled environment of factories and assembled on-site. According to their company website, the company majorly completes prefabricated modular steel structures on a turnkey basis in various places with in-house engineering, procurement, manufacturing/production, logistics, on-site assembly, infrastructure, and superstructure works with more than 40 years of expertise. In recent years, they have emphasized globalization and internationalization as a strategic goal. Hence, they complete many projects worldwide and have a global presence in more than 60 countries. Moreover, the company is one of the biggest 250 contracting companies in the world, as stayed by ENR (Engineering News-Record) for the last ten years (ENR, 2018).

3.3.1 Competitive Advantages of the Company

The company's competitive advantages are analysed through the information and reports from the company website and the conformed certifications to understand their strategic goals (e.g., mission and visions) and their resources/capabilities for further improvements. Furthermore, the details of the company's requirements and their perspective on digitalization are further investigated in the initial group modelling session in Chapter 4.2. Finally, the information regarding the company is examined regarding the concepts of Construction 4.0 as follows.

a. **Building Information Modelling:** The company stated that they are already using BIM to manage the entire lifecycle of projects, as in-house design, construction, and operation services. The preference for BIM over traditional methods provides following the necessities of concepts, such as Modern Methods of Construction (MMC), Design for Manufacturing and Assembly, and Designing for Industrialized Methods of Construction.
b. **Modularization:** In addition to the fact that the company itself have operations in modular construction at the project level, they also adapt industrialized construction methodology and lean principles as a company goal to maximize the value for their customers and minimize waste. Moreover, as stated above, the company follows the trend of MMC or "smart construction", which is a way of working more effectively and benefits from off-site construction techniques and mass production in factories. It is a well-acknowledged fact that modular construction is an outstanding trend for the construction industry, especially to reach sustainability goals (Innella et al., 2019; Loizou et al., 2021).
c. **Sustainability:** The company promote sustainability strategies to achieve greener construction goal and protect natural resources. With the recent interest in the circular economy and technological advancements, the construction sector has started to evolve into prefabricated modular steel structures, which is the direct working area of the company. Moreover, the company's sustainability goals encompass energy efficiency, human value, and societal investment.

d. **Health, Safety and Environmental Policies:** The company proposes the continuous improvement of health, safety and environmental performance and takes precautions to minimize risks. There are strategies like providing necessary training, periodic reviews and implementing technologies. Moreover, the company encourages the adaptation of the 3R initiative (reduce, reuse, and recycle) with their project partners.

3.3.2 Main Roles of the Company in this Research

The role of the case company in the research is summarized as follows:

1. **Understanding the Requirements for Digitalization/Technology Selection:** As it is also stated in the research background, the concept of Construction 4.0 involves several technologies, which make the investigation of all of them unpractical and unrealistic for companies to adapt. Hence, in the initial sessions with the case company, the existing project processes, strategic positioning, and digitalization goals are investigated, and the technologies are selected. Since strategic decision-making cannot be examined without considering the company's characteristics, it is suitable for the research to focus on specific/chosen technologies.
2. **Determination of Business Process and Initial Requirements:** In the initial session with the company, the existing process chain of the case company is evaluated, and strategic goals are clarified for further improvement by technology integration.
3. **Development of Conceptual and Computerized Model:** Different group modelling sessions (GMB) are conducted to understand the system components, interrelationships, feedback, and environment (external conditions) for the conceptual diagrams and computerized stock-flow models.
4. **Validation and Scenario Analysis:** The developed system model is validated with the contribution of the case company, and scenario results are discussed.

3.3.3 Participants Profile

In this study, the opinions of three experts are used with different backgrounds, job titles and experiences. It should be noted that, for the new technologies that are considered with the case company and entire digitalization parameters, the feedback of Expert 3 was used specifically since she has experience in her position and prior use of these technologies in similar projects. The profile of the experts is given in Table 3.1.

Table 3.1: Expert profiles

Expert ID	Education Level	Years of Experience in Industry	Current Title	Experience in Digital Transformation
1	MSc	10	BIM/Digitalization Expert	High
2	MSc	10	BIM/Digitalization Expert	High
3	PhD	15	Chief Transformation Officer	High

3.4 Business Process Engineering Approach

In recent years, company structures have shifted from vertically tall and functionally aligned to horizontal, process-oriented, and, most crucially, customer-focused. This shift results in several practices for process improvements. Hammer and Champy (1993) presented the concept of Business Process Reengineering (BPR). The method mainly aims to understand the process chain of businesses and eliminate non-value-added activities. In addition, these strategic changes are decided according to the mutually defined goals, resources, capabilities, and rules of the industry (Evans et al., 1995). The research agenda in construction management literature addresses construction's high fragmentation and low productivity. Moreover, BPR attempts to produce efficient interfaces for the procurement of materials, redesigning the roles and standardization of construction firms (Betts & Wood-Harper, 1994).

For this research, this approach is used since the case company proposed to use the technology integration for improvements in the existing process chain. Similar research has been conducted by Cheng et al. (2006) on reengineering organizational human resource planning for construction projects. In the study, the authors firstly investigate the process model and organization structure and reengineer it by finding the hidden problems in the processes and management. The suggested new process model utilized the information technology systems.

The initial step of the BPR is to understand the companies' existing process chain and business objectives relating to the processes. In the second step, the non-value-added activities are eliminated, or the process factors are changed to redesign the systems. The way of use and the results obtained in this project are presented in Chapter 4.2.

3.5 Strategic Management by System Dynamics

The strategy research takes advantage of system dynamics since it provides analysis of the dynamics of different managerial actions and performance criteria in nature with the feedback logic and simulation (Gary et al., 2008). Since the problem of technology adaptation needs a more comprehensive holistic approach and needs to be addressed as a strategical problem, the system dynamics modelling approach is convenient for the research. Moreover, the managerial decision-making of construction projects has complex, dynamic and interrelated components that influence the benefits of different technologies. Hence the system dynamics approach analyses the complex systems and evaluates different strategic objectives as scenarios. In this research, the strategic digitalization goals of the case company are modelled with the existing project dynamics. To do that, different group modelling sessions are conducted. The methodology adapted from Vennix (1995). The model is constructed with the direct incorporation of the management and digitalization team of the case company. The approach is beneficial to getting different opinions of experts and creating a model that has qualitative (conceptual)

and quantitative (computerized mathematical) aspects. The steps and aim of each session are presented in Table 3.2.

Table 3.2: GMB sessions structure

Phase	Steps	GMB Sessions	Aim of the Session
Preliminary Study	**Step 1:** Understanding the current situation of the company and intentions for digitalization	**Session 1**	Understanding the strategic positioning of the company in terms of digitalization
			Clarifying the strategic goals for digitalization
System Dynamic Modelling	**Step 2:** Problem Articulation	**Session 2**	Defining the system boundary
	Step 3: Conceptual Modelling	**Session 3**	As-is conceptual modelling of the project processes
		Session 4	Final conceptual loop diagrams for future scenarios (including the technologies)
	Step 4: Computerized Modelling	**Session 5**	Identification of external factors and model parameters
		Session 6	Technology impacts on the model and stock-flow diagrams
	Step 5: Simulation and Scenario Analysis	**Session 7**	Scenario testing and discussion of the model outputs

3.6 Research Design

According to the explained research methodologies, the followed research framework is given in Figure 3.1. Firstly, the existing Construction 4.0 concepts, trends and digital technologies have been configured from the literature. In addition, the usage areas of system dynamics in construction and project management were examined from the literature. Examples in the literature in project planning, performance and strategic management were taken as examples for modelling. Then, an initial study was conducted to understand the needs of different digital technologies that have been presented as key technologies of Construction 4.0. In

this study, the case company's strategic position has been discussed regarding technology integration. After that, the existing and aimed/future process chains were drawn according to the BPR methodology.

The conceptual and computerized models were created as the two main steps of the system dynamics modelling. The validation steps are conducted following the model development, and according to the results of these tests, the computerized model (e.g., structure, model formulations) are iteratively changed. Finally, the validated stock-flow model has been simulated and analysed for different scenarios for dynamic external conditions and advanced technology adaptations.

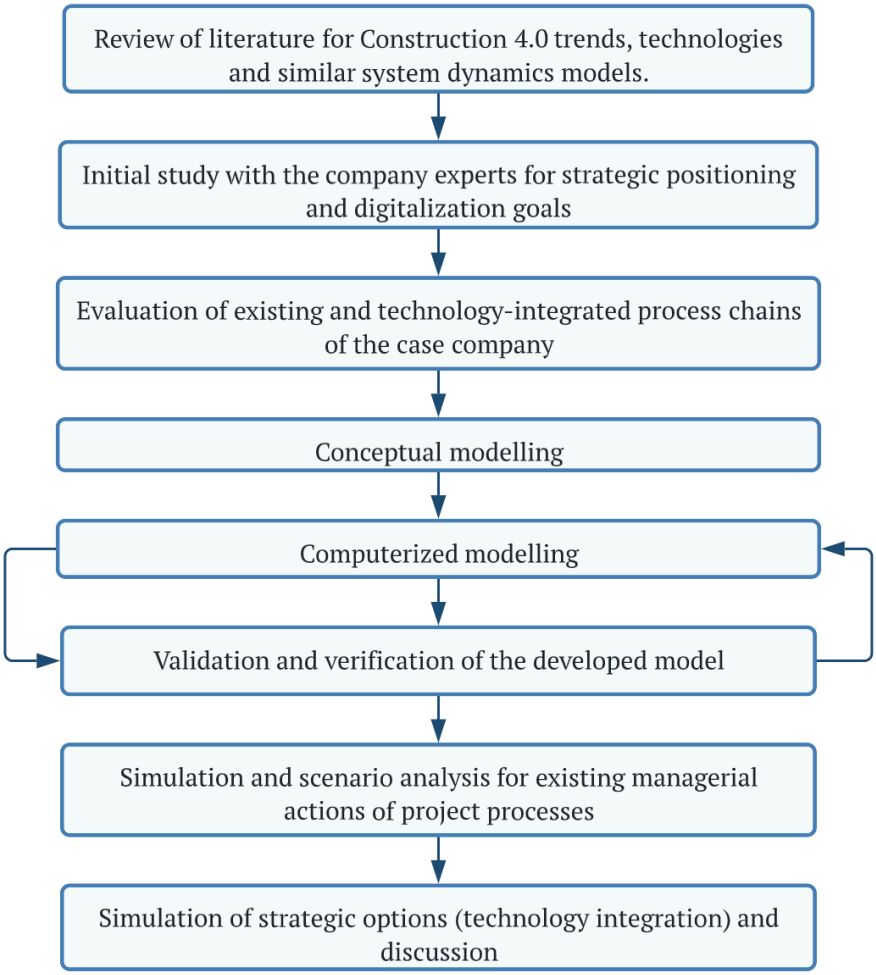

Figure 3.1: Research design

CHAPTER 4

THE CONCEPTUAL MODEL

This section summarizes the key findings of the research and analysis of different digital technologies for the strategic decision-making of the case company. The chapter is structured as follows. Firstly, an initial study has been conducted to understand the possible digital solutions and the strategic positioning of the case company. Then the existing process-chain and technology integrations are considered with group modelling sessions. After that, the project's as-is and technology integrated causal loop diagrams are drawn for the case company.

4.1 Initial Study for the Needs of Digital Technologies

Since the study's main aim is to contribute to the existing systems of strategic decision-making of construction projects by different technologies, selecting them is essential. Hence, before the initial session with the case company and clarifying their needs for digitalization, the Construction 4.0 technologies, corresponding trends, and functions are introduced to the case company, as stated in research background chapter, in Table 2.1. After considering different technologies, an initial group modelling session was conducted with the case company to understand their strategic goals, existing utilization of technologies and their leading key performance indicators.

4.1.1 Strategic Positioning of the Case Company for Digitalization

To make a strategic analysis of the case company, the organization's current state should be understood, which can be referred to as strategic positioning. This definition includes describing the internal (resource-based) and external (market

conditions) environment of companies for both current and future scenarios (Price & Newson, 2003). For the scope of this study, the main strategic goal is to take one step toward digitalization. Therefore, the current situation in the use of technology, the reasons behind the decision of digitalization, technological adaptations that are needed, and related key- performance criteria have been tried to be evaluated together with this session.

As the theoretical background of the strategic analysis, generally, there are three main principles as describing external conditions, internal scenarios and strengths, weaknesses, opportunities, and threats (SWOT) analysis. First, the external audit examines the environment, sectoral, market, competitors, and overall business analysis. For the internal audit, the strategic resources and capabilities of the companies are investigated, such as the core competencies, the value chain, and possible improvements in non-value-added processes. Therefore, internally focused models emphasize efficiency and how to benefit from external factors according to companies' internal capabilities. As a combination of these two perspectives, Porter (1980) introduced strategic power as the exploitation of the market with the competitors. Moreover, the author proposed the value chain describing the activities within and around an organization that create a service or product. The third principle is the SWOT analysis which is highly utilized tool in strategic management. It is composed of combining the internal resources and capabilities (strengths and weakness) and external business environment (opportunities and threads). The strategy maps are depicted as meta- SWOT tools that combines both qualitative and quantitative aspects with systematic approach (Agarwal et al.,2012). Hence for the initial session with the case company, the strategic analysis is conducted by considering these aspects from the theories of strategy.

4.1.2 Findings from the Initial Session with the Case Company

The initial session with the company has been conducted according to the main questions presented in Table 4.1. These questions were asked to two experts of the

case company who are specifically responsible and experienced in the digitalization department. This session aimed to answer these questions in a group brainstorming and understand the key motivations of the company toward digital technologies.

Table 4.1: Main questions for the initial session with the case company

Q1	How to describe the main value chain of the company?
Q2	What is the company's current state in terms of digitalization (the integration of technologies into different processes)?
Q3	What are the reasons behind the company's digitalization decision?
Q4	What are the company's key performance indicators (objectives) in digitalization?
Q5	What technologies are you considering integrating? What are your main digitalization goals in the short and long term?

According to this session, determined questions were answered, and critical oral feedback from the discussion, which is necessary for model development, is depicted as follows.

- ***Q1- Value Chain of the Company:*** For the value chain realization of the company, the framework of Porter (1980) was used. The primary activities are defined as the ones that are directly related to the creation of products/services. The experts of the case company stated that their primary process-chain is composed of: Design, Supply of materials (Inbound Logistics), Production/Manufacturing in the factory, Outbound Logistics and Construction on site. Although only the supply of materials is defined as a supporting activity in the proposed definition of Porter (1980), due to the modularization of construction, the case company stated their significant independence to raw materials several times in the session. Hence, the supply of material process was noted as one of the activities which should be investigated for technology integration. Moreover, the experts stated that they have a technology development process managed by a technology team. This team is mainly responsible for the design stage and working to integrate BIM into different steps

of projects and coordination among different departments. In addition to that, the experts indicated that, especially for the production and construction processes to increase overall work rate, there is effective human resource management for recruiting and managing activities. It should be noted that the strategic assessment of digital technologies is limited to the project perspective in this research. Hence the process chain, which will be further investigated in model development, is mainly drawn by considering the project-level benefits of technologies.

- ***Q2- As-is Case of Digitalization in the Case Company:*** The experts stated that the company is currently using BIM as a modelling and simulation tool, particularly for design stages. Hence from Table 2.1, the company utilize "Design Automation". Although the experts mentioned that there is still room for further departmental collaboration, the company has the adaptation of BIM into different activities, such as electrical and mechanical departments. Moreover, they stated that the technology team uses cloud systems of BIM for further data sharing and communication purposes among different parties in business processes. In addition to using BIM, the company has an ERP system that they have been using for many years for supply chain management purposes. It is used for controlling the inventory, creating material lists for procurement and overall planning of logistics and production.
- ***Q3- Needs for Digitalization:*** The company stated several reasons behind the decision to integrate different technologies and combine them into a shared digital ecosystem. Firstly, the experts expressed that there is a need to increase productivity in general for the projects. Although the modular construction principles (e.g., producing the main units in a controlled environment) can increase productivity, the dynamics of projects, particularly the requirement of quickly responding to the client's needs, may negatively influence productivity. It is mentioned that, due to the change in market conditions, immediate remedies such as procuring materials, hiring people, and doing overtime became more difficult and in general there are considerable cost overruns due to that. Hence

the company believes that integrating digital technologies can increase the productivity of different resources (e.g., employees, equipment) and compensate this problem. Moreover, the experts stated there is room for further improvement in collaboration between departments in the company, and technologies can decrease the information coordination problems. Secondly, the experts indicated the entailment of reducing human errors as an essential factor for the company. These errors may influence client satisfaction at the project level, leading to reputation and profit losses at the company level. Especially further improvement of BIM with different technologies (increase in the maturity level) can decrease the chance of errors and improve the acceptance rate of works. Additionally, although the company has a competitive advantage and strategies for health and safety management, the experts said that the company is following trends of new technologies to decrease the chance of accidents and emphasized the importance of making a safe work environment. Since the production/manufacturing of building units is in the controlled environment of factories, the company focused on the construction stage for safety concerns. Lastly, the company signified the importance of the supply of materials for the overall effectiveness of the process chain. The company noted that the current material lists in ERP modules are not entirely up to date, and there is a disconnection between automized models and these lists. Hence, for better inventory management, the company wants to improve the integration of ERP systems.

Consequently, within the scope of this discussion question, the company's need to increase performance in overall project success is apprehended as the primary point for the incorporation of technologies.

- ***Q4- Key Performance Indicators:*** For this discussion question, it is asked to define the company's key performance indicators for the digitalization decision. The experts articulated that the main criteria are finishing the project in expected duration, budget, and success in the client's overall satisfaction, which can be expressed as quality. Rather than these common project success factors, since

productivity is an important aspect that technologies can improve for the company, this is also considered a performance criterion. As the intangible benefits of the technologies, the research team noted the company reputation, learning and growth of technologies as used in projects and increase in the motivation of employees in addition to the company's performance indicators.

- ***Q5- Future Goals for Digital Technologies:*** As the last step of the initial session, the configured trends, and technologies in Table 2.1, have been presented to experts, which gave them different options to think and configure the connection between the recent trends and the company goals. After that, the experts shared the company's digitalization intentions according to the priorities and listed the technologies that wanted to be integrated, as tabulated in Figure 4.1.

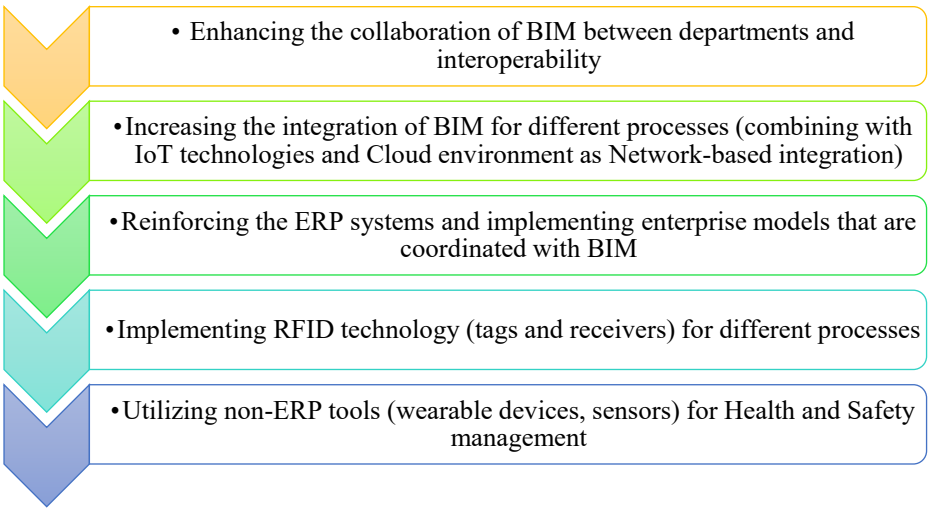

Figure 4.1: Strategic goals of the case company for digitalization

Hence, the company mainly focused on integrating IoT and Cloud technologies for improving the BIM integration, considering ERP-BIM integrated systems and utilization of RFID and sensors/devices (non-ERP tools) for safety as the new technologies, among those presented in Table 2.1 in literature.

The findings from the initial session with the company can be summarized as follows. The experts stated that, although there are competencies of the company for digitalization, such as the presence of the technology team, utilization of BIM tools

and ERP system for supply chain, the company expect to implement further and integrate technologies to enhance processes and improve project performance. Rather than solving the project inefficiencies with instantaneous traditional methods such as recruiting workers, overtime, the company aims to make technology investments that are more sustainable and advantageous for projects and the company's long-term success.

Since the main of the selected technologies and indicated integrations is "process improvement", in the next section, the used methodology of business process engineering is presented.

4.2 Business Process Engineering Approach for Integrating Technologies

Since it is understood that process and project-level improvements are the main goals for the digitalization of the case company, the process chain of their projects should be drawn for further investigation. In this research, the project-level processes are analysed for technology integration rather than reducing the number of processes or completely changing the organizational structure of the company (e.g., forward or backward integrations). Then, Business Process Simulation (BPS) has been conducted by system dynamics methodology because of the dynamic project environment and understanding of the behaviour of the system for different conditions of technology involvement.

System dynamics provide capturing feedback on the processes and better understanding of the project environment. Rather than the external changes in the projects the internal aspects such the reworks, delays, management actions and their side effects cause different feedback mechanisms affecting the project's success. Since technology integration has some positive impact on different project variables, these feedback loops can be simulated for both as-is case and future scenarios to make a trade-off for the case company.

As the initial step of the BPS methodology, the objectives should be defined, which is already been presented in the previous section. Then the existing process chain of the company is drawn in Figure 4.2. Then according to the goals of the company as stated in Figure 4.1 the new business process chain was drawn to give the general picture of the improvements by the technological integration in Figure 4.3.

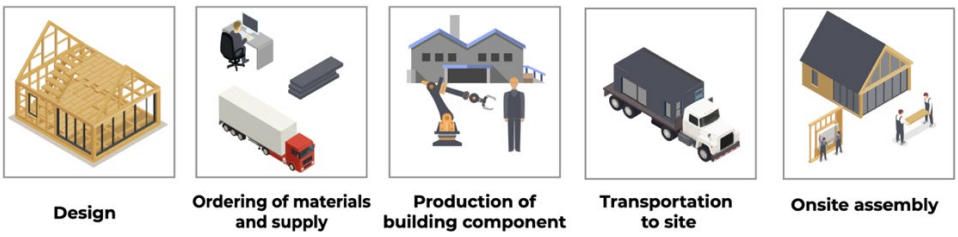

Figure 4.2: General process chain of the case company

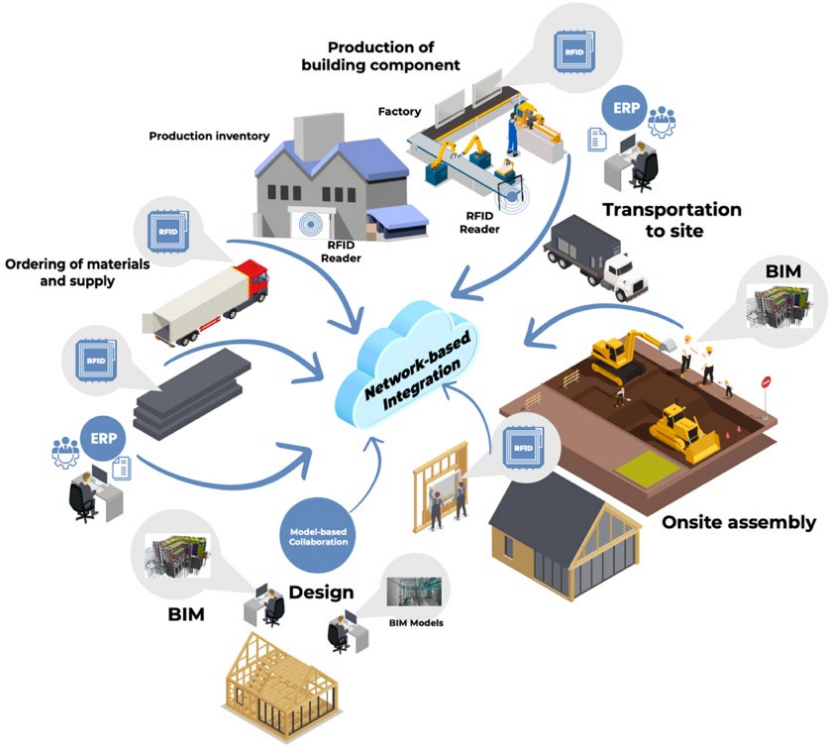

Figure 4.3: Digitalized business process chain

According to Figure 4.3, in the design stage, the company expects to further implement BIM collaborating through models for different process. Then, the

company makes the orders from the ERP system. For the supply process, as a future implementation, the company aims to attach RFID tags into the materials and enhance tracking during the supply process. Moreover, the RFID reader (smart gateways) will automatically track incoming materials to the factory. In the factory, the RFID readers on the building components can increase the overall productivity of the resources (workers and equipment).

Additionally, as visualized at the right side of the production line, ERP systems ensure production planning and control during the production stages. Then the finished product transported to the construction site for implementation. At this stage, BIM used for effective communication and coordination in the site. Besides, RFID tags implemented on the building components provides the construction workers identify and track the assets.

It should be noted that, the demonstrated as-is and digitalized business process chains are generalizable for similar modular construction companies. Hence, for another case company, the above picture in Figure 4.3 can demonstrate a "strategic picture".

The next section presents a more detailed evaluation of business processes and activities for system dynamic model development. Then, after clarifying the strategic position and future digitalization goals of the case company in GMB-1, the conceptual system dynamics models are presented in the next section.

4.3 Conceptualization of System Dynamics Model

The system dynamic modelling consists of mainly three stages (i) problem articulation (boundary selection), (ii) conceptual mapping and (iii) computerized model (stock-flow diagrams) according to the given research background in Section 2.3. The findings of group modelling sessions have been investigated in an iterative manner for each step, as depicted in Table 3.1. Then the system model was simulated for different scenarios to evaluate policies conducted in isee-systems Stella Architect Software.

4.3.1 Problem Articulation (Boundary Selection)

For this step, a second modelling session has been conducted. In this session, the system dynamics methodology is briefly introduced to experts, and the pre-developed Stella Architect model is exemplified for the case company's process chain. Even though the concept is new to the experts, after this presentation, according to their feedback, the possibility of being unfamiliar with the SD idea is reduced.

After re-evaluating the process chain and goals of technology integration, the sub-systems are configured as the major project activities as Design, Ordering, Supply of Materials, Production and Construction. At this point, the Outbound Logistic is not considered for the model because the experts stated that the company generally uses the risk transfer strategy for this process and works with experienced logistic firms. Moreover, the company stated that it is not planned to use technology implementation for the logistics stage. Therefore, even though it is an important part of the project process chain, it was neglected because digitalization is the main target for model design. Moreover, the operation and maintenance process at the end of projects is also considered outside the system boundary.

Although system dynamics provide simulation for the depicted system, the "environment" around the system influence the system itself; hence in the following steps of the model development, different conditions of the project environment such as market conditions, labour employment conditions, and demand growth in project-level are integrated into the model explicitly.

Since the connectivity in dynamic system methodology is based on "cause-effect" and "accumulation of flows into stocks" in a time-dependent manner, the sequence of processes should also be analysed. In construction projects, this sequencing of processes is generally managed by different time management techniques such as critical path method, program evaluation review technique, and line of balance etc., the system dynamic modelling can also be utilized especially for dynamic planning

of schedules under circumstances of reworks, productivity losses and change orders. Moreover, the SD is widely employed for determining the overall effects of delays and feedback on project schedule performance as stated in Chapter 3. For the model in this research, the experts stated their logic for their process chain and the general sequencing of the activities for a medium-size generic project as follows:

> *"Firstly, the design team starts to do designs according to the requirements of the client. At the design stage, the technology team mostly come up with solutions to complexities or ambiguities of the design through automated models. However, sometimes human mistakes and coordination problems can cause rework. This may impede the design. The planning and creation of shop orders continue parallel with the design. According to the design of the buildings, the orders are created, and material lists are checked depending on the existing inventory. Then the orders of materials are supplied with a supplier. Generally, the company's supply and production processes are connected in a start-to-start manner, with a positive lag. The production procedure can start when the supply of materials has been also started, a one- or two-week waiting period. Hence the incoming materials are transferred to production inventory. Since our company's processes are mainly dependent on the material, the planning of logistics, missing materials and supplier performance are critical. During the production, the production modelling phase is important. Again, like the design phase, the errors and delays due to productivity losses are critical for the company. Because the construction can only start when the production is over, and the units are successfully transported to the construction site. The production and construction phases are logically connected in a finish-to-start manner, but there is the outbound logistics between these processes. Although there are technologies to improve the performance of logistics, it is not in our company's integration policy anytime soon."*

After investigating these oral feedbacks, the identified process chain is sequenced according to the company's logic. In SD modelling, the "stocks" are the parameters

by which “flows” are accumulated, hence the parallel processes: Design- Ordering and Supply-Production are connected to each other by flows (e.g., design rate, supply rate). On the contrary, the finish-to-start activities and Production-Construction are completely separated from each other for modelling to investigate the durations separately and sum up consecutively for total duration calculations. The details of these assumptions are further examined in the Computerized Modelling section.

Following the examined system boundary and order of processes, the conceptual modelling is explained in the next section.

4.3.2 Conceptual Modelling

This section explains the development of conceptual models. The process diagram of conceptual modelling is given in Figure 4.4.

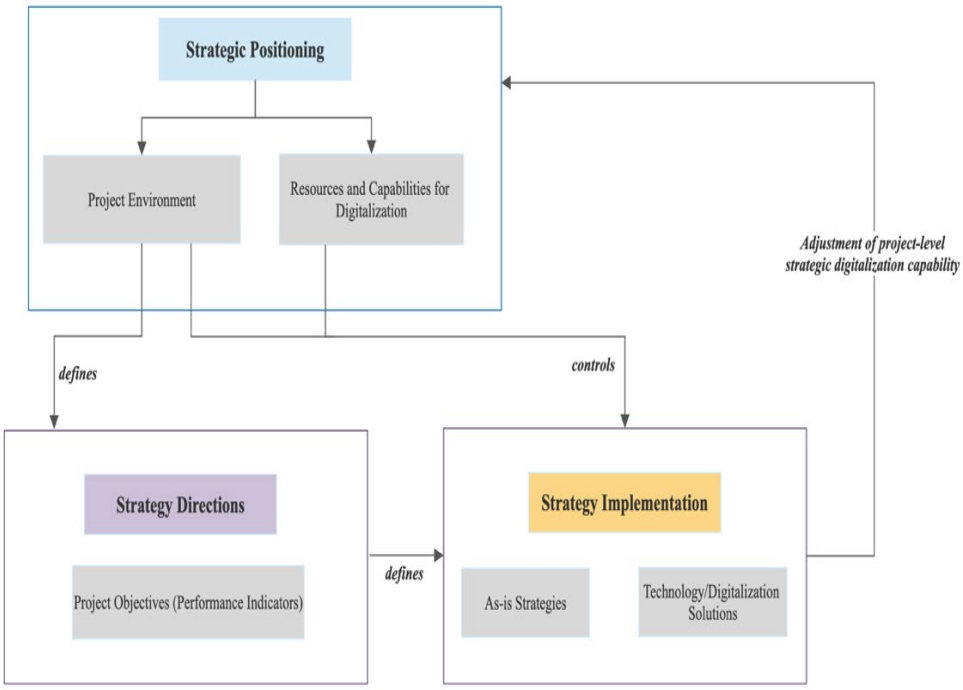

Figure 4.4: Process diagram for the conceptual modelling

The conceptual modelling is the first step of the SD model development. It is all about determining the main system parameters and developing their relations (causalities). For this, different CLDs are created to understand the conceptual maps for the scenario analysis and digitalization effects. As it is presented in Figure 4.4, firstly, the project environment is analysed according to the company's strategic positioning in Chapter 4.2. The project environment encompasses both the internal dynamics of processes and external factors, which are further investigated in the next section of the Computerized Model. The company's strategic position and project environment define the strategy directions, such as stated performance indicators of the case company, time, cost, client satisfaction, productivity etc. Since the SD modelling is based on the time-dependent connection, the time/duration objective is first considered throughout the conceptual mapping. Then the time sector is utilized for the analysis of the cost sector and other objectives. The details of each sector and calculations are presented in Computerized Model. Accordingly, the as-is strategies are configured for the initial causal relationships between system parameters and schedule performance. In Group Modelling Session 3, the generic layout of the as-is CLD is constituted. Then in the next step, in compliance with the case company's resources and capabilities for digitalization (integrated technologies, maturity levels etc.), new CLDs are drawn for technological solutions for each project process. It should be noted that, although the technology integration is presented as "action", it is controlled by the "system" itself (project environment and company's current technological status).

4.3.2.1 As-is Causal Loop Diagram

Firstly, the as-is conceptual model of the project processes is configured according to construction management model structures in the literature and feedback from the experts in Session 3. In this session, the logic of the conceptual model is presented to experts as follows.

The basic feedback structure of the construction management system is composed of essential elements such as (1) project progress, (2) errors and reworks, (3) project planned schedule and requirements, (4) actions such as overtime and resource employment and consequences of the actions.

Then, similar project progress and schedule performance models as mentioned in Chapters 2.4.1 and 2.4.2 are presented to experts. These models encompass the project progress logic, error and rework models and managerial actions such as labour employment and overtime for the schedule performance. The experts of the company stated that the company follows similar logic to the ones in the literature while dealing with the reworks and losses in productivity. Moreover, the experts mentioned that for different processes, the management teams prefer different remedies, which are taken into consideration for model parameters in the quantitative modelling stage.

At the end of Session 3, after understanding the general parameters for CLD, the experts configured the logic behind the essential elements and supported by the literature. The conceptual loop diagrams in this section are drawn by the SD modelling tool, CLD feature of Stella Architect.

1. **Project Progress**

The first causal link is for the general flow of the work. The project progress terminologies are decided based on the model structure of Figure 2.3 (Lyneis et al., 2001). Accordingly, at the beginning of the flow, there is "Work to do", then this work is decreased by "Rate of task completion". The generic formula of this parameter throughout the model development is as follows.

Equation 2: Completion rate equation

$$Rate\ of\ task\ completion = Productivity * Resource$$

In this equation, the task completion rate has the work units divided by time, which the work that is done for each unit of time.

Project managers and construction professionals define productivity as the ratio between the earned work hours and spent work hours in general. It can also be defined ratio of the total input of resources on a task and the total output of products (Nasirzadeh & Nojedehi, 2013). In this research, productivity is the work done for a unit of time for one resource. The resource in the equation represents the expanded definition of used sources for the specific task, for instance, it can be construction labours, design teams, or production equipment and workers.

Then following the "Rate of task completion", the "Remaining work" is decreased. However, at this point, the projects may encounter some errors and rework due to the errors.

2. Errors and Reworks

For the feedback loops of the error generation and flow of the rework to the work that needs to be done, the frameworks of Lyneis et al. (2001) and Lyneis and Ford (2007) are used and CLD of this portion is drawn in Figure 4.5.

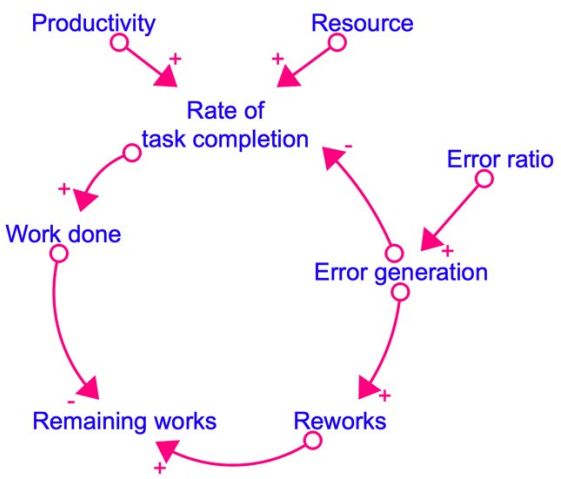

Figure 4.5. Error and reworks causal loop diagram

According to the figure, an "Error ratio" is defined. This parameter represented the wrongly done portion of the rate of work done. This parameter has different representations in the literature such as error fraction (Lyneis et al., 2001; Love et al., 1999) and considering the positive denotation: acceptance rate of completed tasks

(Wang & Yuan, 2017), quality (Pargar & Kujala, 2021). In this research, the experts stated that the error ratio is much more convenient for the processes of the case company, and they can predict the error as a percentage for each process for the further steps of the quantitative model. As a result, the generated error cause reworks and the remaining work that needs to be done increases. It should be noted that the change management research in construction management literature configures the changes and errors according to their approving mechanisms in a more detailed way, such as investigation of request-for-information dynamics, latent changes, predecessor, and successor work's errors effect on overall project quality management (Park & Peña-Mora, 2003; Motawa et al., 2007). In this research, error generation is considered only within the context of digitalization and selected technologies with the case company. Moreover, since each project process (design, construction etc.) is analysed separately in the model the errors that are not realized in the predecessor activities are reflected in the successor activities by the conceptualization, which is discussed in detail in the next sections.

3. **Project Planned Schedule and Requirements**

The schedule pressure terminology is widely used in the context of project management with SD modelling. The term defines the ratio of actual completion time (required time to correctly complete the work) to planned completion time. The actual completion time is defined by the productivity and number of resources (effort applied). The increase in the schedule pressure has some consequences on the project regarding the work rate and productivity.

4. **Control Actions and Feedback Consequences**

When a project falls behind the planned schedule there are general remedies such as overtime and an increase in the resources. Firstly, overtime is a common action for instantaneous delays. Furthermore, overtime may result in both balancing and reinforcing feedback loops. Firstly, in proportion to the schedule pressure, the overtime factor increases the work rate (working more, increasing the manhours), consequently alleviating the schedule pressure. However, most construction projects

have a specific limit for the overtime amount. In other words, it will not be possible to do more overtime after this limit, and the entire schedule pressure may not be compensated. Secondly, overtime may induce reinforcing feedback due to employee fatigue, inducing productivity loss and decreasing the number of accomplished works. Similarly, the extended period of overtime causes a higher rate of errors, thus further delaying the project, generating schedule pressure again over time, which constitutes a self-reinforcing loop (Sterman, 1992; Al-Kofahi et al., 2020). The feedback loops of the overtime policy are shown in Figure 4.6.

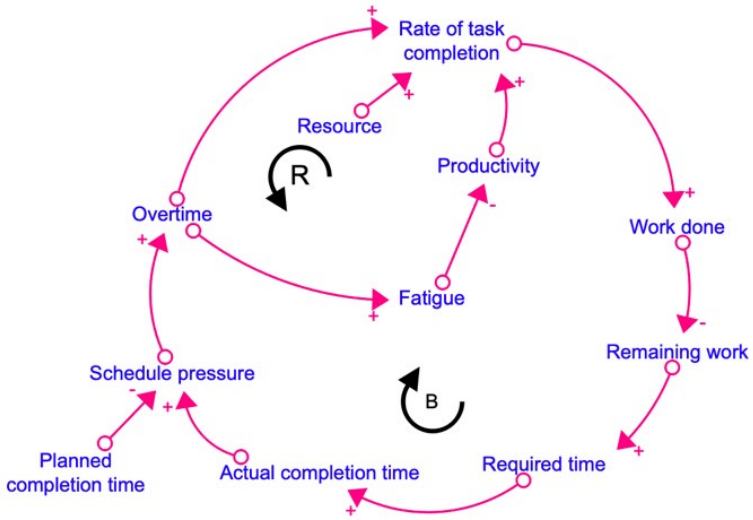

Figure 4.6: Overtime policy causal loop diagram

Having mentioned the overtime action for possible extensions in the planned duration of the process, increasing the resource is another remedy for project dynamics. Hiring resources (workers, teams etc.) directly result in the rate of task completion. Rather than proportioning the schedule pressure, the required resources are configured through the difference between the planned completion time and the time that is spent. The resource allocation is carried out according to the difference between these two parameters. Especially for construction projects, the action is logical considering the other projects continuing in the meantime from the company portfolios. The action of increasing resource/labour is generally preferred for more

human-workforce oriented processes of projects such as production or construction. However, this action has also a feedback loop and effect on the system itself. Most of the working environments have a capacity and after this limit and additional hiring may outcome congestion in the factory or construction site, lowering productivity, increasing the errors and possibility of accidents (Sterman, 1992; Lyneis & Ford, 2007). Rather than the overcrowding issues, the literature additionally mentioned the inferences such as experience dilution, training requirements and errors due to the trainees. In this research, by taking the opinions of the experts, all these issues combined into one parameter as "crowding effect on productivity".

After considering each element, explained causalities and feedback loops are combined. The finalized CLD that presents the as-is management is given in Figure 4.7; this figure displays the five feedback loops as three balancing (B1, B2, B3) and two reinforcing (R1, R2) loops as previously explained. The explanation of each loop is presented below.

B1. Rate of task completion⇒ Work done⇒ Remaining Work⇒ Required time⇒Actual completion time⇒Schedule pressure⇒ Error ratio ⇒Rate of task completion

B2. Rate of task completion⇒ Work done⇒ Remaining work ⇒Required time⇒Actual completion time ⇒Schedule pressure ⇒Overtime⇒ Rate of task completion

B3. Rate of task completion⇒ Work done⇒ Remaining work⇒ Resource required ⇒Resource adjustment ⇒ Resource ⇒ Rate of task completion

R1. Rate of task completion⇒ Work done⇒ Remaining work ⇒Required time⇒Actual completion time ⇒Schedule pressure ⇒Overtime ⇒ Fatigue ⇒Productivity⇒ Rate of task completion

R2. Rate of task completion⇒ Work done⇒ Remaining work⇒ Resource required ⇒Resource adjustment ⇒ Resource⇒ Crowding effect of productivity ⇒ Productivity ⇒ Rate of task completion

The finalized as-is CLD represents the management dynamics of the case company and is developed in accordance with the generic models in the literature as mentioned. Moreover, this model creates the main layout for processes while integrating technologies in the next section.

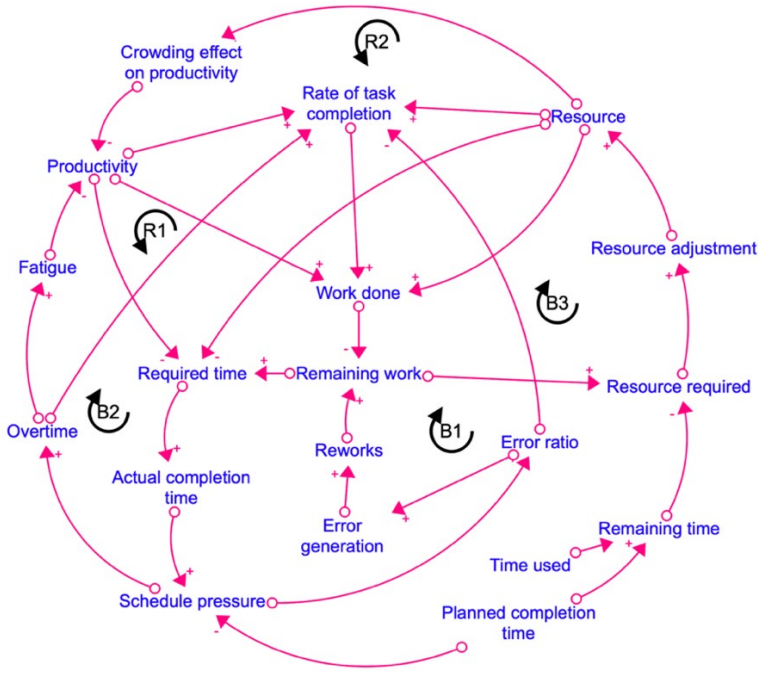

Figure 4.7: As-is causal loop diagram of the project management processes

4.3.2.2 Digital Technologies Integrated Conceptual Models

As it can be followed from the process map in Figure 4.2, after clarifying the as-is models by understanding the project environment and causalities between parameters, different technology adaptations are integrated into existing project dynamics in this section. Group Modelling Session 4 has been conducted with the case company experts for this step. In this section, the case company's strategic positioning, resources and capabilities for digitalization are considered to precisely

modify the existing CLD and understand which features of technologies should be integrated into which variables. Moreover, the technologies and effects are controlled by the strategic directions of the case company (i.e., performance criteria, project objectives). Therefore, each process and strategically intended adaptations are discussed with the company experts to clarify these. As it is mentioned in Figure 4.3, the processes in the project flow that are planned to be digitalized are (i) design, (ii) ordering and supply, (iii) production, and (iv) construction. For each process, the research team and company experts discussed how to reach the strategy directions considering the project environment and existing digitalization conditions of the case company.

i. Design

For the design process, it is stated that BIM methodology and related technologies (e.g., modelling tools) are currently used and desired to be improved for the case company. Although there are different opinions regarding the measurement of BIM benefits, it is a well-acknowledged view that the automation capabilities of BIM are one of the most effective outcomes for the digitalization of the projects. In the Session 4, one of the experts summarized the benefits and objectives of BIM integration in the company as follows:

> *"Similar to the rest of the AEC industry, our company has also adapted the shift from 2D Computer-Aided Design (CAD) drawing to more information-rich BIMs. The integration and automation through BIM increase productivity, fewer RFIs and decreased errors. For the design automation, the design team can easily notice the clashes that need to be corrected before going to the production stage, which reduces the production errors and saves the time and cost of projects. Apart from this, the coordination that can be realized through the model within and between departments also provides proactive situation analysis and solution generation. However, at this point, the acceptance of BIM methodology instead of traditional mechanisms by employees can be limiting factors. As our strategic goals, we would like to*

increase the implementation of BIM further to create automation in design processes, which directly increases the design team's productivity."

Since the expert mentioned *"Automation of Design"* more than once, it was decided that it would be a factor to be integrated into the new CLD for the design process as a factor that affects productivity and design errors. The Computerized Model section presents the details of the parameters and converts the causal relations to mathematical equations.

The company referred to the *"Automation of Design"* parameter by the level of BIM integration. In addition, the maturity models in the literature are reviewed to clarify the BIM parameters used in the model and understand the current and future capability of BIM in company processes.

- **BIM Maturity Levels in the Conceptual Modelling**

In the literature, there are many maturity and capability models for choosing the appropriate levels for BIM assessment purposes of construction companies. For example, Succar (2010) proposed three fields for BIM activity process (industry players, structures, leadership), policy (regulatory, contractual, benefit/risk analysis) and technology (software, hardware, equipment) fields based on the definition of it as an inclusive methodology. In this research, even though the process-related benefits are considered, the defined parameters/levels of BIM enclose overlaps of these fields (e.g., the interoperability level of the case company requires consideration of both technology (software) and policy (research) players).

The proposed model of Succar (2010) for the maturity levels is utilized for this research. Accordingly, the author presented three stages 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 as well (Yilmaz et al., 2019; Khosrowshahi & Arayici, 2012). It should be noted that the represented BIM stages in this research defined the levels by their minimum requirements (i.e., to be defined as the level 1, there should be at least object-based modelling tools). Moreover, the

pre-BIM status of the maturity models is not included in this research since the case company has already started implementation. According to the mentioned research in the literature, the defined maturity levels for the conceptual modelling are as follows.

- **Level 1- Object-based models** represent the level of details in the object-oriented 3D models and deployment of parametric software tools which incorporate automation and coordination. These models are generally composed of architectural design models which enable 2D documentation and 3D visualization. Hence, the "Automation of Design" parameter is broadly in parallel with the level of details in these models.

Although the case company utilizes 3D parametric modelling tools, it is unclear whether these models are incorporated into management with 4th (time) and 5th (cost) dimensions. Hence this level is separated into two segments.

- **Level 1.2- The integration of time and cost data** into the models represents both the availability of detailed models and time and cost data in the company. This maturity level is designated *"Effectiveness of Project Management"* in the drawn conceptual models. It is assumed that the quantity take-offs for 5D models and importing schedules into different software for 4D models for simulation provide important insights for effective project management. Although most of the mentioned literature categorizes this feature of BIM as Level 2, in this study, considering that the company has already developed itself in terms of the first level, it was decided to put this feature directly in the conceptual models as a parameter to reflect the importance for planning, especially for schedule performance.
- **Level 2- Model-based Collaboration** reflects the active collaboration between different disciplines. Hence the interoperable exchange of information through models is the main criteria for this maturity level. It implicates the Design-Design (between architectural and structural/mechanical/electrical models), Design-Production, and Design-

Construction (between architectural/engineering models and fabrication/steel models) exchanges, ensuring clash detection between different disciplines. Although the communication between models is still asynchronous, the project mechanism takes place in which the boundaries between phases, roles and disciplines are softer, and the flow of information is more accessible.

- **Level 3- Network-based Integration** indicates sharing semantically rich models through the entire project life cycle. The collected real-time data from processes are combined with multi-dimensional models. In the literature, the integration of construction processes into BIM features is amplified with the shared data environment (cloud computing technologies) and collected data from IoT technologies (Tang et al., 2019) for this level, and even further examined with digital twin studies (Douglas et al., 2021). This maturity level and parameter signification also overlapped with the second strategic direction of the case company, as previously given in Figure 4.1. Moreover, this level contains the company's capability to direct/manage different interfaces for different processes and corresponding models (i.e., integration of interfaces). The communication is synchronized for this level, which includes the business intelligence and enhances the analysis of constructability, lean applications, sustainability etc., with a unified model.

After clarifying the maturity terminologies for BIM implementation, for the design stage, the technology integration is discussed with the case company for these levels, and changes/additions to the existing generic project management CLD drawn in the previous section are decided.

The experts stated that for the design process, the company does not recruit workers in case of possible delays. So, increasing resources is not available as a managerial action. Instead, the resources do overtime depending on the schedule pressure. The main resource for the design process is defined as the design team, which is responsible for design in different segments. This team's productivity directly affects the design task's completion time. *"Automation of Design"* increases productivity

and reduces the frequency of design errors and reworks. Moreover, with the experts and research team, it is decided to relate the *"Effectiveness of Project Management"* to the schedule pressure variable. The schedule pressure may be released by increasing the correctness of planned durations and payment arrangements through the availability of project management features by automized models. The details of the parameters and quantification of relations are given in the next step for stock-flow diagramming. According to the feedback from the experts and maturity levels of the BIM, the finalized CLD of the design process is given in Figure 4.8 for the related feedback loops and causalities. As it can be seen from the figure, changes have been made for the generic CLD, coloured two parameters and causalities are added for the digitalization strategy.

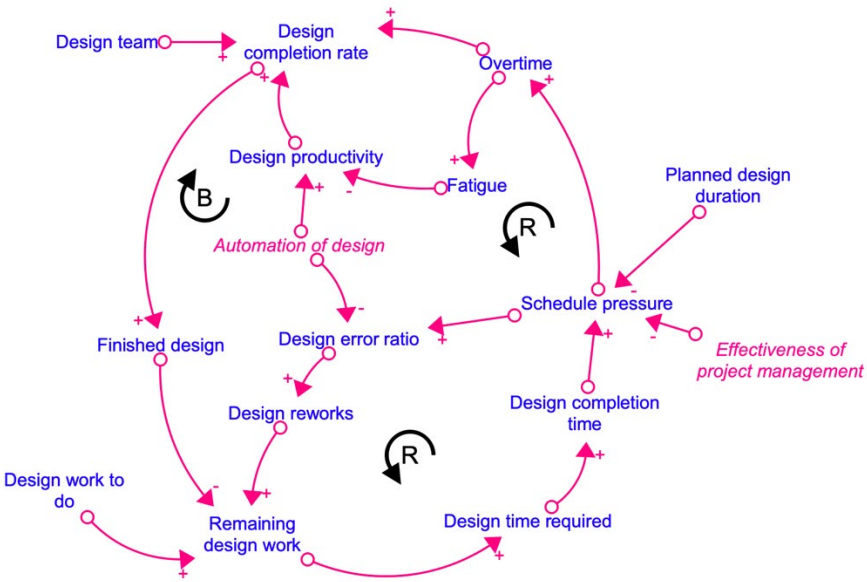

Figure 4.8: Design process digitalized conceptual loop diagram

ii. Ordering and Supply

After clarifying the design process, in the Group Modelling Session 3, the dynamics of getting order and supply of materials are discussed. As mentioned before, in strategic positioning, the case company has an ERP system already integrated for

several years. This system was implemented for creating coordinated material lists and general planning of logistics. However, the company needs to improve the accuracy of the material list for accurate inventory adjustments. The experts stated the overall logic of causalities and strategic objectives of the company for this process as follows:

> *"The ordering stage in the project is directly linked with the design. The required raw material is ordered parallel to the designed units through the ordering system. In addition to the exact needed material, the company adds an order contingency to be on the safe side for future problems or changes. During the supply process, the performance of suppliers and market conditions are critical. The company aims to increase the integration and update of ERP systems further and implement new technologies like RFID for this step. Because supply is a very critical process for the rest of the project since the modular construction is deeply material oriented."*

According to the discussions in the session, it is realized that the first strategic objective for supply is regarding the ERP systems. Similar to BIM, the maturity levels for ERP are also investigated, and related parameters are decided for the conceptual model.

- **ERP Maturity Levels in the Conceptual Modelling**

The literature about the maturity of ERP systems is mainly comprised of different modules of ERP and how it is incorporated into business processes. For instance, Holland and Light (2001) divided the ERP integration stages into three; initial management of legacy systems, implementing ERP modules and functionality over the entire organization, and as the last stage creating strategic value from the system by additional frameworks such as customer relationships, entire supply chain management and knowledge management. Nevertheless, ERP integration has been going on for many years for the case company, and the main goal is to ensure that the lists of materials are up to date for projects. Hence, ERP systems were considered together with BIM integration in this study. Furthermore, since different systems

such as planning, inventory management, transportation management, and supply chain management are part of ERP, the company needs to combine these processes with the information on the BIM side and create a common management system. For this reason, in the quantitative part of the modelling, the evaluation of ERP is carried out accordingly.

Considering the effectiveness of material management throughout the supply chain, ERP systems provide updated material lists, status visibility and business information sharing among different parties. Furthermore, in line with the shift towards lean production, ideal inventory control is started to be emphasized more among businesses. The experts of the case company stated the direct relation of ERP to inventory control in GMB-4 as follows:

> *"The accuracy of material quantities is critical for the company. Sometimes when the material lists in the ERP systems are not up to date, there may be problems such as wrong material orders or re-purchasing the materials in the inventory. Integrating ERP systems decreases these risks and provides a correct analysis of the existing safety stocks. In addition, the order contingencies should be managed correctly to prevent the risk of extra material left in the inventory."*

Hence, for the conceptual model, *"Accuracy of material quantities"* is considered a parameter which is directly linked to the strategic objective of the case company for ERP. This parameter has a link with the "Order contingency", which refers to inventory and overall material management through the ERP systems (Tambovcevs & Merkuryev, 2009; Powell, 2013). Moreover, RFID technology has been considered for the mentioned missing materials during the supply from material management aspects. Therefore, it is concluded by the case company experts as a digitalization strategy and supported by the research in literature. For instance, Demiralp et al. (2012) stated the benefits of using RFID technology for the prefabricated construction supply chain as eliminating incorrect delivery and missing components. For the ordering/supply process, the RFID technology integration

encompasses the automized information flow for current material tracking systems. Unlike other technologies, the integration level of RFID technology is not divided into maturity levels; instead, it is added to the model according to how the case company can benefit from it on a process basis. For the supply process, the case company aims to integrate RFID tags to material packages and trucks to read the management information (supply time, amount etc.) when it has arrived at the factory.

For this reason, the benefits of RFID technology correspond to the "Missing material" in the supply model. It was assumed that the percentage of missing or defective raw materials could be reduced by effective material tracking and real-time captured data. Moreover, for the missing materials, it is stated that since the ERP systems increase the performance of material management, it influences the response of the supply process in case of disruptions. Therefore, although ERP systems do not directly reduce the percentage of missing material, a causality was defined since it can manage the delays in this case. According to these inferences, the finalized supply process CLD is given in Figure 4.9.

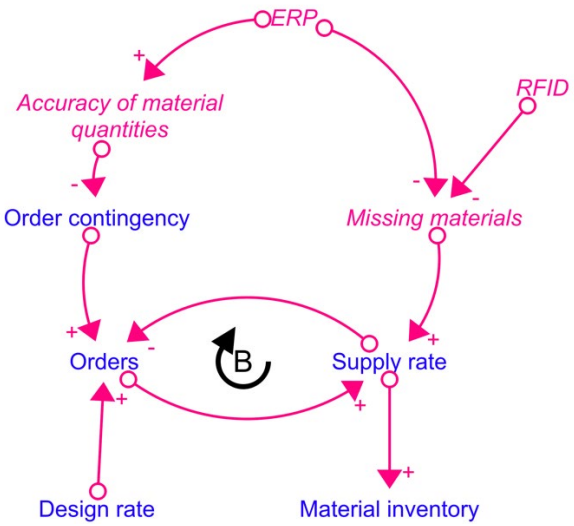

Figure 4.9: Ordering/supply process digitalized conceptual loop diagram

As it can be seen from the figure, the only feedback loop is between orders and supply rate, a balancing loop. Because since the company transferred this process to

a supplier, in the CLD, there are no traditional management actions (e.g., increasing resources, overtime) or changing the supplier. Since *"Accuracy of material quantities"* and *"Missing materials"* parameters directly affect the supplied work, the effect of technology for this process only be observed for total supply duration and inventory level.

iii. Production

The existing management strategies are revised for the production process, and technology improvements are discussed. The oral feedback of the experts in GMB-3 is summarized as follows.

> *"In the production process, the main remedy for possible time delays is increasing the resources (e.g., hiring labour, increasing the number of equipment). Generally, the production factories work the maximum work hours, so there is no overtime option. Since the resources can be utilized for other projects in the portfolio, the company follows an increasing resource strategy. Moreover, the main objective of production is the productivity of resources. The company considers the utilize new technologies to improve productivity in the factory environment. For the production planning and control, the existing ERP modules are used to create simultaneous planning combined with the supply side. Nevertheless, there are human errors and wrong productions, which should be minimized. Additionally, since the BIM models prepared on the design side and the fabrication models are not interoperable, two different modelling efforts may be required. This negatively affects productivity because a job that can be completed in a shorter time can take longer. While developing the BIM integration, we aim to harmonize with the production side."*

According to this feedback, the related parameters are considered for the conceptual model of the production process. Firstly "RFID" directly influences labour productivity, particularly by real-time information on product positioning. Furthermore, the time-consuming identification and location of materials/units can

be decreased by automatic reading of information (Lu et al., 2011; Demiralp et al., 2012). For the production process, RFID integration includes the tagged units in the factory and hand-held or stationary RFID readers as shown in Figure 4.3.

The experts stated that existing ERP systems benefit this process by providing effective production planning and control. These modules of ERP systems allow the company to track production and examine production processes to meet customer demand and requirements. The identification of code for different types of inventories increases the management capability of the company (Sarkar et al., 2021). Accordingly, it is assumed that the project-level ERP integration can decrease the production process's schedule pressure through better planning and control. For this, a causality is defined as shown in Figure 4.10.

Moreover, through the Level 2 BIM Maturity, *"Model-based Collaboration", "Production modelling"* efficiency may increase. As stated before, for this maturity level, the main aim is to enable interoperable models between different processes. In addition, with Level 3 BIM Maturity, *"Network-based Integration",* the data integrated into the production process can become more meaningful and enable better management, which decreases the frequency of errors and reworks because this network-based common environment provides the close-loop visibility and traceability of progress through the real-time status. Accordingly, the decided final causalities of the production process for the case company are given in Figure 4.10.

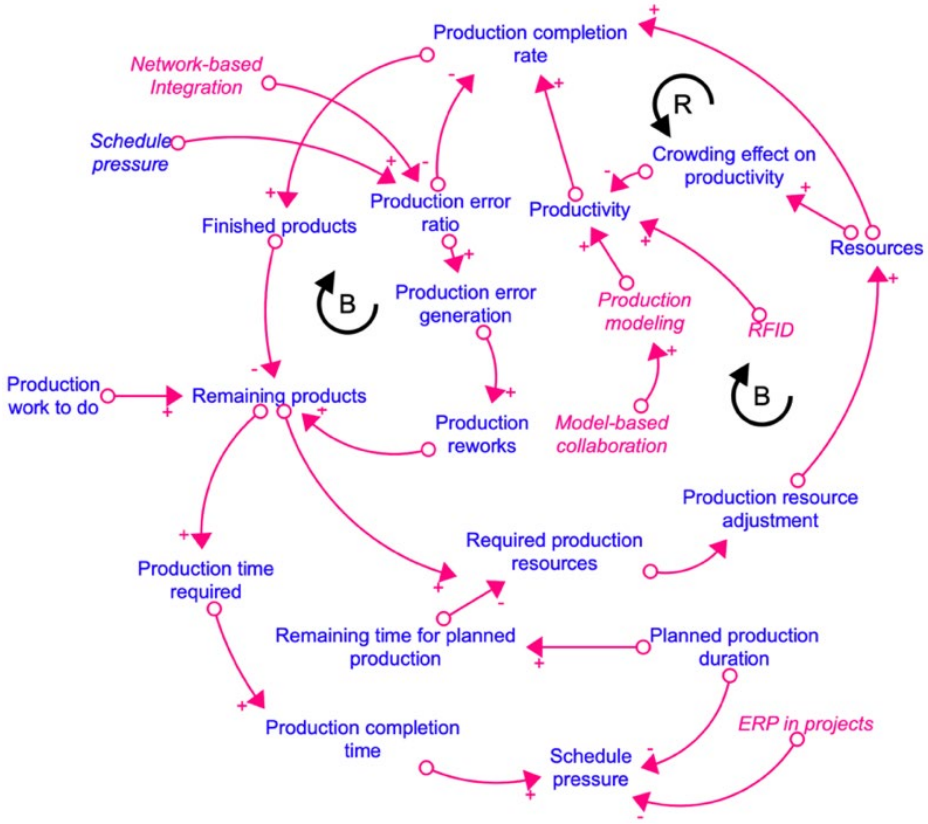

Figure 4.10: Production process digitalized conceptual loop diagram

iv. Construction

For the construction process, the experts explained the current management system and the digitalization-related strategies in GMB-4 as follows:

> *"The modularization of the project provides several benefits, especially for the construction process, such as less time spent on site, increase in the overall productivity of construction workers, and a more predictable environment in general. But still, the company encountered some delays due to the errors (reworks) or external changes (design change requests, production work increases etc.). To mitigate the construction process delays, overtime and increasing resources (hiring labour) can be preferred. Especially the lack of effective project management may require forming solution strategies in a short time. Usually, overtime is done, as well as*

recruitment of workers according to the conditions/capacity of the construction site. The company aims to decrease errors and improve the quality of the construction process. For instance, remanufacturing the missing/damaged units during construction causes serious delays. Moreover, the delays caused by the communication inefficiencies influence productivity. BIM and RFID may respond to these issues. Also, as we mentioned before, since the company cares about health and safety, technologies can be offered for the safety of workers in the next stages."

According to the feedback, the pre-defined *"Effectiveness of project management"* parameter is also integrated into the construction process, with a causal link with schedule pressure. Moreover, Level 2 BIM, as *"Model-based Collaboration",* enhances communication and coordination on-site, affecting labour productivity. For this context, the *"Communication on-site"* parameter is added to the model and related to the corresponding BIM level.

The network-based process information integration can generate solutions for the construction errors and corresponding reworks. For instance, the construction managers visualize the progress on site, coordinate workers and offer quick solutions by virtue of a common working environment. In addition, as already mentioned for this maturity level before, constructability is increased by integration with other processes, which reduces rework. Hence BIM-related *"Network-based Integration"* parameter is added to the model associated with construction errors.

Lastly, since the experts mentioned the safety concerns and the digitalization goal for this issue, the "Health and Safety Management" parameter is decided and related to the "Non-ERP tools". This is because the experts and research team are meant to

use sensors or wearable devices. Accordingly, the finalized CLD of the construction process is given in Figure 4.11.

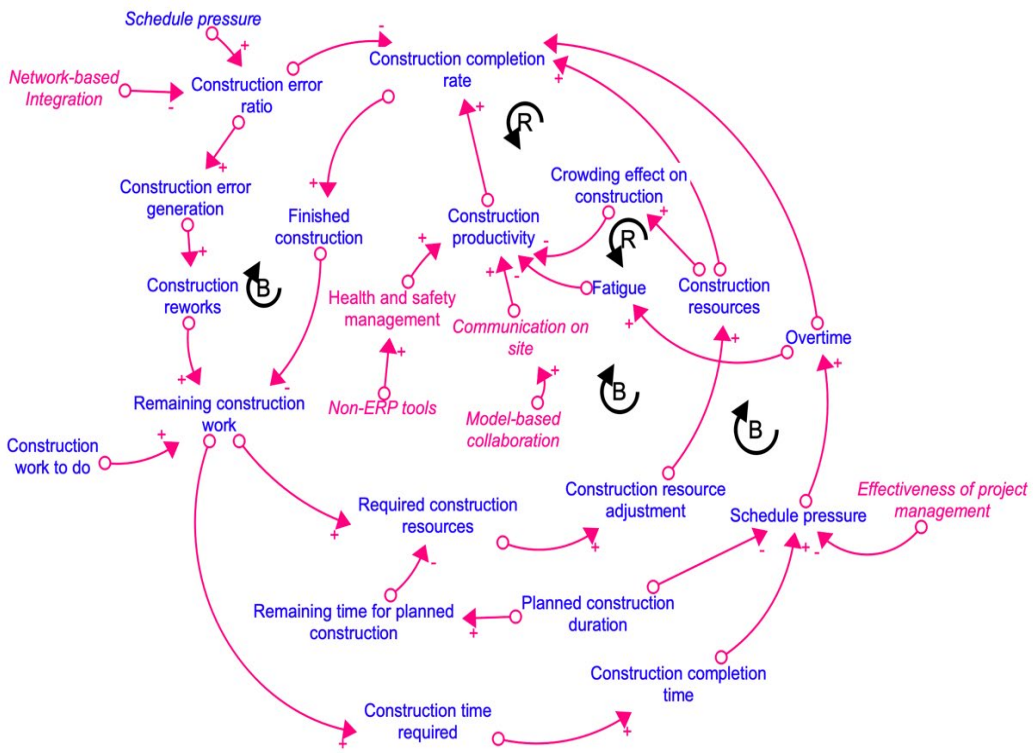

Figure 4.11: Construction process digitalized conceptual loop diagram

After clarifying the basic concepts of system parameters and understanding the interrelations by drawing each process causal loop diagram, the computerized model is presented with stock-flow diagramming in the next section.

This chapter explains the development of the computerized model, which is the last step before simulation for SD modelling.

CHAPTER 5

THE COMPUTERIZED MODEL

5.1 Methodology of the Development of Computerized Model

For the development of the stock-flow model, Stella Architecture software is utilized. The model was developed using different tools in the Model Window (MW). The steps in MW are as follows:

1. **Stocks and Flows:** Firstly, according to the feedback from the group modelling sessions for conceptualization, the researcher decided which parameters should be defined as stocks (accumulation/decumulation) and flows (rate, time-dependent inflow, or outflow) for the model. Since the main aim of this modelling is to simulate the project environment for different scenarios, the nature of the project flow is considered for this step. For instance, the process diagram drawn as an initial step of this chapter is used for sequencing different stocks and flows. For the Stella model, the time unit is selected as "Week". Because the experts of the case company referred to the activity durations as weeks, it is more convenient to model remedies like overtime for the project in this time unit. As an example of stock-flow logic, the "finished design work" is an example of a stock which accumulates. On the other hand, the "design completion rate" is a flow parameter with a week dimension.

   It should be emphasized that the Computerized Model's creation was an iterative process, as after adding a new parameter to the model, its fit and relationship with existing parameters needed to be explored. For each parameter, dimensional (unit) consistency should be guaranteed, and equations should be reconstructed as further parameters may be connected. For example, each parameter that inflow and outflow to the stocks had to have the same unit.

2. **Converters:** The converters in the Stella software have mainly three purposes. Firstly, it holds constant values. For instance, the model's predefined (planned or initial) project values (e.g., initial design work, planned construction duration). Secondly, it integrates external variables into the system. For example, the technological parameters (e.g., RFID, ERP etc.) behave as external variables for the scope of this study. The other external variables, including sudden changes in the project, will also be explained in this section later. Thirdly, it enables converting one unit of measure to another to ensure dimensional consistency. For instance, raw material for the unit parameter converts the production units to material units.

   Moreover, in Stella software, there are different types of converters, such as standard, summing and delay. The standard type of converter can be used for any stated purpose. The delay converter type can change over time in response to changes in input. It has some stock properties; hence it contains a box inside the converter in the software. Moreover, it can be involved in the feedback loops in which no stocks exist. In the presented model, the only delay converter is the "fatigue" parameter. To create the related feedback loop, the "fatigue" parameter is defined by delay over "overtime". The summing converter has not used in this study.

3. **Connectors:** After building the stocks, flows and converters, the connectors link the interrelated factors. In addition, an equational relationship must be established between the two factors with the connector drawn in the model. Finally, the connectors are added to the model according to the presented causal loop diagrams in Chapter 4.3.
4. **Developing Model Equations and Boundary Conditions:** After developing the parameters and their interrelationship in the MW, the model equations and boundary conditions are defined for each parameter. The stock variables only need initial values from the model. These values are considered with the company Experts in the following steps for simulation. For the model equations of flows and converters, different Built-in functions of the software are used,

such as data built-ins (e.g., initial, previous), logical built-ins (e.g., if then else), mathematical built-ins (e.g., max, min), and miscellaneous built-ins (e.g., look-up). The details of the used built-ins in the model are explained in more detail in each process's model assumptions.

5. **Units of Parameters:** After model equations are decided, units are assigned to each parameter. For this step, the Unit Editor is used in the MW interface to check the required units and the software directly suggests units for each variable. The Dimensional Consistency check is also conducted in Chapter 6 for validation, and inconsistencies are corrected as an iterative process.
6. **Running the Model:** The model simulation running is performed after assigning the equations and units in MW. To begin the simulation, the Run Specs Dialog Box specifies the simulation length and unit of time. The time units are selected as Weeks, as stated before. Since the model aims to understand the benefits of different aspects of digital technologies on a medium-size project, a one-year (52 weeks) was found to be reasonable as simulation duration by the company experts.

   The model configured different integration methods for solving the model equations when simulated. 1) Euler's approach, 2) Cycle-time method, and 3) 4th-order Runge-Kutta method are the standard integration methods. The Euler Approach is selected as the numerical integration method for the model run in the Computerized Model.

The program also allows running the model for different modules or sectors separately. To put it another way, modelers can choose whether to execute the full model or only selected modules and/or sectors. The Computerized model was developed first for the time sector since the SD modelling technique function as time-dependent simulations. Each process was modelled according to the conceptual diagrams in the time sector. Then, the results of the processes were transferred into the cost sector. Moreover, other objectives of the case company were evaluated for different scenarios, such as productivity and client satisfaction (errors).

5.2 Model Assumptions and Boundary Conditions

5.2.1 Boundary Conditions

As also depicted before, the boundary of the model is configured according to the strategic objectives and related project processes for the digital technologies of the case company. Although the considered technologies may have an influence on the outbound logistics or operation and maintenance of the projects, from the initial group modelling sessions, the intentions of the case company focused on the selected processes (design, supply, production, and construction). The picture in Figure 4.3 is used for the model boundary. Moreover, for each process, the boundaries comprised the project's initial requirements, the resources and capabilities and external uncertainties. As the initial requirements, the workload, planned durations, and contract conditions (e.g.., liquated damages) are considered. The model reflects the initial level of resources and competency of the technology team and the technology parameters for the resources and capabilities. Lastly, uncertainties, internal dynamics, errors and reworks, and external conditions are integrated into the model boundary, such as change orders. Moreover, project objectives (KPIs) are incorporated into different sectors' boundaries.

5.2.2 Assumptions about Project Process Dynamics

Stock Flow Formulations: In the model, there are three types of stock representations that are used, (1) stocks that represent the work that needs to be done and finished work, (2) accumulated wrong works/errors, and (3) resource level. For the first group, “design work” and “finished design work” can be examples. It should be noted that the finished project activities in the model comprised the correctly finished amounts; in other words, the work with no further rework required and errors resolved entirely.

The second type of stock was modelled the cumulative generated errors during the process. These defects became reworks with a delay, corresponding to "rework discovery time" regarding the "speed of decision-making" in further steps. Then, the reworks flowed to the initial work to be done. An example of stocks for (1) and (2) for the design process is given in Figure 5.1.

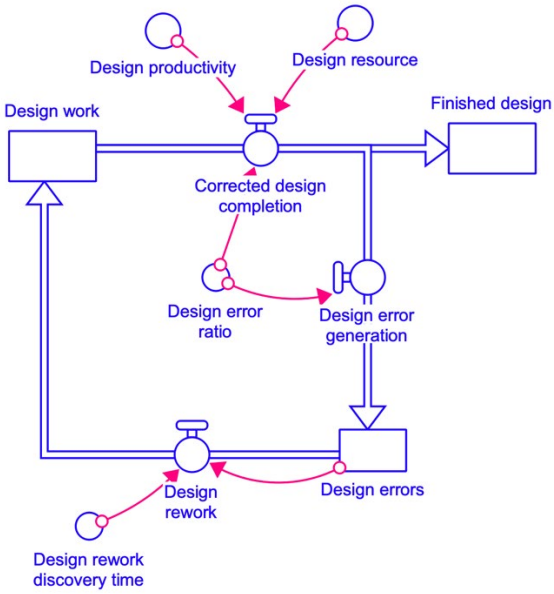

Figure 5.1. Stock flow example of the design process

Thirdly, since the resources were levels, it was modelled as stocks. As a managerial action, there is the initial level of resource, and according to the required changes, the resource level is altered in the progress of the project. On the contrary, the overtime management strategy was modelled as a converter since it is reflected in the model as the converted version of the schedule pressure and added to the equation as a constant value, not as an increasing/decreasing level.

It should be noted that the technology parameters were not considered as stocks for this model, which means that as the project progressed, the increase in the capabilities of the technologies due to the increase in the level of knowledge was neglected in this study. In other words, technology parameters were added to the model by the company as external factors that reflect the as-is cases. Afterwards, the

project-based impact of technologies for different scenarios was observed by changing these values.

Modelling the Connections between Processes: To accurately reflect the actual project environment and dynamics, the transition between processes must be modelled correctly. The company experts stated the overall flow of the project activities in Chapter 4.3.1, Problem Articulation. According to these feedbacks, firstly, the design process was modelled in Stella software. The start and finish of the process were not connected with other activity parameters. Then in the second activity, the ordering was linked with the "design completion rate" flow. However, since the units of design rate and order are not compatible with each other, converters were added to this link. The details of this step are further examined in the Ordering/Supply Process Model Formulation. In the Stella software, connecting two flow parameters means that while one stock is filled up ("Finished design"), the other ("Orders") is filled with the same flow, making the processes parallel, which is convenient for the rationale of the case company's project flow. After that, the "Orders" stock was discharged with the "Supply rate" flow.

As with other parallel activities of the case company, the experts stated that the supply and production processes progressed similarly to the ordering and supply. Thus, as the material is procured, production begins in the project. However, experts predicted that there would be a lag time of 1-2 weeks between these two processes, especially considering the arrival of materials and the temporary waiting time until the factory is ready. Nonetheless, while the supply rate has the unit of critical material in the project, the production process is based on the produced units. Hence conversion converters were implemented to this connection as well. Consequently, the supplied materials came to the factory as "Production inventory", and in line with the production rate, they accumulated in the "Finished products" stock.

For the last step of the project in the scope of this study, the construction activity was modelled. The experts stated that the finished products were in a temporary factory inventory and delivered to the construction site after completing all the work. Hence

it is decided to model the connection of production and construction similar to the "finish-to-start" logic in CPM. To reflect this aspect of the model, production and construction activities were separated from each other (i.e., no incoming flow to the "Construction work" stock and the initial value of this stock externally entered by the modeler according to the final production work that needs to be constructed/installed).

External Factors of the Processes: Until this stage, the external factors whose effect will be simulated in the model were only as-is and the intended technological integration factors. However, the project dynamics cannot be considered without the changes in the external environment. Hence in the GMB- 5 with the company experts, the sudden changes and external factors were discussed. In this session, the following two questions related to the external environment were asked to the experts and feedback is given in Table 5.1.

According to the given feedback, external parameters were implemented to Stella software. The first parameter is the "Change order" flow, which inflows to the "Design work" stock at the time of change orders. The second parameter is the "Production work increase" flow, as a parameter that compounds the "Production Work" at the given time. It should be stated that both the design change order and the production increase time were uncertain since they can vary depending on different projects. Hence, different assumptions were made and randomly simulated at this step, as explained in the Model Simulation part. The third external parameter is the "Order increase" to present the amount of additional order requirement in case of non-sufficient materials for increased work. As can be understood, for the construction stage, there was no additional change factor considered. The reason behind this is that, as can be seen in Table 5.1, the experts stated that most of the time, the construction change orders change the design work, and major work increases happen during the production process. Therefore, the design change order parameter is arranged accordingly as its time has been set so that it can receive different inputs and be simulated.

Moreover, all external change parameters were assumed to increase the work that needs to be done. Changes in quality were considered with the modelled error/rework values for each process. Besides, while examining the errors of each process, the inputs were given according to the errors not found in the predecessor activity. Additionally, the external factors such as subcontractor risks, weather, unavailability of specific equipment, force majeure etc., were neglected as model parameters within this study since the technologies would not affect reducing them.

Table 5.1: GMB-5 results for external dynamics of the project

Questions	Feedbacks
Q1- What are the situations that cause a change in your projects, and in which processes do you encounter them?	**EXP1-** "There is the risk of change orders from clients. Generally, there may be change requests during the design process that should be done correctly for material orders. The design changes generally increase the amount of work that needs to be done in the design stage and influence the entire project." **EXP2-** "Rather than the design changes orders, with the same design there may be production work increases. For instance, the client may ask for additional units (panels, modules etc.), which should be carefully managed for the risk of delays in material supply due to the market conditions. Since a large part of the project is completed during production, possible work increase requests are usually observed until leaving the factory. So, we often don't see the construction change orders in traditional construction projects. But of course, at this stage, there may be requests for changes from the client in terms of quality, although not particularly in quantity. Also, generally, the construction changes orders change the design of the building components."
Q2- What are the overall effects of these changes on the project?	**EXP1- "**For the design change orders, the company generally solved the issue of additional design work during the design process itself. Since the design is the core process for the production, possible change requests are managed by the design team, usually through automation by BIM tools. The overall effect of design change requests is the increase in total work for production and construction. At this stage, the company can generally compensate for the related delays with the contract conditions since it is due to the client." **EXP2- "**The production work increase may result in the requirement of additional material orders if the contingency amount/existing inventory level is not adequate. This return from the production process causes possible delays, and in most of our contracts, this risk is transferred to us. Hence the delays are not compensable. Generally, to manage the work increase, the company prefer resource allocation, which return as cost overruns. Also, it is our responsibility to manage the changes during construction."

5.2.3 Model Parameters Conceptual Types

This section presents the model parameter categorization to make a general signification before model formulation and stock-flow diagramming. In addition, the rationality of the determined conceptual types and parameter groups was consulted with company experts at GMB-5. Experts stated that it is suitable for the case company and project features.

In the model totally, six-factor groups are utilized (1) KPI, (2) Resource and Capability, (3) Managerial Actions, (4) Initial, (5) Formulation and (6) External factors. The explanation and examples of parameters are stated as follows.

1. **Key Performance Indicators (KPI):** These parameters indicate the project objectives of the case company on the Stella model. For this step, the determining criteria in Chapter 4.1 are used. Since the model was firstly established for the time factor, each process "Actual completion time" and "Total project duration" was considered. Then the resource costs were examined according to the time-varying levels of the production and construction resources and constant design team costs. The design team value was kept constant and modelled as a converter since the company experts indicated there is no employee allocation option for the design. Moreover, in overtime activities, the total resource cost was estimated depending on this factor.

   Rather than the resource cost, the material cost was also examined, considering the level of "Material inventory" stock. Lastly, for the cost sector, the "indirect cost" and "non-compensable delays" factors were added to the model by the unit prices. Rather than time and cost sectors as KPIs, the error rates for each process are used to determine the client satisfaction sector, which can also be referred to as the project quality.
2. **Resources and Capability (R/C):** The model parameters under this category reflect the general resources and capabilities of the case company for projects. The parameters were divided into two perspectives as project resources (human, equipment etc.) and technology integration capabilities. For the project

resources, both the number of initial resources (the number of the design team, initial construction resources etc.) and planned productivity values were considered. Since it is known that productivity for each process is difficult to measure or predict by the company, the opinion of the case company experts was taken for this configuration during GMB-5. The experts stated that generally, the planning team determined the duration of activities by considering the productivity of resources based on their experience. Hence, the productivity values (e.g., planned design productivity) were determined as an important criterion for the company's case performance and added to the model for computation in the simulation step.

The technology-related capability parameters were defined as parameters according to the conceptual maps. For each parameter, the company will assign their competency, and the digital integration will be increased with different scenarios to understand the behaviour in the project environment. The related parameters are listed in the next section.

It should be noted that all the R/C parameters are exogenous variables in the model, which means that it is a measure that is determined outside of the model and imposed on it. Moreover, productivity variables and the technology integration capabilities have undergone exogenous changes for different simulations in the model.

3. **Managerial Actions:** In the model, two managerial action parameters were specified as "Overtime" and "Resource change" as a converter and flow, respectively. In the design process, there is no resource increase flow considering the management mechanisms for this stage. Similarly, there is no overtime converter in the production step since the company experts stated that the employees are currently working to a maximum hour in the factory.
4. **Initial:** This category of parameters reflects the planned or initial levels and rates of different variables. For instance, the "Initial design work" is an exogenous variable that is entered into the initial value of the "Design work" stock. As

another example from the design process, the “Planned design duration” is an initial parameter.

5. **Formulation:** These variables encompass the converters, which aim to provide dimensional consistency between processes and transfer information between different flows or converters. Moreover, the rates and the consequences of managerial actions on the system (e.g., fatigue) are conceptualized under this category.
6. **External:** As stated in GMB-5 in Table 4.4, the defined parameters such as “Change orders”, “Production work increase”, and “Order increase” are configured as external dynamic factors.

5.3 Development of Stock-Flow Diagrams of the Model

This section presents the model formulation assumptions and finalized stock flow models for each process. Firstly, model formulation assumptions of technology parameters, rating conversions and efficiency values for productivity which were applied to all processes, are introduced. Then, each project process is examined separately with the regarding parameters, units, and stock-flow diagrams. During the GMB-5, continuous discussions have been made for the model representation of technology parameters.

5.3.1 Model Formulation Assumptions

Technology Parameters: The specified digitalization-related factors and maturity levels in the digitalized conceptual models in Chapter 4.3 were included in the model. Firstly, for the formulation of BIM maturity levels and automation of design, different factors were decided by the company experts in the GMB-5 and presented with the related assumptions and rating scales in Table 5.2. These factors represent the company's overall capability in related technology integration. As it can be seen from the table, a 5-point Likert scale (1-Lowest to 5-Highest) was selected for the

parameters to make it easy and understandable for experts while evaluate. These factors in the table were embedded in the model parameters of BIM maturity levels and automation instead of being put directly into the model for simplification (hence represented as Factor IDs in the table). Rather than the BIM parameters, RFID and ERP systems were also evaluated with related assumptions and directly added to the computerized model as converters (represented as Model Factors, M1 and M2 in the table).

Then these factors were used for the formulation of different model parameters related to BIM-maturity levels and overall automation of design. Since numeric data must be entered into the stock-flow diagrams of the software, the qualitative ratings are converted into numerical values. The conversion was made by multiplying the ratings by twenty and dividing by a hundred to get a percentage scale of 0 to 100. This rating conversion logic was used throughout the model development. Accordingly, the related model parameters and formulation assumptions are presented in Table 5.3. All the assumptions were made according to the stated maturity levels and details in Chapter 4.3 and discussion with the company experts in GMB-5.

Table 5.2: Evaluated technology parameters

ID	Factor	Assumptions/Explanations	Rating Scale
F1	Level of detail in object-based models	Evaluates the level of LOD in CAD models (3D models etc.)	1-5
F2	Level of integration of time and cost data into the models	Represents the availability and capability of integration of time/cost data into 4D/5D models.	1-5
F3	Level of interoperability	Determines the level of interoperability between the other models, such as mechanical, electrical etc. in design level and other process models (production, construction)	1-5
F4	Level of integration of processes and models	Evaluates the level of collection and interoperability of data from all project information into a network-based model as a collaboration tool. Moreover, the factor identifies the company's capability to direct/manage different interfaces, which are necessary for all the technologies.	1-5
F5	Competency of the technology team	Relates to the capability of the technology team to integrate different technologies. The referred technology team is responsible for completing the technological integration in the design process.	1-5
M1	RFID	Represents utilization of RFID tags, and receivers in the processes, both in the supply of materials (material tags and smart gateway in the factory) and produced materials (for production and installation)	1-0 (Yes or No)
M2	ERP	Evaluates the ERP integration with the following scale: 1. Insufficient ERP tools. 2. Sufficient ERP tools without integration of BIM 3. Effective ERP with the integration of BIM	1-3

Table 5.3: BIM capability model parameters

ID	Model Parameter	Assumptions	Equations	Units
M3	Coordination through models	The model parameter reflects the BIM Level 1, using object-based models.	**(F1)** *20/100	%
M4	Effectiveness of project management	This model parameter demonstrated the BIM Level 1.2. The above factor, 4D/5D model integration, is directly related.	**(F2)** * 20/100	%
M5	Model-based Collaboration	The model parameter depicts the BIM Level 2. The above factor, level of interoperability, is directly related.	**(F3)** *20/100	%
M6	Network-based Integration	The model parameter represents the BIM Level 3 and it is related to the integration of processes and models factor.	**(F4)** *20/100	%
M7	Detection of clashes	The parameter's model equivalence is the Model-based collaboration because this encompasses the interoperability between design-level models, such as architectural, structural, MEP etc.	Model-based Collaboration	%
M8	Automation of Design	This model parameter is reflected in specific design processes in the stock flows to depict the direct influence of automation with predefined parameters, such as coordination through models, detection of clashes and competency of the technology team. For the equation, the average of corresponding BIM maturity Level 1 and 1.2-related parameters were used, and the competency of the technology team factor limited it with multiplication.	(**M3**+**M7**)/2) * (**F5**) * 20/100	%

As it can also be seen from the Automation of Design parameter as well, for the rest of the model formulation, it was presumed that all the parameters in each equation have the same weights by ignoring the relative importance weights. For instance, "Coordination through models" and "Detection of clashes" parameters are assumed to have the same importance weight and averaged.

Impacts of Technology Parameters: To understand the effect of the technology parameters on productivity and error ratios, another group modelling session (GMB-

6) was conducted with the company experts. In this session, different aspects of selected technologies were evaluated. As the company experts were especially experienced in BIM and ERP, their comments about the effects in future scenarios were reflected in the model formulations. In addition, the literature was consulted for the coefficients that the experts could not predict.

Apart from BIM and ERP, since RFID and Health Safety (Non-ERP tools) technologies are in the plans of the case company, the experts had limited experience with these technologies. At this stage, Expert 3 was also consulted with the rest of the parameters. In the session, the details of the research and proposed strategic goals were presented to the expert to take her opinion. It should be noted that these percentages/effects of technology parameters may be changed for different projects and companies.

Noting that, considering the rating conversion of the technology parameters, IF statements are constituted according to the basis of the intermediate level (3 out of 5, %60) and the above and below conditions were examined in general. In addition, the effect of the full automation status was discussed with the experts and equations were created. The feedback from the GMB-6 is directly related to the formulations as assumptions in the following sections.

After clarifying the evaluation and impacts of technology-related parameters, the project processes of the case company were transformed into stock-flow diagrams with the presented methodology in the first chapter. Firstly, the time sector was developed for the entire project process chain (i.e., the whole project is modelled according to the time-based definitions, such as work done per unit time (weeks)).

Efficiency Parameters: Productivity is defined as the unit of work that is done in a week by one resource (units/weeks/resource) for each process. However, these parameters reflect the planned/initial estimations of the companies. Due to the changes in circumstances in the project dynamics, inherent consequences of managerial actions, or technology integration, it can be changed in a positive or

negative way. In this context, the efficiency parameters were added to the model as converters collected these impacts and transferred them to actual productivities.

Similar logic has been followed for the error loops by modelling the initial/estimated error ratio and actual error by the impacts of different endogenous (e.g., the effect of schedule pressure on errors) and exogenous variables (technology parameters).

Rework Discovery Time: According to the error loop presented in Figure 4.5, there is a delay in recognizing the wrong works as rework and inflowing into the initial work stock. The logic is compatible with the project dynamics and benefits from the SD modelling capability to model Time Delays.

The parameters are stated as "Rework discovery time" for design, production, and construction processes. Since there is no error loop in the ordering/supply process. Although this parameter is necessary both for project management logic and modelling purposes, getting an exogenous value for simulation directly as Weeks will be challenging. Hence it is evaluated as follows.

The parameter is evaluated as Speed of Decision-making for Reworks. It is a project team capability factor used for calculating "Rework Discovery Time". During the simulation, the factor was considered with the experts, and according to their rating, the below calculation has been made.

Equation 3: Rework discovery time calculation

$$Rework\ Discovery\ Time^{*} = \frac{1}{Speed\ of\ Decision - making\ for\ Reworks^{**}}$$

* Weeks

** The values are normalized and dimensionless. High: 0.9, Medium: 0.7, Low: 0.5.

The logic of the parameters and rating are referenced by Pargar and Kujala (2021). Accordingly, the rework discovery time was defined as between 1 to 2 weeks. Nevertheless, as referenced by Wang and Yuan (2016), there is a nonlinear relationship between rework discovery time and the ratio of completed tasks, which means that the speed of decision-making does not remain constant over the

processing time and decreases as the project progress. Because the workers are familiar with the procedures and techniques, detecting errors is easier. Moreover, at the beginning of each activity, there is an adaptation duration of quality monitoring systems. Thus, the authors depicted this nonlinear relationship with the Graph Lookup built-in SD modelling software. Similar to this logic in this research, the experts were asked to rate the speed of decision-making for each process and, accordingly, the limit of the look-up function was set. Then, the model determined the rework discovery time according to the ratio of completed tasks. This terminology will be further examined for each process in the stock-flow development and validation stage.

After clarifying these assumptions for the model development, each process parameter, assumptions, and stock-flow diagram are introduced in the next section.

5.3.2 Design Process Stock Flow Development

The initial stock is the "Design work" for the design process. The stock parameters take initial values from the modeler to run. The "Initial design work" represents the expected design work that should be done at the beginning. For the unit of design work, the company experts stated that at the beginning of a medium-size project, different building or module types are designed. According to these designs, repetitive units or panels are produced and installed on the site. Accordingly, the research team decided to the unit of design work as "Buildings" to comply with the project functioning of the case company. Then with the "Design completion rate" flow, the "Finished design work" stock is filling up. The rate of design rate depends on the three converts as: "Design team", "Actual design productivity", and "Overtime". The company experts in GMB-6 stated that, rather than resource or employee, the "Team" unit is more convenient for the design process, as a term that combines employees of different design processes (e.g., architectural, structural, mechanical).

The “Actual design completion time” was defined as the summation of time that passes (TIME built-in) and design time required. The “Design time required” parameter is calculated as follows.

- **Design time required=** Remaining design work/ (Planned designer productivity*Design efficiency*Design team)

According to the conceptualization step, the design productivity increase with the “Automation of design” and decrease with “Fatigue” because of overtime. These related factors are implemented into the “Design efficiency” converter formula as follows. For the design efficiency, it is assumed that when the level of design automation is equal to or higher than 60%, there will be a design productivity increase of 20%; else, it will only be decreased by the fatigue parameter. Moreover, if there is full automation, it was assumed to have a 50% productivity efficiency increase.

- **Design efficiency=** IF (Automation of design>=0.6 AND Automation of design<1) THEN 1.20*Fatigue ELSE IF Automation of design=1 THEN 1.5*Fatigue ELSE Fatigue
- **Actual design productivity**= Design efficiency * Planned designer productivity* Overtime (D)

As the time project objective (KPI) of the design process, the actual design completion time was defined and endogenously calculated by the model as the summation of “Design time required” and passed time. The “Design time required” parameter was formulated according to the “Remaining design work”, “Actual design productivity”, and “Design team”. Data built-in PREVIOUS was used for the “Actual design completion time” formulation. Because, since the TIME built-in return the passing time, it increases perpetually. Hence the PREVIOUS built-in returns the final variable when the work is finished. The same logic was applied to other process as well to find the actual completion times.

- **Design time required=** IF (Remaining design work)>0 THEN Remaining design work/ (Planned designer productivity*Design efficiency*Design team) ELSE 0
- **Actual design completion time=** IF (Design time required>0) THEN (TIME)+Design time required ELSE PREVIOUS (SELF, 1)

There is a non-linear relationship between overtime and schedule pressure. In the study, the schedule pressure in between 1 and 2, and the maximum overtime factor was decided as 1.5 with the experts. The non-linear relationship between two parameters was described by the Graph Lookup function, the miscellaneous built-in of Stella software. The curve between the two variables indicates that when the schedule pressure is near one, the overtime is also close to one, but when the schedule pressure is more than 1.5, the overtime also increases incrementally. Similarly, the "Effect of schedule pressure on errors" parameter was defined with Graph Lookup. For "Fatigue", similar logic has been applied with overtime with one week delay; as the overtime factor ascends, the fatigue increases gradually. This one-week delay was added because it was stated by experts that the effects of employee fatigue would not be seen as soon as there is overtime. In addition, circular connection is provided by this delay converter in the model. It should be noted that the fatigue parameter was identified between 0.8 to 1 since the company experts stated that the effect of burnout on design productivity is not noticed that much (e.g., getting used to the overtime and decreasing the fatigue with existing technology adaptations). The lookup function puts a small wave inside the converters to represent the nonlinear graphical formulation, which can be seen from the presented stock flow diagrams. As an example of the implementation of the Lookup function, the relation between schedule pressure and overtime is given in Figure 5.2.

- **Overtime (D)**= LOOKUP (Schedule pressure) Points: (1.000, 1.0000), (1.200, 1.100), (1.400, 1.3200), (1.600, 1.4300), (1.800, 1.4800), (2.000, 1.5000)

Similar assumptions have been made for the rest of the Graph Lookup functions of different processes, which are given in the Appendix with the rest of the model formulations.

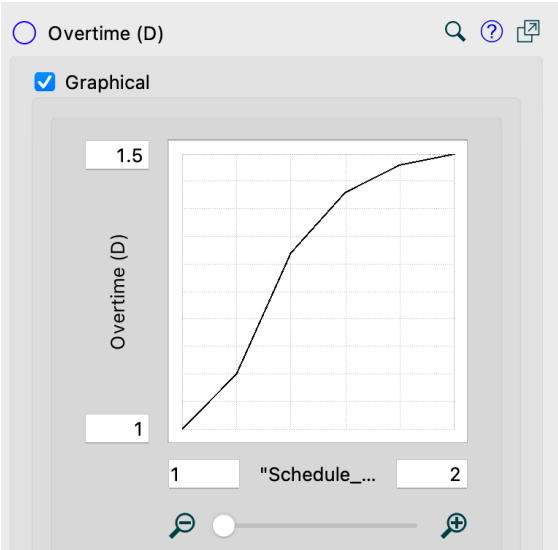

Figure 5.2: Graphical lookup function example for overtime and schedule pressure of design process

Similar to design productivity logic, for the design error loop, "Actual design error ratio" is changed by "Automation of design". When the level of automation of design is 100%, it is assumed that the errors will be zero. This assumption was made by considering that, during the design process, errors may happen due to human factors or modelling stages which automation of design parameter meets both issues with enabling coordination through updated models and clash detection. Moreover, if "Automation of design" is not one hundred per cent, instead of equal and higher than 60%, the error ratio decreases by 20%**.** Moreover, for each process, the effect of schedule pressure on errors was added to error ratios.

- **Actual design error ratio**= IF (Automation of design) =1 THEN 0 ELSE IF Automation of design>=0.5 THEN Initial design error ratio*0.8 *Effect of schedule pressure on errors ELSE Initial design error ratio*Effect of schedule pressure on errors

Accordingly, the design completion rate was formulized as follows:

- **Design completion rate=** Design team*Actual design productivity* (1-Actual design errors ratio)

For the design rework discovery time, it was assumed that the speed of decision-making of the team could be increased by "Model-based collaboration", and the time delay between errors and rework detection can be reduced with one level (e.g., speed of decision making from medium to high). Reason of the BIM Level 2 enhances information exchange between design team members for different disciplines and increases visualization for improving the speed of decision-making, especially by the clash detection. Since the rework discovery is majorly dependent on the models, drawing etc., for the design process, the non-linear relationship between "ratio of completed tasks" and "rework discovery" was neglected. Hence, the model equation was defined directly according to the relation between the speed of decision making in the simulation stage. Noting that the 0.75 coefficient derived from the three levels of "speed of decision-making" as stated before in Chapter 5.3.1.

- **Design rework discovery time=** Design rework discovery time= IF (Model-based Collaboration)>0.6 THEN Initial Rework Discovery Time*0.75, ELSE IF Model-based Collaboration=1 THEN 1 ELSE Initial Discovery Time

As it is decided in GMB-5 with company experts, the design process has an external factor, as "Change orders". Accordingly, in the stock-flow diagram, this parameter is defined as a flow to increase the "Design work" stock. However, since this increase will happen in a time unit, not during all design process, the formulation has been arranged for this specific time, "Time of change orders". Moreover, since the flows should be defined per unit time, the change order is divided with DT to ensure dimensional consistency. In the below equation, TIME is a simulation built-in representing the actual time that is passed during the simulation (e.g., first week, second week), and DT describes the time unit (week).

- **Change orders=** IF TIME =Time of change orders THEN INIT (Design work) *(Design change percentage)/DT ELSE 0

In a similar logic to find the total design work (which is necessary to formulate the remaining design work, required time and schedule pressure), the STEP function was utilized. This built-in generates a one-time step adjustment of a specified height at a predetermined time (STEP (height, time)). Therefore, in the model, the height is the change orders, and the time is the specified time of it.

- **Total design work**= INIT (Design work) + STEP ((INIT (Design work) *Design change percentage), Time of change orders)

The rest of the model equations for the design process is presented in Appendix. The related parameters of the design process and stock flow diagram are given in Table 5.4 and Figure 5.3, respectively.

Table 5.4. Design process model parameters

Parameter	Units	Conceptual Type	Computerized Type
Initial design work	Buildings	Initial	Stock
Design completion rate	Buildings/Week	Formulation	Flow
Finished design work	Buildings	Formulation	Stock
Design change percentage	%	External	Converter
Time of change orders	Weeks	External	Converter
Initial designer productivity	Buildings/Week/ Team	Initial	Converter
Design team	Team	R/C	Converter
Planned design duration	Week	Initial	Converter
Remaining design work	Buildings	Formulation	Converter
Design time required	Week	Formulation	Converter
Actual design completion time	Week	KPI	Converter
Schedule pressure (D)	Dimensionless	Formulation	Converter
Overtime (D)	Dimensionless	Managerial Action	Converter
Fatigue	Dimensionless	Formulation	Delay Converter
Design error ratio	Dimensionless	KPI	Converter
Effect of schedule pressure on design errors	Dimensionless	Formulation	Converter
Design rework discovery time	Week	Formulation	Converter
Automation of Design	Dimensionless	R/C	Converter
Model-based Collaboration	Dimensionless	R/C	Converter

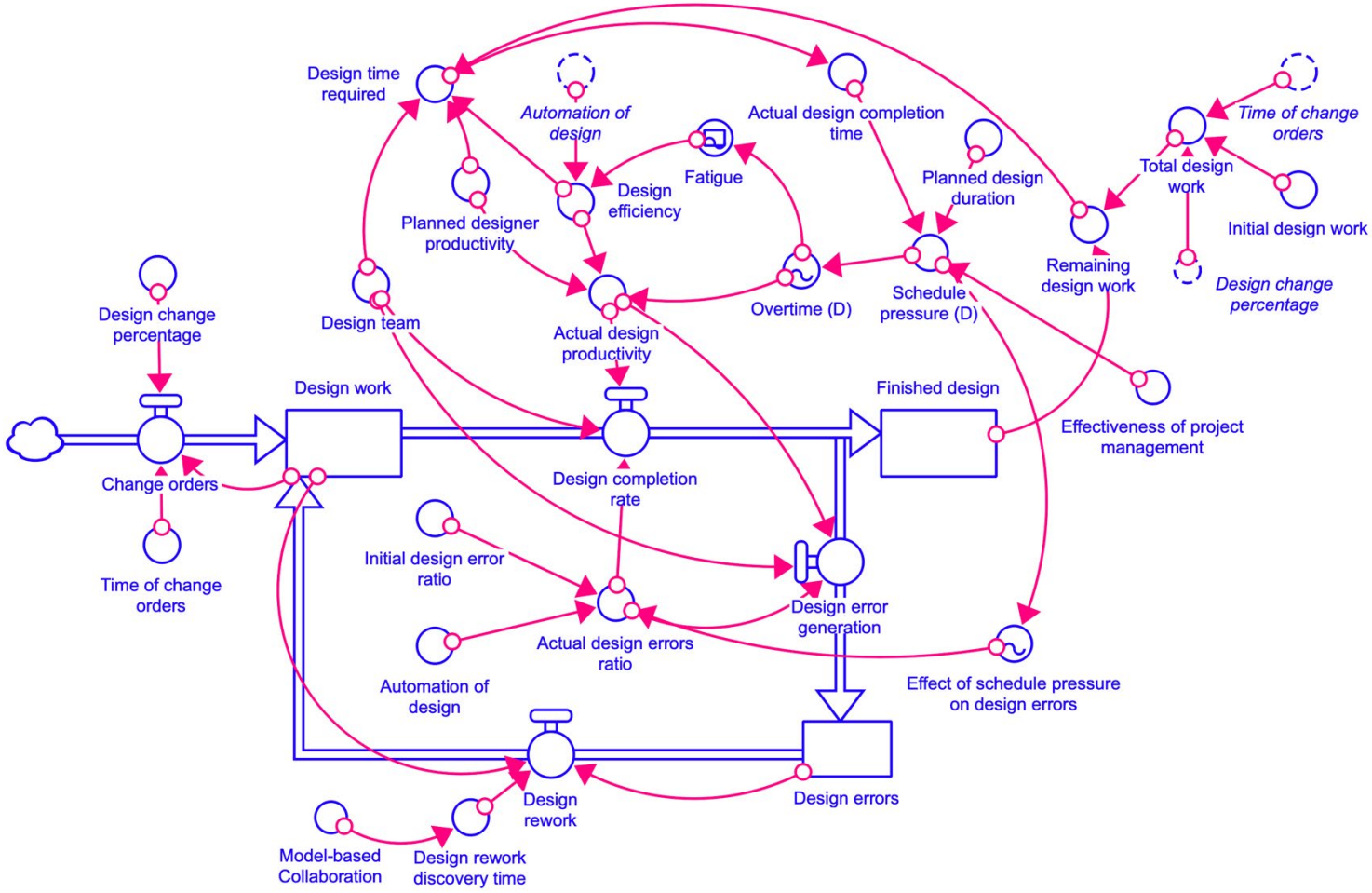

Figure 5.3: Design process stock flow diagram

5.3.3 Ordering/Supply Stock Flow Development

For the ordering stage, the "Design completion rate" flow from the previous process was linked with the "Order rate flow" considering the project flow dynamics stated by the company experts in the previous sections. For the order stage, in the GMB-6, the company experts stated that the priority material is "steel", especially for medium-sized projects. The order and supply unit were specified for the steel as "Tonnes". At this step, other materials and units may also be selected, and parameters may be expanded for different projects and companies.

Since the design rate and order rate have different units, two converters were added to the model as "Units per Buildings" and "Raw material per unit". The first parameter transfers the design work (Buildings) to "Units", which will be produced in the factory and installed on the site. The second parameter converts the "Units" to "Tonnes" for ordering and supply. Moreover, for the formula of ordering rate, "Order contingency" was incorporated according to the feedback of the company experts at the conceptualization stage, GMB-4. However, this contingency estimation may be reduced by the integration of the maturity of "ERP in projects" by increasing the "Accuracy of material quantities". This can become an important criterion as companies aim to reduce materials left in inventory. Accordingly, if the accuracy of material lists is complete, the order contingency was determined based on the company's minimum contingency value of 10%. Then, when the accuracy of the list decreases, the contingency level gets higher due to lack of effective management.

- **Order rate=** Design completion rate*Raw material per unit*(1+Order contingency) *Units per building
- **Accuracy of material quantities=** IF (ERP in projects=3) THEN 1 ELSE IF (ERP in projects=2) THEN 0.7 ELSE 0.4
- **Order contingency=** IF (Accuracy of material quantities=1) THEN 0.1 ELSE IF (Accuracy of material quantities>=0.7) THEN 0.15 ELSE 0.30

In the sequel, the steel material that has been ordered flow into “Material inventory” stock, with “Supply rate” flow. The supply rate was calculated by the planned supply duration and planned material supply. While the planned duration is exogenously taken from the users, the supply amount is determined by the system itself through the total design work and stated converters. At this point, another converter named as “Missing material” was added to the rate to represent the possible external delays due to the discrepancies in the inbound logistics due to the supplier. This parameter is represented between 0 to 1, stating that if there are no unexpected material discrepancies, the supply rate will occur as planned.

- **Supply rate**= (Planned material supply*(1-Missing material))/Supply duration

Moreover, the integration of RFID technology decreases the probability of missing material by improving the traceability of materials. It should be noted that, for inbound logistics, the RFID parameter stands for the passive tags in material carriers and smart gateways of factories.

To comprehend the impact of RFID application, the discussion was made with Expert 3 as stated in the findings of GMB-6. According to the feedback, the RFID technology is assumed to reduce the missing material percentage by 50%. Since the company does not undertake this process and cannot prevent the risks completely, there are no additional time-dependent managerial action converters for this stock-flow diagram.

As stated in GMB-5, the supply process has an external factor, as “Order increase”. This parameter is defined as a flow coming to “Orders” stock. However, to formulate this parameter, the “Inventory gap” should be defined to understand whether the planned contingency is sufficient or not. The “Inventory gap” is calculated according to the “Desired material inventory” converter. Moreover, like change order modelling, the “Demand increase time” was defined.

- **Inventory gap=** IF (TIME=Demand increase time) AND (Desired material inventory-Planned material supply>0) THEN Desired material inventory-Planned material supply ELSE 0

For the order increase flow, the "Inventory gap" and "Time to adjust order" was implemented to the model formulation. The time to adjust order substitutes the elapsed time between demand increase and creating order for this. The parameter is directly linked with the ERP-related "Accuracy of material quantities" by providing automated reporting of materials and visibility among different parties. Thereafter, if the accuracy of the lists is a hundred per cent, the time for adjusting is assumed as 0.5 weeks, considering that there will be delay of a few days in any case. In the worst-case scenario, if the accuracy is below 50%, it was supposed to be two weeks, which was also accepted with the case company experts.

- **Time to adjust order=** IF (Accuracy of material quantities=1) THEN 0.5 ELSE IF (Accuracy of material quantities>=0.7) THEN 1 ELSE 2
- **Order increase =** Inventory gap/ Time to adjust order

The supply process model parameters are given in Table 5.5.

Table 5.5: Supply process model parameters

Parameter	**Units**	**Conceptual Type**	**Computerized Type**
Orders	Tonnes	Initial	Stock
Order rate	Tonnes/Week	Formulation	Flow
Material inventory	Tonnes	Initial	Stock
Desired material inventory	Tonnes	Formulation	Converter
Inventory gap	Tonnes	Formulation	Converter
Raw material per unit	Tonnes/Units	Formulation	Converter
Units per building	Units/Buildings	Formulation	Converter
Order contingency	Dimensionless	Formulation	Converter
Planned supply duration	Week	Initial	Converter
Actual supply duration	Week	KPI	Converter
Missing material percentage	Dimensionless	Formulation	Converter
Order increase	Tonnes/Week	External	Flow
Time to adjust order	Week	Formulation	Converter
Accuracy of material quantities	Dimensionless	R/C	Converter
ERP	Dimensionless	R/C	Converter
RFID	Dimensionless	R/C	Converter

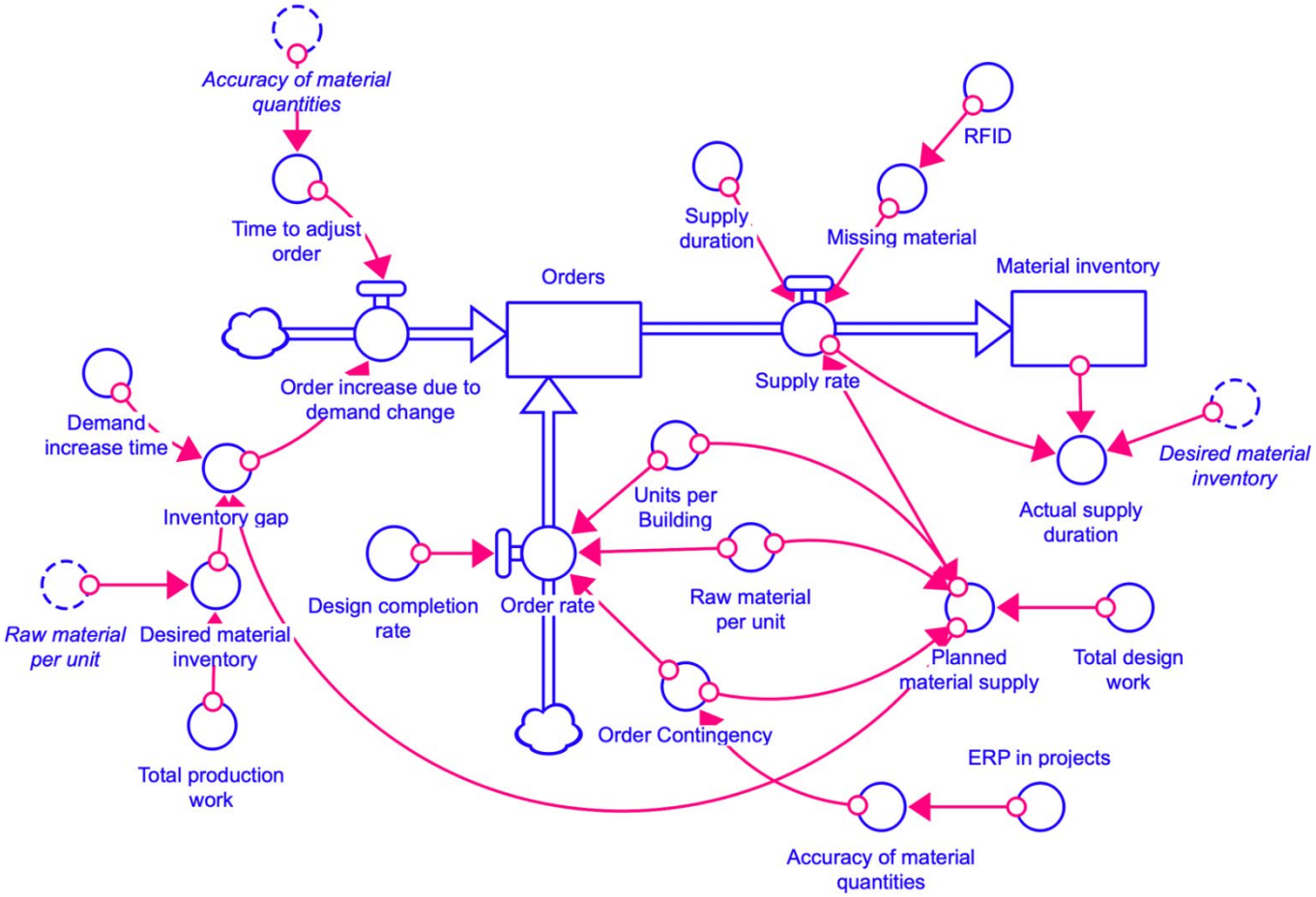

Figure 5.4: Supply process stock flow diagram

5.3.4 Production Process Stock Flow Development

The company experts explained that, for each building (e.g., modular structure), there are certain standardized units to be produced. Since the production members may be altered for different buildings and projects, in the scope of this study, it is assumed to be indicated as "Units". These units can be panels, sections etc., which will be joined together to create the building in the construction phase. For each building at the design stage, basic units will be produced. The units per building are supposed to be the same for different building types. Therefore the "Production work" stock has the initial amount regarding the "Initial design work" and "Units per building".

- **Initial production work=** Initial design work* Unit per Buildings

Since the company experts stated different external factors for the production process during sessions, the "Production work" stock gets an inflow as "Production work increase". This flow is comprised of two different dynamics as the increase of production work due to the design change orders and demand for more products with the same design, with the "Demand increase" converter. Both aspects transformed into the flow parameters in their specific times:

- **Production work increase=** IF((TIME)=Demand increase time) THEN (INIT (Production work) *(Demand increase percentage)/DT) + (Change orders*Units per Building) ELSE Change orders*Units per Buildings

For the above equation, when the time is equal to the demand increase time, the production work increases both with the related demand increase and change orders. Because when the design work increases, it directly piles up the units that need to be produced. Since it is foreseen that design change orders can occur when the project comes to the production stage as well; this situation has been created in a way that can be simulated by changing the change order time. In other words, if the model

user puts a change order time more than the planned design and supply durations, the model behaves accordingly.

Considering the conceptual models, the production and supply processes need to be connected to each other in a start-to-start logic. To reflect this logic into the production process, an outflow was drawn from the “Production work” stock as “Supplied work rate”. This outflow represents ordered and supplied work and fills up the "Production inventory" stock. The production inventory is also depicted in Figure 4.3 and represents the level of units that is on hand for the production process.

Since the supply rate has the unit of Tonnes/Weeks, for dimensional consistency, the “Supplied work rate” is configured by the raw material per unit parameter. Additionally, since the experts mentioned the lag time between the start of production and supply, the flow parameter is formulized with two weeks delay.

- **Supplied work rate=** DELAY (Supply rate/Raw material per unit, 2, 0)

The corresponding delay built-in accounts for the time required for the supplied material to become a production work. Thus, it can also be considered that the work will not start until a certain amount of material for the project arrives at the factory by this formulation in the model.

Then the “Production inventory” needs to be manufactured with the flow of the “Product completion rate”. This rate demonstrates the weekly corrected production. For the formulation of this parameter, the “Actual productivity”, “Resource” level and “Error ratio” are considered. Moreover, the rate is limited according to the “Max. production capacity” of the factory. The experts stated that this parameter should be defined since the production rate cannot exceed this capacity.

- **Product Completion Rate** = Actual productivity*Resources (P)*(1-Actual production error ratio)

For the production resources, the experts stated that in the factory, both the workers and equipment are used. But considering the related managerial action (increasing the number of resources, i.e., hiring/firing) and overall productivity, the modelling

was conducted majorly focusing on the human factor. According to the experts, there is no overtime option for production. As the only managerial action for this process, the resource adjustment stock flows were modelled in accordance with the conceptual model in Figure 4.5 and detailed equations are given in Appendix.

For the "Resource change" flow, for each time unit, the model should clarify the "Required Resources" and use this parameter to find the "Resource gap" as the difference from the existing level of "Resources" stock. The "Required resources" is formulized by the "Remaining products", which compare the amount between the "Finished products" and "Total production work". The total required production work is modelled considering the total design work, spike in demand increase the time by STEP function.

- **Total production work=** Total design work*Units per Building + STEP (INIT (Production work) *Demand increase percentage, Demand increase time)

Since this flow should be defined according to the time unit as the requirement of SD modelling, the "Resource adjustment time" parameter was added as converter. IN GMB-6, the company experts stated this parameter could be assumed as one week, which will be applied to the construction process.

As it is also stated in the conceptual model, there is the consequence of the resource increase as "Crowding effect on productivity". This model parameter is decided according to the "Upper limit of labours". The experts stated that considering other projects in the portfolio; there is no limit to the recruitment of workers in the factory. However, the related "Upper limit of labours" was decided by considering the congestion in the work areas for the specific project and possible communication/coordination in the production line. In addition to that, even though the upper limit of the labours may be considered slightly more than the capacity, the production rate was limited considering the "Max. production capacity". For the formulation of the "Crowding effect of productivity", the Graph Lookup function was utilized to demonstrate the non-linear relationship between the ratio of upper

limit and congestion. The details of the LOOKUP functions and graph points are given in Appendix.

It is assumed that the RFID directly increases productivity for the production efficiency parameter by reducing the time-consuming identification and locating of units. According to the discussion with Expert 3, it is assumed that the RFID increases productivity by 50%. Moreover, as another technology integration into the production process, "Production modelling" becomes more interoperable with "Model-based collaboration", BIM Level-2, which indirectly increases productivity by decreasing the effort for additional modelling. Hence, it is decided that in the model, when model-based collaboration is more than 60%, the production modelling increases productivity by 25%. Moreover, suppose there is a total interoperability between different models in the project. In that case, the production efficiency is assumed to increase by 50% according to the discussions with the company experts and their foresight about the production process.

- **Crowding effect on productivity**= LOOKUP (Resources/Upper limit of resources)
- **Production efficiency**= IF (Production modelling>=0.5) AND RFID=1 THEN 1.5 *Production modelling*Crowding effect on productivity ELSE Production modelling* Crowding effect on productivity
- **Actual productivity**= Planned productivity* Production efficiency

As it was demonstrated in conceptual models, the error ratio of production can be decreased, especially by the "Network-based integration" by enabling entire process tracking in a common environment. It was assumed that if the "Network-based Integration", BIM Maturity Level 3, is one hundred per cent, the error ratio will be 0.05, which depicts that the complete error elimination cannot be possible in any environment.

- **Actual production error ratio**= IF (Network-based integration) =1 THEN 0.05 ELSE IF Network-based integration >=0.6 THEN Initial production error ratio* 0.4 * ELSE Initial design error ratio*Effect of schedule pressure on errors

The logic stated in Chapter 5.3.1 was used for the production rework discovery time. Since this process is highly worker-dependent, it was assumed that as resources finish the work and the project progress (i.e., ratio of completed tasks approaching to one), the rework discovery time decreases. Accordingly, “Rework discovery time” is defined with a non-linear relationship with the “Ratio of completed tasks” by the Lookup function. The methodological reason for making this parameter endogenous (determined by the model) was that, after the "Parameter verification test" in the validation step, the users stated that this value was not very realistic. Iteratively to validate, this new formula has been applied for production and construction. Thus, users were only asked to rate the speed of decision-making levels for that process. This level was reflected in the model as the upper limit of the Lookup function. Moreover, RFID technology expedites the decision-making and saves time for inspections by traceability and better control. Hence it was assumed that if there is RFID implementation, the rework discovery time is 1, as the minimum specified interval defined with the company experts. Accordingly,

- **Production rework discovery time=** IF (RFID=1) THEN 1 ELSE LOOKUP (Ratio of completed tasks)

According to the given assumptions, the model parameters and stock flow are presented in Table 5.6 and Figure 5.5, respectively.

Table 5.6: Production process model parameters

Parameter	Units	Conceptual Type	Computerized Type
Production work	Units	Initial	Stock
Production work increase	Units/Week	Initial	Flow
Demand increase percentage	Dimensionless	External	Converter
Demand increase time	Week	Formulation	Converter
Supplied work rate	Units/Week	Formulation	Flow
Production inventory	Units	Formulation	Stock
Product completion rate	Units/Week	Formulation	Flow
Max. production capacity	Units/Week	Formulation	Converter
Actual productivity	Units/Week/Resource (P)	KPI	Converter
Production efficiency	Dimensionless	Formulation	Converter
Production modelling	Dimensionless	R/C	Converter
Model-based collaboration	Dimensionless	R/C	Converter
RFID	Dimensionless	R/C	Converter
Planned production resource productivity	Units/Week/Resource (P)	Initial	Converter
Planned production duration	Week	Initial	Converter
Resources	Resource	R/C	Stock
Resource change	Resource (P)/Week	Managerial action	Flow
Resource adjustment time	Week	Formulation	Converter
Production error generation	Units/Week	Formulation	Flow
Actual production error ratio	Dimensionless	KPI	Converter
Production rework	Units/Week	Formulation	Flow
Production rework discovery time	Week	Formulation	Converter

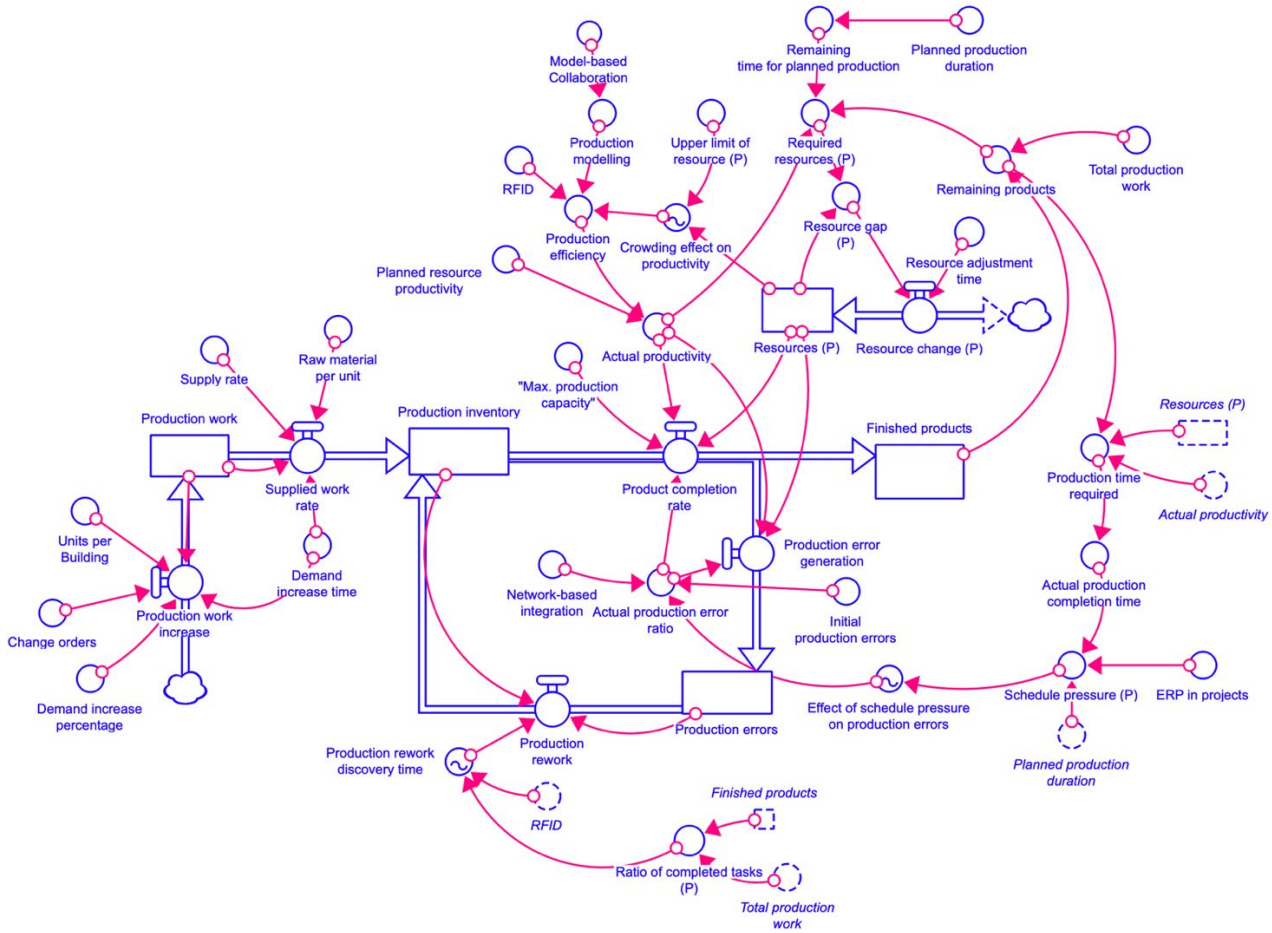

Figure 5.5: Production process stock flow

5.3.5 Construction Process Stock Flow Development

According to the views of the experts, construction can only begin after production ends, and finished products are transported to the field. In the scope of this study, the outbound logistic process is not modelled by considering the strategic goals of the case company for digitalization. Nonetheless, since the production and construction processes relate to each other in a similar finish-to-start logic, the stock flow diagram of the construction process is completely separated from the other processes (i.e., the initial stock does not have any inflows from any predecessor activities). Hence, the "Construction work" stock has the initial value as the "Total production work to represent the number of total units to be installed.

It should be noted that, although the quality/instructions of unit installations may vary, since the time-dependent process was modelled according to the productivity values (unit/week/resource), the amount of work was the input for the construction process as well. Then, the construction work outflow with the "Construction completion rate". This rate indicated the correctly finished installation rate. According to the company experts, both considered managerial actions might be implemented during construction, such as "Overtime" and "Resource adjustment". Hence the endogenous overtime factor was converted into the rate.

- **Construction completion rate=** Actual construction productivity * Resources (C) *(1-Actual construction errors ratio) *Overtime

As the consequence of the overtime to the model, the "Fatigue" parameter was added as delay converter, the same as described for the design process. Different from the design process, the Graph Lookup points were defined between 0.5 to 1 by assuming that the fatigue on the construction site due to overtime is more influential than the design team's fatigue since the works on the site are rooted in manpower.

For the "Actual construction productivity, the "Construction efficiency parameter" was considered. The "Communication on site" and "Health & Safety management"

parameters were reflected into this parameter to evaluate the technology parameters. Model-based Collaboration enhances the communication through model-based collaboration, visualizing through models and accurate share of information among different parties. For the Health & Safety management, the experience of Expert 3 was used. The expert stated that, in a similar project, the integration of safety tools enhances the H&S management by nearly 40%.

- **Communication on site=** IF (Model-based Collaboration)>=0.8 THEN 1.5 ELSE 1
- **Health& Safety Management=** IF (Non-ERP Tools) =1 THEN Initial H&S management*1.4 ELSE Initial H&S management
- **Construction efficiency=** Communication on site* H&S management* Fatigue* Crowding effect on construction

For the error ratio, it was assumed that BIM Maturity Level 3 parameter, "Network-based Integration", decreases the construction errors by better analysis of constructability. For the equation of "Actual construction error ratio", it was assumed that due to the resistance of the worker on site to perceive the information from BIM, even if the network-based integration is a hundred per cent, there will be small amount of human-related (e.g., experience, skill) error fraction according to the discussion with the company experts in GMB-6. If the network integrated BIM level is more than 60%, the initial error ratio decreased only by 40%, again by considering the gap between the theory and application on the construction site. Moreover, if it is less than this per cent, the initial stated error ratio was considered for the formula.

- **Actual construction error ratio=** IF (Network-based Integration) =1 THEN 0.05 ELSE IF Network-based Integration">=0.5 THEN Initial construction error*0.40*Effects of schedule pressure on construction errors ELSE Initial construction error*Effects of schedule pressure on construction errors

Similar to other processes, the schedule pressure formulation was made according to the planned and actual completion time and can be mitigated by the "Effectiveness

of project management" by better planning. During the GMB-6, the experts stated that by the integration of 4D and 5D models in BIM, the schedule pressure could be reduced, by nearly 50%, considering the tight schedule estimation risk and late payments.

Table 5.7: Construction process model parameters

Parameter	Units	Conceptual Type	Computerized Type
Construction work	Units	Initial	Stock
Construction completion rate	Units/Week	Formulation	Flow
Finished construction	Units	Formulation	Stock
Resources (C)	Resource	R/C	Stock
Resource gap (C)	Resource	Formulation	Converter
Resource adjustment time	Weeks	Formulation	Converter
Construction error generation	Units/Week	Formulation	Flow
Construction error ratio	Dimensionless	KPI	Converter
Planned construction resource productivity	Units/Week/Resource	Initial	Convert
Construction efficiency	Dimensionless	Formulation	Converter
H&S Management	Dimensionless	R/C	Converter
Communication on site	Dimensionless	R/C	Converter
Actual construction productivity	Units/Week/Resource	KPI	Converter
Overtime (C)	Dimensionless	Managerial action	Converter
Fatigue (C)	Dimensionless	Formulation	Converter
Construction time required	Week	Formulation	Converter
Schedule pressure (C)	Dimensionless	Formulation	Converter
Effectiveness of project management	Dimensionless	R/C	Converter
Required resources (C)	Resource	Formulation	Converter
Resource change (C)	Resource/Week	Managerial action	Converter
Effect of schedule pressure on errors (C)	Dimensionless	Formulation	Converter
Construction reworks	Units	Formulation	Flow
Construction rework discovery time	Week	Formulation	Converter

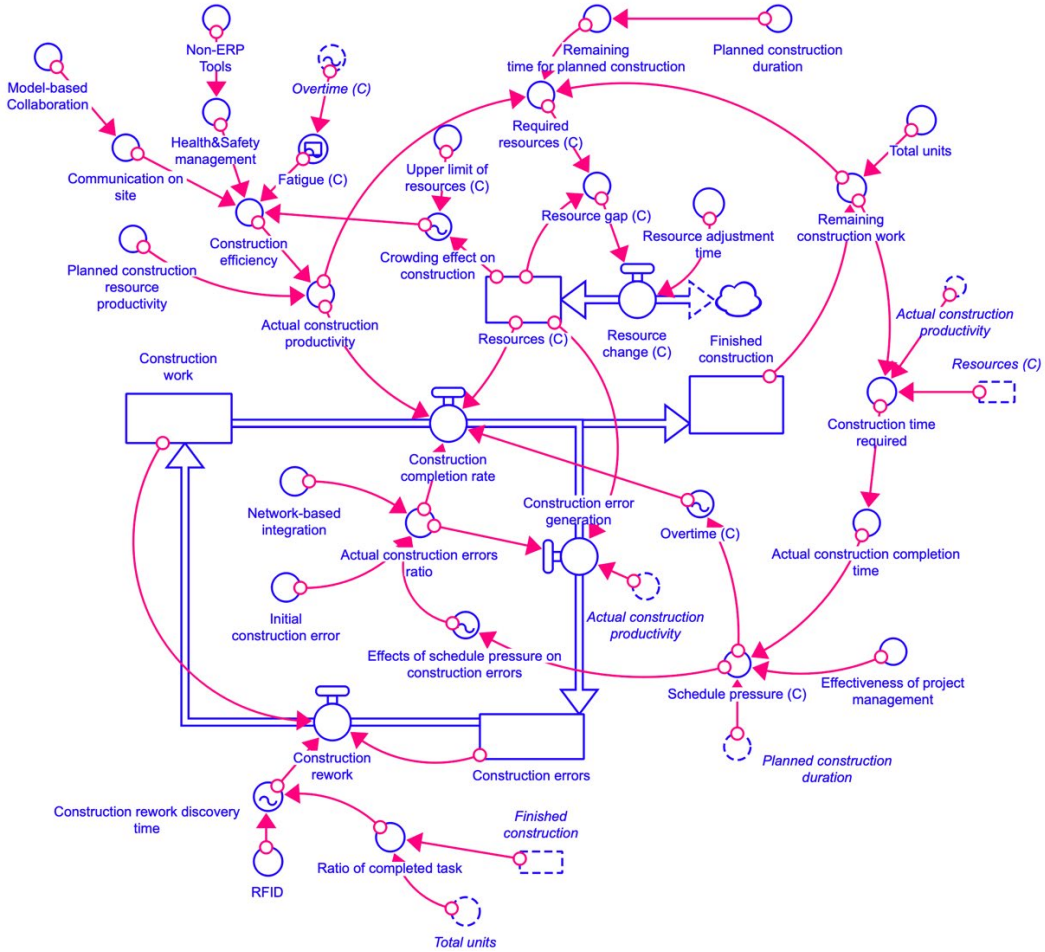

Figure 5.6: Construction process stock flow

After considering all the process stock flows, the time-sector is directly constituted according to the actual completion time of each process. For the configuration of the uncompensable delays, since the change orders can be compensated with the owner, the difference between actual and planned design duration was extracted as given in Appendix. The time-sector is depicted in Figure 5.7.

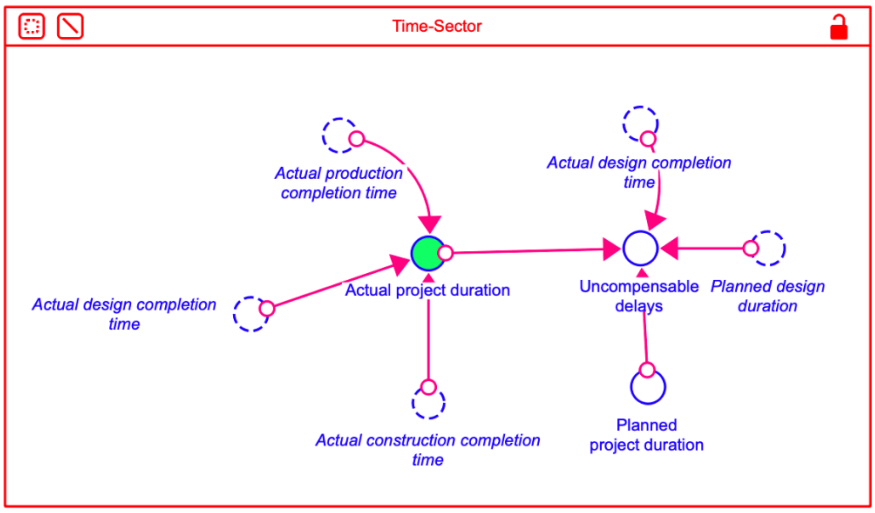

Figure 5.7: Time-sector

Then some of the model output stocks and converters are used to constitute the cost-sector. For the cost consideration, firstly, the total resource cost stock was modelled by each processes resource amounts (considering the managerial action as resource increase for production and construction). The design resource (design teams) cost was directly converted since there is no resource increase rate. Moreover, the overtime factors were connected to the resource cost flows for the resource costs to depict the weekly additional pay rate. Secondly, the actual total project duration is related to the weekly indirect cost. Then the material inventory stock was connected to the material unit cost. Lastly, the uncompensable delays were transferred to cost with the specified unit liquidated damage cost. It should be noted that, since the experts state that they can share the percentages by total cost rather than monetary values, each cost parameter was considered accordingly (e.g., construction resource cost has unit of %/Resource/Week).

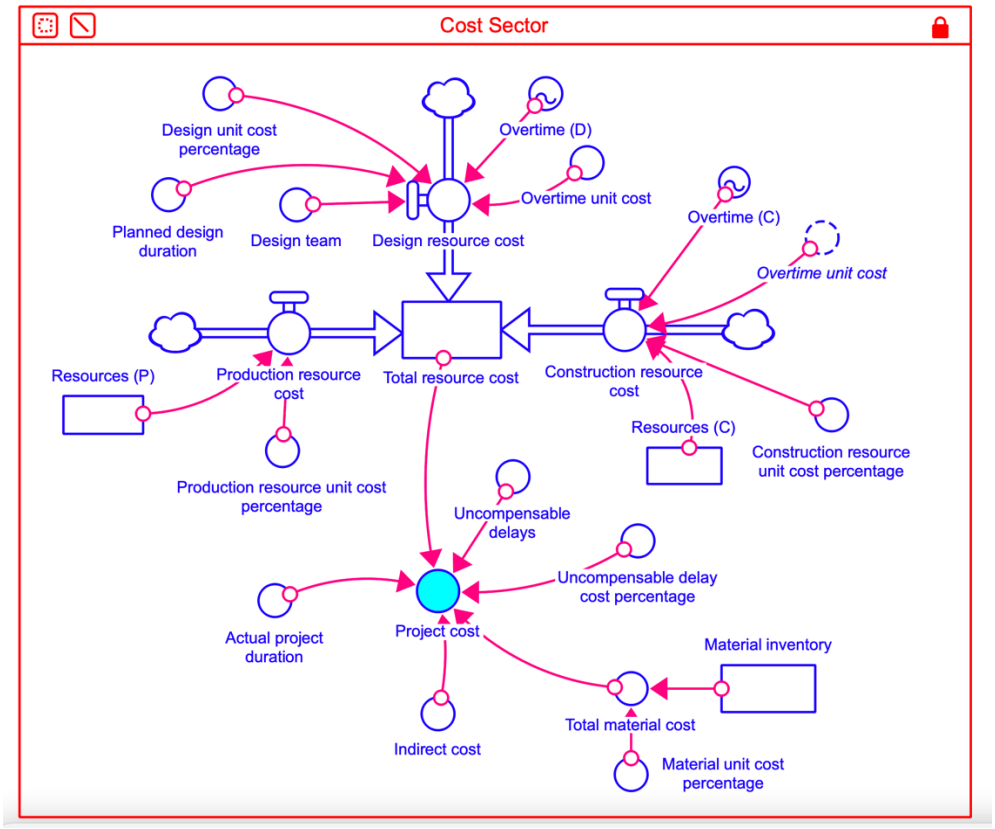

Figure 5.8:Cost-sector

The other project objectives of the company, such as productivity and errors (client satisfaction), are directly configured from the developed model parameters.

After considering each processes stock flows, from the Equation Viewer option of Stella software, the model equations and parameters are documented. From that, all the model equations are presented in Appendix. To simulate the model and analyse different sectors (KPIs), the model should be verified and validated, which are explained in the next section.

CHAPTER 6

MODEL VALIDATION AND VERIFICATION

This chapter explains the methodology and findings of model verification and validation for system dynamics modelling. For this, firstly, a brief theoretical background on SD model validation is provided, followed by an explanation of basic structured validation approaches. After that, the corresponding SD model validation and verification results are explained. In this regard, the model validation step is divided into two as conceptual validation and computerized verification. The conceptual validation step encompasses testing the system model's structures and assumptions according to the model's intention and sufficient representation of the real-world behaviour. The tests conducted in this section provide the structural and behavioural validity of the SD model including the conceptualization and computerized model with the assumptions and equations.

6.1 Theoretical Background for Validation

Jay Forrester, who developed the system dynamics established the groundwork for model validation. However, the author questioned whether there are objective and uncontroversial methods to determine the reliability of the system (Forrester, 1961). Moreover, in line with the increase in the utilization of SD in different contexts, various research has been done for verifying and validating SD-based models.

Coyle (1977) defined SD validation as the process as it can be used for its purpose and sufficiently confident for the reflection of the real world. Moreover, the model validation must be substantiated by the outputs of the system. Hence, especially in the construction management literature, several research conducted the model validation with the case studies and comparing with the real world data by consulting

with the industry experts (Dangerfield et al., 2010; Ogunlana et al., 2003). In the scope of this study, the model validation is investigated for two angles (i) validation as the extent that the model's structure and assumptions meet the purpose, (ii) verification as check whether the equations and implementation are technically correct.

Since the SD models are built for a purpose and the structure of the model directs its behaviour, the ultimate goal of system dynamics model validation is to verify the model's structure's validity. The accuracy of the model behaviour's reproduction of real behaviour is also assessed after assuring adequate confidence in the model's structure. Thus, the usual logical sequence of validation is to evaluate the structure's validity first and then to test the behaviour accuracy if the model structure is appropriate (Barlas, 1996). For structural validity, the model should mimic the real well enough for the stated purpose. Forrester and Senge (1980) stated that the model should be tested with empirical information. The author stated that the model structure can be compared with the descriptive knowledge of the real system, and model behaviour may be tested regarding the observed real-system behaviour. Moreover, the model validation is used for terminologies like "usefulness" and "soundness" of the model in operation. In the same research, the author emphasized the importance of the selection of model boundary (i.e., what is included and excluded from the model) having a great impact on the model's validity.

As it can be understood from the brief survey of the literature about SD validation, the main concept is to understand whether the model is consistent with the real-system structure and behave like it (e.g., the model should do the same things that will the real system do under same circumstances for same reasons) (Coyle, 1977). However, the literature also argued about the absolute validity of SD is not possible since the extent of the systems can not contain every aspect of the real world. Hence it is stated that the model validation of SD should depend on realism rather than absolutism (Barlas, 1996; Stephan, 1992). Moreover, since the system is modelled by approaching the real system, some error is unavoidable. This also brings the discussion that it is not possible for the modeller to validate the entire model alone.

For this aspect, in the literature, it is stated that involvement of stakeholders can increase the credibility of both the model development and validation (Kleindorfer et al., 1998).

Besides, a system dynamics model cannot be validated with a single test, rather the more tests that the model pass, the more valid it becomes (Forrester & Senge, 1980). Additionally, the validation should be an iterative process, where both the conceptual and computerized model should shape accordingly.

In the literature, several research utilized different structural and behavioural validity tests to understand the models' degree of confidence. Almost all the authors referred Boundary Adequacy Test, Dimensional Consistency Test, Structure Verification Test, Parameter Verification Test and Extreme Conditions Test for the structural validity. In addition, qualitative tests are conducted for the behavioural validation (e.g., behaviour abnormality test).

In the next section, the methodology, conducted tests and findings are presented for the SD model of this study.

6.2 Model Validation Methodology and Tests

As it is stated in the previous section, the validation process of SD model should be an iterative process and proceed while model development and testing. Hence, in this study, the case company experts were incorporated into model development stages, starting from the problem articulation (boundary selection) to conceptualization of the system. The tests that Forrester and Senge recommend (1980) and Sterman (2000) were used for the validation and verification of Computerized Model. Firstly, structural validity tests were carried out based on these authors' thoughts. During these tests, behavioural validation was tried to be provided by evaluating whether the model accurately reflects the project stages of the case company and the plausibility of the results in the trials.

According to the frameworks of the stated authors, four structural tests and one behavioural test were conducted as (1) Structure Verification Test, (2) Boundary Assumptions Test, (3) Dimensional Consistency Test, (4) Extreme Conditions Test, (5) Boundary Adequacy Test, (6) Parameter Verification Test.

1. **Structure Verification Test**

Purpose: The Structure Verification Test intends to compare the structure of the model with the real represented model (Forrester & Senge, 1980). The test's conduction includes reviewing the model assumptions with people who are knowledgeable about the real system structure and relevant literature.

Methodology: In this research, before developing the Computerized Model, several group modelling sessions have been made with the case company experts to create reliable conceptual models. The feedbacks from the experts, related assumptions and findings of these models can be found from previous chapters. Moreover, for the causal loop diagrams, both the construction and project management literature were referenced for similar dynamics between system parameters. For instance, as the managerial actions of the project, each processes unique dynamics were considered according to the statements of the experts, which ensures similar structure between the model and real system.

Findings: Since the main aim of the research to investigate the effects of digital technologies into the project dynamics, the existing technological integration and future impacts were analysed for model development. The technology selection and integration to the as-is conceptual loops were determined according to the discussions with the company experts and comprehensive literature review of similar research. Moreover, before the model development, during the initial sessions with the experts, the existing process chain was clarified and strategic positioning was made for the case company, which was also based upon for the model structure. Hence, it was accepted that the model is structurally verified according to the six-group modelling session during both Conceptual and Computerized models, which

provided the “empirical” validation, as guided by the experience of the participants and descriptive knowledge of the real-system.

2. **Boundary- Assumptions Test**

Purpose: This test verifies whether the important concepts and structures for addressing the subject questions/issues are endogenous to the model and the model structure is appropriate for the model purpose.

Methodology: When the structural verification enables validation of elements that should be implemented into the model, boundary assumptions were considered in a similar manner. During the GMB-3 and 4 the boundaries of each process and related parameters were continuously discussed with the experts. As the test aims, the effects of technological integration into different endogenous variables were provided (e.g., consequences of managerial actions, effect on productivity, errors, actual durations) and presented in technology-adapted causal loop diagrams in Section 4.3.2.2 with the assumptions. During the related group modelling sessions boundary assumptions were supported with the views of the experts.

Findings: The boundary assumption were clearly defined by the researcher and different alterations were made by the Company Experts during the sessions for the finalized version of Conceptual Models.

3. **Dimensional Consistency Test**

Purpose: As one of the key validation steps for the Computerized Modelling, this test entails the dimensional unity of model’s equations. The test aims to check whether the units of measure of variables on both sides of the equations are equal. Moreover, the dimensions of the variables should be meaningful corresponding to the real system.

Methodology: Most of the time the related software can conduct the test since the Computerized Model cannot be runed if there is a unit error. Similarly, Stella Architect was used for the test by using the “Units check” feature in this study. The function automatically defines the errors and suggests units as shown in Figure 6.1.

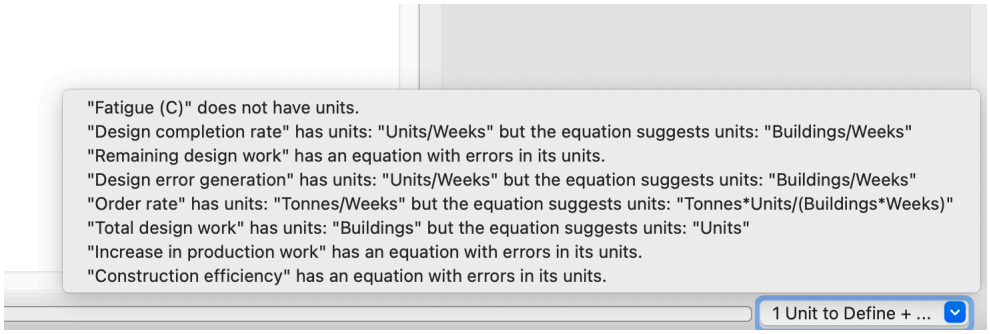

Figure 6.1: Unit check errors and suggestions from stella architect

Findings: At the beginning of the transfer of conceptual models to stock flows, it was realized that the model has more than 50-unit warnings. Then the unit modifications were made to ensure the consistency. Moreover, as it is stated in Computerized Modelling section, the experts defined the main units for processes (e.g., units for production, tonnes for supply). To correct the errors, if it is necessary, different conversion factors were implemented into the model as stated in Computerized Modelling section.

As an example, the conversion of design units to supply in the stock-flows shown in Figure 6.2. At the beginning, Stella software gave errors since the unit of design completion rate is “Buildings/Weeks”, but the Order is “Tonnes”. To correct this error, firstly the parameter “Units per Building” was added to the model to represent the units need to be produced and installed for one building, then the “Units” and converted into material unit by “Raw Material per Unit”. However, when considering these unit conversion parameters, there should be reliability to the real system. Therefore, for that step Parameter Verification Test was conducted in the following pages, again with the contribution of the case company experts. Finally, after clarifying and making different changes in the units, the dimensional consistency was verified from Stella Architecture.

Moreover, the external flow parameters (“Change orders”, “Order increase”, “Production work increase”) behaves as instantaneous increases in the stocks. Nevertheless, to ensure dimensional consistency and logic of flows, they should be defined dependent on time (i.e., increase in unit time). Therefore, the built-in of DT

(time interval) was used in the denominator of the equations of these parameters, providing the dimensions such as Buildings/Week, Units/Week. The dimensional consistency is assured at the end of all of these corrections.

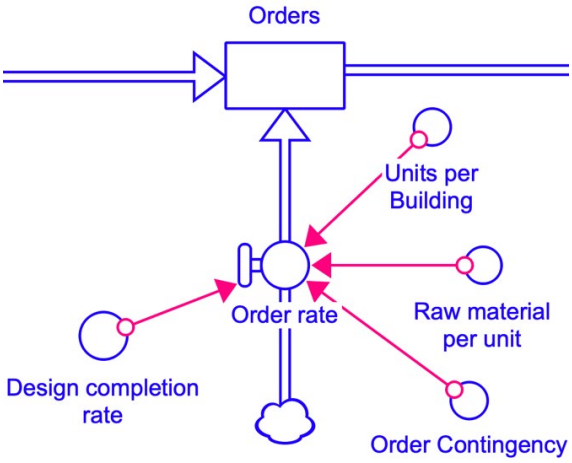

Figure 6.2: Unit conversion example from supply stock flow

4. Extreme Conditions Test

Purpose: The test aims to understand whether each equation in the model makes sense even when the inputs take extreme values. Moreover, the model should respond reasonably to the sudden shocks and parameters (i.e., the model's behaviour should be similar to the behaviour of the real system under these extreme conditions) (Ding et al., 2016).

Methodology: As the methodology of the extreme condition test, Forrester and Senge (1980) proposed examining each rate equations in the model and tracing back through any auxiliary equations to the level on which rate depends, and evaluation different imaginary maximum and minimum values. The authors also stated that the counterargument that the extreme values may not happen in real life is not logical since the nonlinearities and approaching extreme conditions

may have unstable impacts on the model's behaviour. In this study, several trials have been made for different parameter. Firstly, the extreme conditions were tested in the

model and checked for the technology-related input parameters (between 1-5, 0%-100%). Then, the sudden shocks, which can be mentioned as extreme parameters such as change orders, demand increase, and material re-order in the model, were tested for worst scenarios and modified according to experts' feedback about the real system's behaviour under these circumstances.

Findings: For the first step, each processes technology parameters are evaluated according to the extreme values. As stated in the previous section, Computerized Modelling, the technological input parameters related to BIM are calculated outside the model and transferred as model parameters by its maturity level. Hence, the rating conversion was made for the qualitative assessment of these parameters by converting to percentage. Accordingly for each technological model inputs, extreme values are tested in its process model and the rationality of the structure and behaviour of the system is considered. It should be noted that, since the validation was done before the scenario testing, the modeler assumed rational initial values to start the simulation.

Moreover, since the technological parameters are exogenous into the model, the linked endogenous were traced as proposed by Forrester and Senge (1980). It should be noted that, since the impact of technology parameters (e.g., effect of RFID on production efficiency) were defined by the experts, the related equations are not additionally validated again. Secondly, the external change parameters were tested for the validation. Related flow or converters were changed for different extreme conditions for these parameters. 61 runs have been conducted, and changes have been made if necessary. The final model works plausible in extreme conditions and passed the validation test. Since the validation process was parallel with the model development and the stock-flows were iteratively corrected, the models presented in the previous chapter were the finalized ones and corrected model formulas are introduced with the rest in Appendix.

Table 6.1: Extreme value test results step 1

	Technology Parameters	Units	# Runs	Problems/Observations	Solutions
Design	Automation of design	0-1 (%)	12	The automation of design parameter directly affects the "Design Efficiency", when the input is 0, the design efficiency is only decreased by Fatigue, which is rational. Then the input was incrementally increased for 12 trials, it was realized that there is no difference between the behaviour of the system when the input is 0.5 and 1 due to the equation. Since full automation will have higher impact on the design efficiency, it was assumed that for automation higher than 0.5 and smaller than 1, the increase is 20%, if it is 1, 50%.	**For Design Efficiency Parameter:** **Previous Formula:** IF (Automation of_ design>=0.6) THEN 1.20*Fatigue ELSE Fatigue **New Formula:** IF (Automation of_ design=1) THEN 1.5*Fatigue ELSE IF (0.6<=Automation of design<1 THEN 1.2*Fatigue ELSE Fatigue)
	Model-based Collaboration	0-1 (%)	3	In the design process, "Model-based collaboration was linked to the "Design rework discovery time". When the input is 1, the process simulated rationally. For 0 input the rework discovery time gets the highest value, 2 weeks, as explained in the Computerized modelling (for a medium-size project environment, the experts defined this parameter between 1-2 considering the "speed of decision-making"). However, it was realized that the process duration gets irrationally high for this maximum value. The reason behind is the work the re-entering the loop even if it is less than one and resulting extension of the ending time. However, this doesn't make sense considering real projects, as work would get at least 1 as value and wouldn't be split into that many parts by precision. Therefore, if the remaining work is less than 1, it was decided to reflect the errors directly. It also prevented this model from doing the overtime calculation again if the work is less than 1. This fix was also made for other processes.	**For Design Rework Parameter:** **Previous Formula:** Design errors/Design rework discovery time ***New Formula:** IF (Design work>1) THEN Design errors/Design rework discovery time ELSE Design errors/DT **Additional connector was drawn from design work to design rework for equation.*
Suppl	RFID	0 or 1	2	The RFID input linked to the "Missing material", which changes the supply rate. The inputs were tested for both scenarios and the supply rate gave reasonable values; hence no modification is needed.	

Table 6.1 (cont'd)

	ERP	1-3	6	The ERP system is linked with the converter "Accuracy of material quantities", which influences another converter ", Order contingency". It was realized that the equation gave reasonable values for both the 1 (extreme minimum) and 3 (extreme maximum) considering the final "Material inventory". Hence the parameter is validated.	
Production	RFID	0 or 1	2	The RFID parameter linked to the "Production rework discovery time". When RFID is 0, the rework discovery time fixed as the maximum, 2 weeks. However, due to the same situation with the design rework, the related change has been made for rework parameter. Moreover, RFID parameter is linked to "Production efficiency" for productivity increase. Therefore, the extreme values behave reasonably for this parameter.	**For Production Rework Parameter:** **Previous Formula:** Production error /Production rework discovery time ***New Formula:** IF (Production inventory>1) THEN Production errors /Production rework discovery time ELSE Production errors/DT **Additional connector of production inventory to production rework*
	Model-based Collaboration	0-1 (%)	8	The parameter related to "Production modelling" was tested for both extreme and random values between the intervals. The structure and behaviour of the parameter was reasonable. Similar check was done for the "Communication on site" parameter in Construction and both are validated.	
Construction	RFID	0 or 1	2	Same correction with design and production have also been done for construction reworks.	**For Construction Rework Parameter:** **Previous Formula:** Construction error /Construction rework discovery time **New Formula:** IF (Construction work>1) THEN Construction errors /Construction rework discovery time ELSE Construction errors/DT **Additional connector of construction work to rework*
	Non-ERP tools	0 or 1	2	This parameter linked to the "H&S Management", for the extreme conditions system gave reasonable outputs.	
TOTAL			**34**		

Table 6.2: Extreme conditions test step 2

	Related Parameter	Units	#Runs	Problems/Observations	Solutions
Change Order	Change order (Flow)	Building/ Weeks	10	The related converter that takes input is "Time of change orders". For extreme minimum (0 Weeks), the finished design work is equal to initially planned design work, which is logical. For extreme maximum, each week was tested till the planned design duration. Moreover, requesting design change orders after the design (production, construction) is also tested. All these tests show that the system works correctly.	
Production work increase	Supplied work rate (Flow)	Units/ Weeks	12	For this parameter, as the extreme conditions, three cases are tested: change order before demand increase; change orders after demand increase; demand increase after supply ends. For the first two tests, the model gave reasonable results. However, for the last one, when the supply rate reaches 0 (finishes), the model behaves like supplied work rate was also zero, even the units left in the production work stock. To correct this, if the demand increase time is after finishing the initially planned supply, the flow continues to transfer the units to the "Production inventory" stock. (Noting that there are 2 weeks predetermined delays between supply and production, as seen from the equations.)	**For Supplied work rate:** **Previous Formula:** DELAY (Supply rate/Raw material per unit, 2, 0) **New Formula:** IF (TIME>Demand increase time) AND Supply rate=0 THEN Production work/DT ELSE DELAY (Supply rate/Raw material per unit, 2, 0)
Order Increase	Time to adjust order (Converter)	1-2	5	The "Accuracy of material quantities" (ERP-related parameter) influenced the "Time to adjust order". It was realized that when the minimum extreme (as 1) of ERP, the parameter defined as 2 weeks. However, since the Inventory Gap defined according to the instantaneous shock of demand increase, the existing formula just decrease the actual required order in the denominator. Hence, it is decided to model the effect of "Time to adjust order" as an external delay to flow. The logic was also explained in Computerized Model Section.	**For Order increase:** **Previous Formula:** Inventory Gap/Time to Adjust Order **New Formula:** DELAY (Inventory gap/DT, Time to adjust order)
TOTAL			**27**		

5. **Boundary Adequacy Test**

Purpose: This test aims to understand the extent of model for its structure and adequacy for the designed aim. Moreover, the important concepts for addressing the problem should be endogenous to the model. This test also configures the limitations of the defined model boundary.

Methodology: For the methodology of the test, Saysel and Barlas (2006) proposed simplifying the model as much as possible considering the model purpose. Forrester and Senge (1980) stated changing the model boundaries and adding endogenous parameters to the system to see whether the conditions are affected unreasonably or not. In this study, the models are simplified at the beginning by considering the digitalization purpose with the case company. Moreover, the model based on the generic structures/feedbacks of the literature and the technology effects are added as exogenous parameters to these models. However, the impacts of technologies differed for different unique endogenous project dynamics, such as managerial actions, external changes, reworks etc. Hence for this validation test, rather than technology variables general boundary condition and process flow were tested.

Findings: Since the case company stated some parallel activities, the model development was conducted accordingly. However, as the boundary adequacy between process-sectors, the previous activities finish time shouldn't be late than successor's finish time (e.g., the production process cannot finish early than supply finish). This concern was checked for different parameters between processes. For instance, the time of work increase selected as 52 Weeks (1 year), as an extreme condition. It was observed that even in this situation, the actual supply time less than production time as required. The example simulation result was given in Figure 6.3.

Rather than this logic, the overall logic of the process model development was rechecked with the experts to investigate whether there is an unreasonable point. Then, the necessary changes are done iteratively, and the model process boundaries are presented in the previous chapter according to its finalized version.

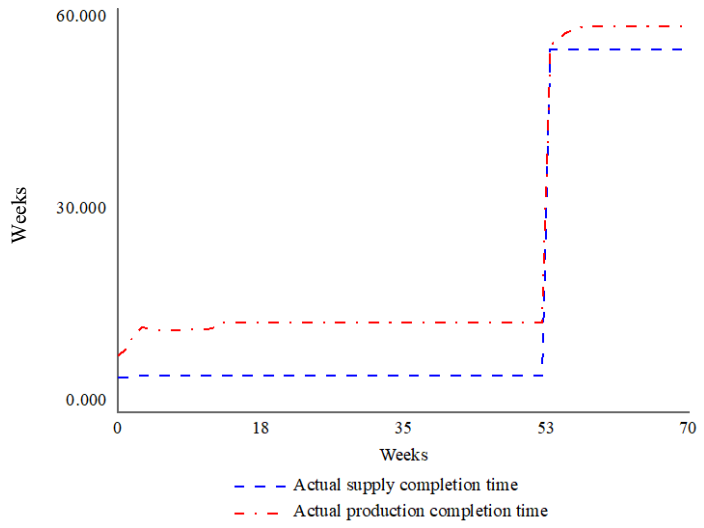

Figure 6.3: Boundary test adequacy test simulation result

6. Parameter Verification Test

Purpose: This test examines whether the parameters are relevant with the system's descriptive and numerical knowledge.

Methodology: Verifying the parameters directly conducted by the individual knowledge of company experts and checking the convenience with the real life and project management dynamics.

Findings: Since it is a "system" modelling, some simplifications were made for the parameters. For instance, the building types directly converted into production units with "Units per Building" parameter. In the real time for each building the amount and type of required units can be different. However, to simplify the model and understand the overall behaviour for digitalization these assumptions was made with the experts. Moreover, the experts indicated that the "rework discovery time" is not a factor that is considered in project management of real cases. For that, rather than directly considering as "Weeks", the modeler transformed this to "Speed of decision-making" capacity rating for each process. Moreover, as the processes progress, the speed of finding errors (increasing learning, getting used to work) has also been added as a formula to make this parameter more realistic after consulting the experts.

These changes have been done iteratively and the Computerized Model passed the Parameter Verification Test since the company experts set the values for each parameter. The list of real data for model parameters is given Chapter 7 in Baseline Testing and Appendix.

After iteratively validating and finalizing the stock flows, the simulation results and discussions are presented in the next section.

CHAPTER 7

SIMULATION USING THE CASE COMPANY DATA: SCENARIO ANALYSIS AND DIGITALIZATION STRATEGIES TESTING

This chapter explains the results of the simulation of the finalized stock flows in Stella Architect software. The chapter is structured as follows. Firstly, the baseline testing was conducted according to the project-related inputs from the company experts. Secondly, for the external parameters, different dynamics were simulated. For both steps, the results of the simulations were presented to the company experts to understand whether the results are reasonable and reflecting the real project dynamics. At the last stage, according to the strategic goals of the case company, in Figure 4.1, different parameters were changed, and results are presented for further discussion.

7.1 Baseline Testing

7.1.1 Initial Values from the Case Company

Before simulating the model for different external conditions and technology integration, for a sample project, the initial values were taken from the experts of the case company. It should be noted that the experts gave the related inputs for the medium-size project, and it can be altered for a different project with different initial parameters in the model. The Company Experts were asked to provide both the qualitative and quantitative input values needed to run the model. As the qualitative data, the company experts indicated rating for the parameters in the table previously presented in the conceptualization stage, Table 5.2.

The parameters related to BIM and automation were integrated into the model with the rating conversion, as stated in Table 5.3. Since these model parameters will be used for further evaluation for strategy testing, the converted values are presented in Table 7.1. From the rating of the experts, it was understood that the company benefits from moderate level BIM (close to BIM Level 2) and ERP integration.

Table 7.1: Rated technology model parameters

Model Parameter	Rating
Coordination through models (Object-based models)	0.8
Effectiveness of project management (BIM Level 1.2)	0.4
Model-based Collaboration (BIM Level 2)	0.6
Network-based Integration (BIM Level 3)	0.4
Detection of clashes	0.6
Automation of Design	0.56*
RFID	0
ERP	2 (between 1-3)

*Automation of design calculated according to the average of detection of clashes and coordination through models, and multiplication of competency of the technology team, as given in Appendix.

The quantitative inputs are the project inputs such as the initial work, productivity, initial resource level and planned durations for each process. Moreover, the predicted error values were also taken as input from the experts. It should be noted that, for each process, the errors were asked from the experts by considering the nature of the project, possible discrepancies with the expected quality and undetected errors in the predecessor activities. For instance, since the case company experienced modular buildings, the initial error ratio of the construction process is relatively smaller than production. Nevertheless, it was observed that the experts indicated the construction

error ratio with the undetected errors in the production process and possible request-for-information from design to clarify the implementation of produced units.

Firstly, the initial values related to design process objectives (productivity, duration, error) are presented in Table 7.2.

Table 7.2: Design process inputs

Parameter	Input	Units
Initial design work	4	Buildings
Initial designer productivity	1.3	Buildings/Weeks/Team
Design Team	1	Team
Planned design duration	3	Weeks
Design error ratio	30	%

Moreover, the experts stated that in the mentioned project, there was a change order of the initially planned design work by 15%. This percentage is reflected into the model as an external flow coming to the initial work, as given in the design stock flow diagram in Figure 5.3. After the design process, the supply data was taken from the experts as the next activity.

Accordingly, to transfer the buildings into units and tonnes, two conversion parameters were determined by the experts by considering this sample project data. The related inputs for the supply process are presented in Table 7.3.

Table 7.3: Supply process inputs

Parameter	Input	Units
Planned supply duration	5	Weeks
Missing material	20	%
Units per Building	250	Units/Buildings
Raw material per Unit	2.8	Tonnes/Units

Then the supplied materials will accumulate in the production inventory, and with two weeks delay, the production will start in the model. For the production stage, the KPI-related factors are given in Table 7.4. The experts stated the initial design work was given as the multiplication of Buildings and Units per Buildings parameters.

Table 7.4: Production process inputs

Parameter	Input	Units
Initial production work	1000	Units
Planned production duration	12	Weeks
Resource (P) Productivity	1	Units/Week/Resource
Max. production capacity	130	Units/Weeks
Initial resource	80	Resource
Production error percentage	20	%
Upper limit of Resources (P)	140	Resource

As another external impact on the project, the experts stated that there was a 30% production work increase from the initially planned units. Accordingly, from the change orders and production work increase, the total units are given as 1450 Units.

$$4 * (1.15) * 250 + (1000 * 0.3) = 1450\ Units$$

Since the production and construction processes are linked to each other in a finish-to-start logic, the construction process is modelled individually (i.e., not linked to parameters of other processes). Hence the initial stock parameter of construction work was also determined by the total production work. The outbound logistics (i.e., transportation to site) were neglected considering the strategic goals of the company in terms of digitalization. The experts indicated the construction inputs as shown in Table 7.5.

Table 7.5: Construction process inputs

Parameter	Input	Units
Initial construction work	1450	Units
Planned construction duration	8	Weeks
Resource (C) Productivity	5	Units/Week/Resource
Initial resource	30	Resource
Construction error percentage	10	%
Upper limit of Resources (C)	40	Resource

To be noted that the project-related inputs rather than the technology integration levels remained the same for the rest of the scenario analysis of different strategies.

For the time sector, according to the given planned durations for each process, the total project duration specified as 25 weeks, as also validated by the logic that the experts shared about the flow of the process (i.e., summation of design, two-weeks delay in start-to-start linked supply and production and construction durations).

Moreover, unit costs such as resource, material, overtime, indirect, and uncompensable delay need to be taken for the cost sector. The experts shared the percentages rather than monetary value for the cost parameters. Since values are calculated by the model on a time basis, the percentages are reflected in the model by proportioning according to the planned durations. Noting that, in the previous sections, the experts mentioned that the delays because of the production work increase are uncompensable according to the contract terms and especially due to the approval of the resource allocation by the owner. Hence, the experts anticipated at least two weeks of delays and gave the uncompensable delay percentage accordingly. The inputs for the cost sector are given in Appendix.

After taking the initial values from the experts, to run the model, two different scenarios were tested regarding the external parameters as time of change orders, production work increase time and order contingency. For the contingency of materials, the company experts expressed that they anticipate about 15% of the material contingency in these types of projects, also considering the existing level of ERP system integration. However, for the time of change orders and production work increase time, random numbers were generated in the model for simulation. Accordingly, two different scenarios were tested and shared with the company experts to evaluate its reliability. It should be noted that the specified scenarios are selected with the experts to interpret the benefits of technologies for different project dynamics, as will be discussed in the strategic options testing step. For these scenarios, the time of external conditions was changed to see the response of the technology parameters.

7.1.2 Scenario Testing for Existing Technology Levels

For the scenario testing, two aspects were considered to run the model as **(1)** time of change orders and **(2)** production work increase time (i.e., increase in building units demand).

1. The experts stated that the change orders may happen at the design step (i.e., within the planned design time) or may be asked from the owner in production or even in the construction stage. Nevertheless, the experts also indicated that the change orders that increase work like this that need design changes again in general. Hence, the change order time is depicted as a random time between one and the planned design duration during simulation. The other changes in the scope of this study, such as order increases or production work increases, directly influenced the quantity of building units since the design will remain the same.

Moreover, other changes that may not change the size of the work, but cause delay with different requests from the owner, were assumed to be included in the error inputs given by the experts because these parameters include human errors and acceptance of the work by the owner.

2. The experts mentioned two frequent scenarios for the production work increase as this request may be experienced in the middle or end of the planned production duration. Experts said that they encountered delays and cost overruns, especially in these cases, and they wanted to see how successful the technology integration could be in reducing this impact as a company. Therefore, the results of the simulation for production work increase at the start (such as at the first week or within the planned supply duration) were not analysed for this study since the experts stated it could be managed relatively easily.

7.2 Results of the Baseline Testing

According to the specified cases with the company experts, the model was checked for different parameters. The results are given for two scenarios.

As the first scenario of baseline testing, the given initial parameters and technology levels in Appendix were entered into the final stock flow model. The change order time is decided as Week 2 and Production work increases at Week 7. The defined order contingency is 15%, and the speed of decision-making is rated as low for design, medium for production and construction process, which is used by the modeler to configure the rework discovery times as explained in the model development chapters. Accordingly, nearly 50% work increase (from 1000 units to 1450 as stated above), different error ratios for the process (along with the different speeds of decision-making (rework discovery time)) and existing level of technology integration in the model were simulated.

Time-sector: For this sector, the model depicted the actual completion times for each process and total project duration. Moreover, the uncompensable delays were configured accordingly. The related findings are as follows.

Table 7.6: Baseline scenario 1 time-sector results

Actual design completion time	Actual supply completion time	Actual production completion time	Actual construction completion time
4.24 Weeks	9 Weeks	18.06 Weeks	8.11 Weeks

Accordingly, the project duration was calculated as 30.4 Weeks. Assuming that the delays due to the change orders in the design can be compensated, the uncompensable delay found as 4.17, nearly 4 weeks. From the time sector, it was concluded that the project utilized managerial actions (resource increase, overtime) to finish the project with minimum delay. The experts compared the results with the actual project data and configured that it was logical. Moreover, the observed production and supply delays have connected each other as it was intended to create a parallel logic between the processes. Since the order contingency was decided as

15%, and it is not enough for the 30% production work increase, when the supply finishes, the work goes back to the order stage. Hence the inventory gap was ordered with a one-week delay (time to adjust order value regarding the Accuracy of material quantities by ERP in projects). This return to supply causes delays and idle workforces in production. As it can be seen from Table 7.6, for the construction phase, the delays were prevented mostly by the overtime strategy. For the design process, the major reason behind the delay was the time spent for identifying the reworks and slow decision-making mechanisms. Moreover, the production resource and capacity were not adequate to finish the work on time.

Cost-sector: According to the unit cost percentages depicted by the experts, the total project cost percentage (i.e., overrun) was configured. The model found the total project cost as 152.73%. Hence there is a nearly 50% cost overrun. It was observed that the cost overrun was major because of the total resource cost (66.24%) and material cost (63%). Because the model increases both the production and construction resources to overcome the major project delays. Moreover, although the resources were increased and worked with overtime for the design and construction process, these actions return as crowding effect and fatigue, which influences productivity. The resources of the simulation are given in Figure 7.1. As can be seen, for the production stage, the resource level remains stable to depict the upper limit of resources (140 Resources) between weeks 7-15. The reason is since the required production rate exceeds the Max. Production capacity due to the unexpected work increase, the model, considered this capacity as the rate and upper limit of resources as the resource level.

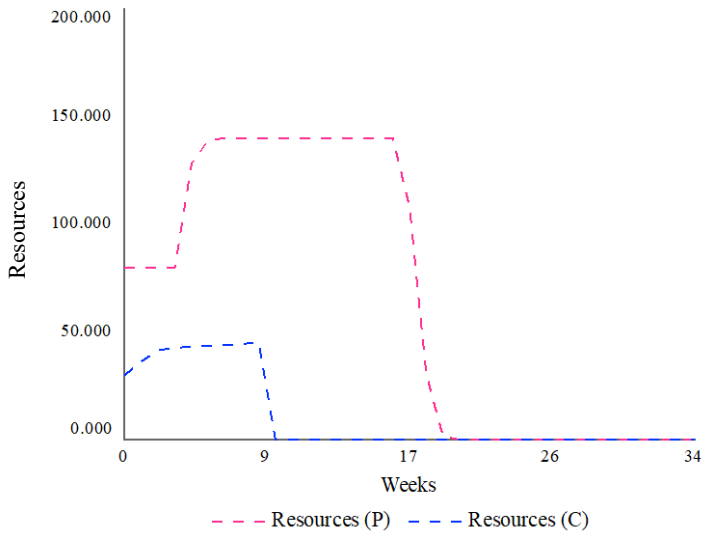

Figure 7.1:Resource levels for baseline testing scenario 1

Productivity-sector: It was observed that the existing levels of BIM integration have a positive impact on the design, production, and construction efficiency to compensate for the negative influences of fatigue and crowding effect on productivity, respectively. Hence although this baseline testing simulated the as-is case for the company, the results gave an overall understanding about the existing level of the technologies as reducing the negative consequences of managerial actions.

Error-sector: For the error sector, the as-is technology integration manages the effect of schedule pressure on errors by the effectiveness of project management (utilization of 4D/5D models) and ERP in projects (production planning features).

The second scenario for the baseline testing was production work increase at Week 12, which is the worst scenario as the new work comes to the factory at the end of the planned production duration. The major differences between the first scenario were the actual supply completion time (14 Weeks), production completion time (19.05 Weeks); hence the total project duration (31.40 Weeks) and total project cost percentage, overrun (56.6 %). The graph of actual production time gives a depiction of to reason behind this 6-week delay and cost overrun.

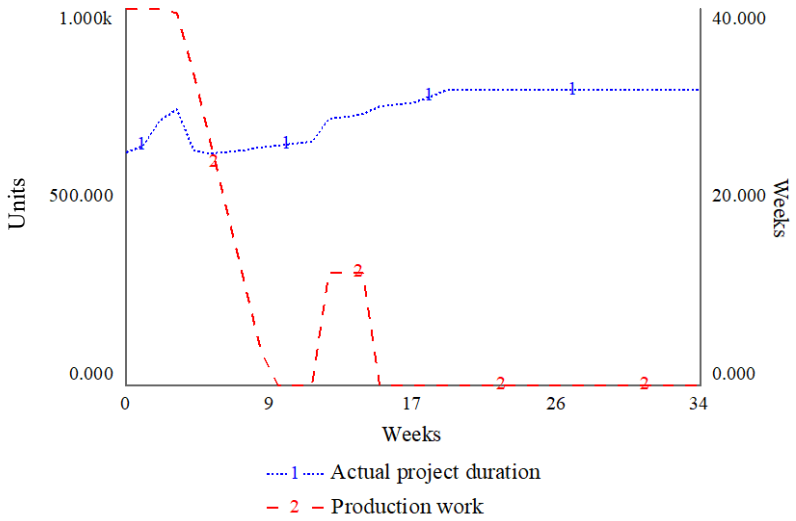

Figure 7.2: Production process for baseline scenario 2

As it can be seen from Figure 7.2, the production work decreased as it was supplied to the factory and increased at Week 12 due to the demand increase. For the actual production duration, there were two peaks as in Week 2 (change order time) and Week 12 for the production work increase. For the first one, it can be seen that by increasing the resources, the delays are managed between weeks 4 and 11. In Week 12, the work increases with no remaining time lefts, which directly increases the duration. Moreover, since there is a limiting max production capacity, the resources cannot compensate for the delays from one point, and the duration continues to increase. The delay in supply is due to the inventory gap similar to the first scenario. The cost overrun percentage difference between scenarios is due to the need for using upper limit (max.) resources for a longer time. After considering the outputs of the scenario testing with the experts, it was concluded that the results of the model are close to the reality and actual project management dynamics. In the next section, the strategies are tested by altering the technology parameters.

7.3 Strategic Goals Testing

For this section, the strategic goals that are given in Figure 4.1 are followed to change the technology integration levels and observe how the model behaves for different

objectives. Since it was understood that the "production work increase time" affects the system, particularly from the dynamics of supply and production processes, for the technologies that are considered for these processes specifically, each scenario is re-conducted with digitalization to observe the effect of the external environment.

1. **Increasing the Automation of Design and Interoperability**

The first goal of the case company was to increase the coordination through models and create effective interoperability between models. The experts indicated the level of details of models as 4 and the existing level of interoperability as 3 out of 5. Hence for the strategic simulation, the object-based model coordination (level of details) increased to 5, 100% (coordination by models) and interoperability to as 80% (clash detection). Note that the internal and external factors assumed the same with Scenario 1. The following changes depicted the configured Automation of Design parameter as 72%. Accordingly, the total project cost was %135.25, which decreased by nearly 18% from the initial scenario. This is due to both resource and overtime decreases. The project duration becomes 28.3 Weeks with nearly 2 weeks of uncompensable delays. The difference in the project duration and resource increase is managed by increasing productivity (the design productivity increase by 32.3% by automation in design (from 1.3 to 1.72), for production by 25% with the production modelling interoperability and construction productivity increase by 35% by the communication effect). Among the error parameters, only the design error ratio is changed according to the configured conceptual models and technology integration with the company experts. Because it is required to create a common-sensor-based environment (network-based integration) to decrease the errors in the production and construction stage through BIM. The design errors decreased by nearly 11.33%. The effect of increasing the level of Model-based collaboration (interoperability) on production and construction resources is shown in Figure 7.3.

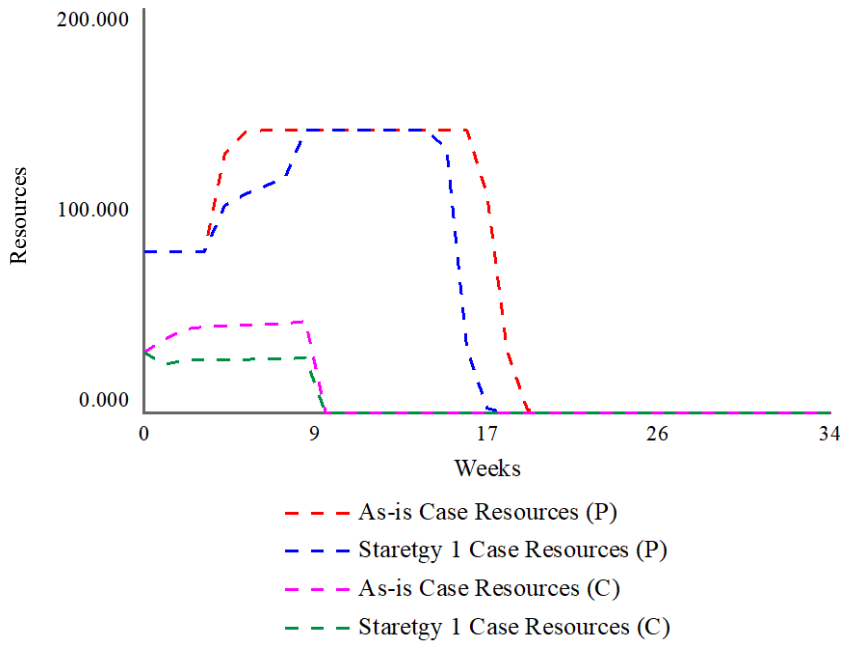

Figure 7.3: Resources for strategy 1 simulation

Moreover, for this scenario, the other aspect of the BIM Level 1 was also tested, as the integration of 4D/5D models into the management dynamics. The company indicated the existing level as 2 out of 5. Hence as a strategy, this digitalization aspect increased to 3 as 60%. This strategy affected the design and construction overtime by decreasing the schedule pressure. Although the project duration remained the same, the total project cost decreased due to less overtime, to 34.15%. The difference in the configured overtime for the design process is given in Figure 7.4.

Additionally, if the automation of design is configured as 100% externally by the modeler, the only change in the model is regarding the design time and errors. The design errors become 0 as decided, and the completion time is 3.30 weeks, nearly with no delay, even with the change orders.

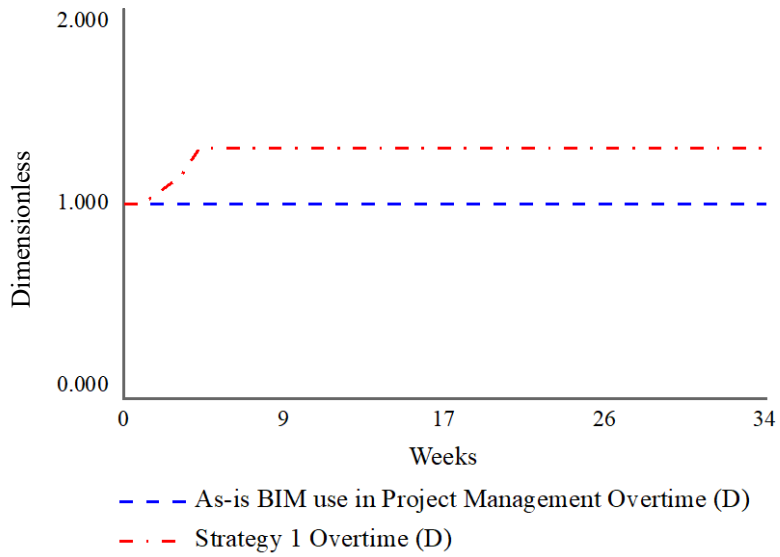

Figure 7.4: Design overtime for strategy 1 simulation

2. Network-based Integration of BIM

From this perspective, the Network-based Integration parameter is considered. The experts indicated the as-is level of integration of interfaces (integration of process through BIM) as 2 out of 5. The parameter was increased by one level to 3 and 60% network-based integration for the strategic option testing. Accordingly, the behaviour of the model is observed. It should be noted that, since the maturity levels of BIM cannot be dissociated from each other, for the BIM Level 3, the values of BIM Level 2 in the first strategic goal values are left unchanged (Model-based collaboration as 80% and level of detail of models as 100%), to make a logical strategic implementation. Note that this factor mainly impacts the error ratio according to the conceptual maps that are configured with the experts. According to the technology integration, the system is simulated. After increasing the network-based integration, the cost overrun became 30.56%. The model depicted the project duration as 27.4 weeks, with 1.3 weeks delays. The integration of processes decreased the overall delay, although there was a nearly 50% work increase due to the change orders and production demand. When the model was observed, the major effect of the technology integration was the decrease in the errors of production, hence client satisfaction and overall schedule performance.

For the strategic goal of this step, rather than the optimum case, the total integration was also considered for the combination of real-time data from all of the processes (production and construction) by IoT devices and BIM. The total project cost overrun was indicated as 29.34%, and the delay decreased to 1 week, which is smaller even than the minimum delay anticipation of company experts. Hence fully integrated BIM have mainly influenced the errors during the production and construction stage, which decreased the delays significantly.

3. Coordinated ERP systems with BIM

As the third strategic objective, the company experts stated bringing the ERP system integration one step further and coordinated the current material lists with the BIM. The expert stated the current level of ERP as 2 out of 3, considering the fact that the case company utilized the systems for many years and is experienced. Firstly, the effect of the existing level of ERP systems for baseline scenarios and two strategic options for BIM levels were re-considered. Accordingly, since the experts indicated the order contingency as 15%, it was not sufficient to fulfil the desired material inventory for production work increase and change orders together with the planned material amount. For all of the strategic options as well, the material cost remained the same since the technology integration up to this test affected the supply. Moreover, the experts and literature indicated that the ERP systems provide better inventory and material management in general that contributes to the supply chain for "leaner" supply chain and production. Hence the equation of ERP in supply served as a parameter that decreases the excessive order contingency. Firstly, for strategic testing, the ERP system level increased to 3, which depicts the updated material lists parallel with the object-based models. After the simulation, it was observed that, since the baseline for this project, an increase of production work by 30%, was an extreme condition, the ERP benefit cannot be observed directly for inventory management.

Another scenario was tested with the collaboration of company experts to understand the benefit of ERP in decreasing the excessive material level. The expert stated that

since the initial values represent "typical" medium-size projects of the case company, the building unit increase during production can be simply 10% for another project. Hence this scenario was tested. When the ERP integration is at the as-is level for this scenario, the cost overrun was 20%. The desired inventory was 3.500 Tonnes. However, since there is still uncertainty in existing material lists, extra material was supplied for the as-is scenario with excessive 203 Tonnes of material which caused an increase in material cost by 7%. This percentage is significant since it directly impacts the total project cost. After the strategy implementation, the excessive material order was decreased to 42 tonnes (considering the minimum safety order) and minimized the cost overrun. The related scenario is given in Figure 7.5.

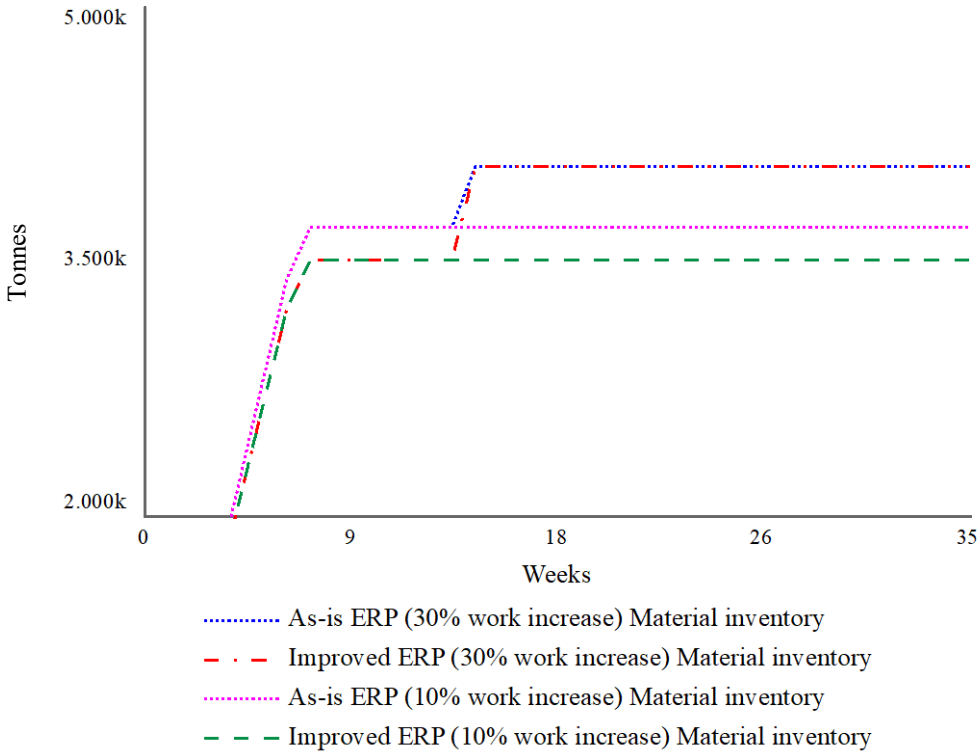

Figure 7.5: Material inventory levels for different scenarios and ERP

Rather than inventory management, the benefit of ERP was also considered during the production planning stage. When the ERP level was considered as 3, the schedule pressure decreased by 60% and influenced the production errors from %26 to %20.

4. RFID Integration

As the fourth step of the strategy testing, new technology was implemented as a factor. Since the company had never used the RFID for the processes before, the experience of the CTO was used for the conceptualization stage. At the beginning, RFID was 0; then, the parameter was converted into 1. It should be stated that similar to the Network-based integration, since the research aims to understand the dynamics and effects of a complete digital ecosystem on projects, rather than individually testing the RFID, it was analysed with the rest of the parameters (i.e., with increased BIM maturity levels and ERP integration). Moreover, the simulation was done according to the initial values of baseline scenario 1 (time of change orders as 2, production work increases 7 and order contingency 15%).

Accordingly, the differences in total resource costs are presented in Figure 7.6.

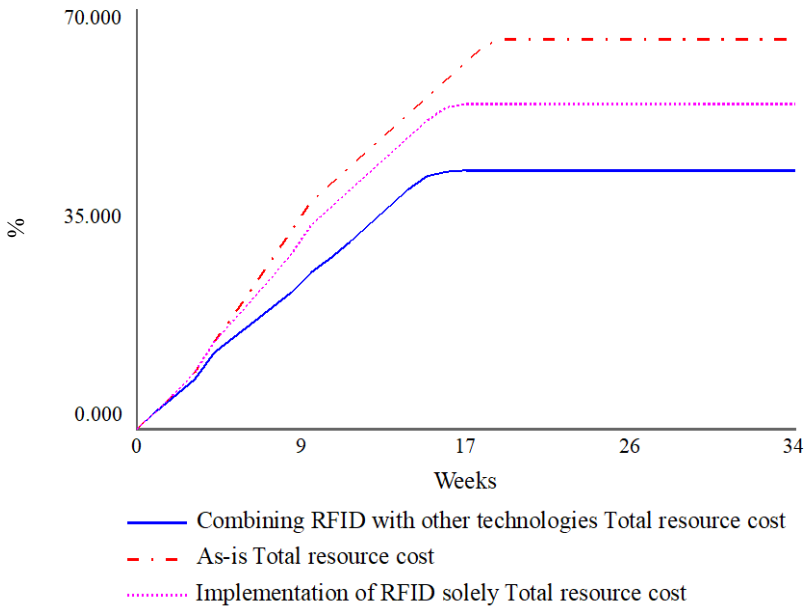

Figure 7.6: Effect of RFID on resource cost

As it can be seen from the Figure, there is a major difference between the as-is case of the company and after conducting the RFID technology. From the graph, it was also observed that when the strategies are conducted together, RFID creates additional value. This implies that rather than individually applying RFID,

combining it with other technologies becomes more valuable, especially considering the cost overrun. Since company expert 3 stated that the RFID increases workforce productivity significantly by reducing the time that is spent for tracking the units in the factory. Hence this also reduced the overall need for additional resources in case of change orders.

Moreover, since it was observed from the simulations that the RFID technology majorly contributed to the productivity and the speed of noticing the errors/rework at the construction site, the external change concerning these processes was conducted as another scenario: by simulating the changes at Week 12 (according to the baseline scenario 2). The results of the project duration for both scenarios are given in Figure 7.7.

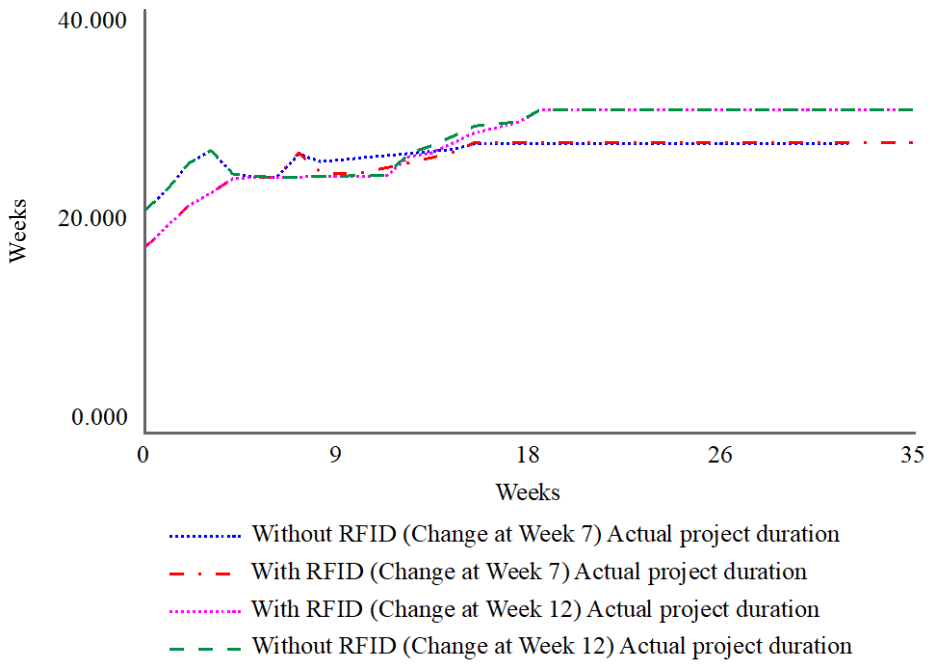

Figure 7.7: Effect of RFID on project duration

As can be seen from the Figure, the RFID is not adequate to respond to the project delays for both scenarios due to the significant effect of external changes. Hence the RFID effect is majorly discovered regarding resources and productivity. As the comparison of resources for production work increases at Week 12, the graph in Figure 7.6 is given. As it can be seen from the figure, the RFID decreased the cost

overrun majorly when the unit increase request was at Week 7. However, the RFID decreases the resource cost relatively smaller at Week 12 since it is an exceptional situation where there is a need for additional resource allocation at the end of the planned production duration.

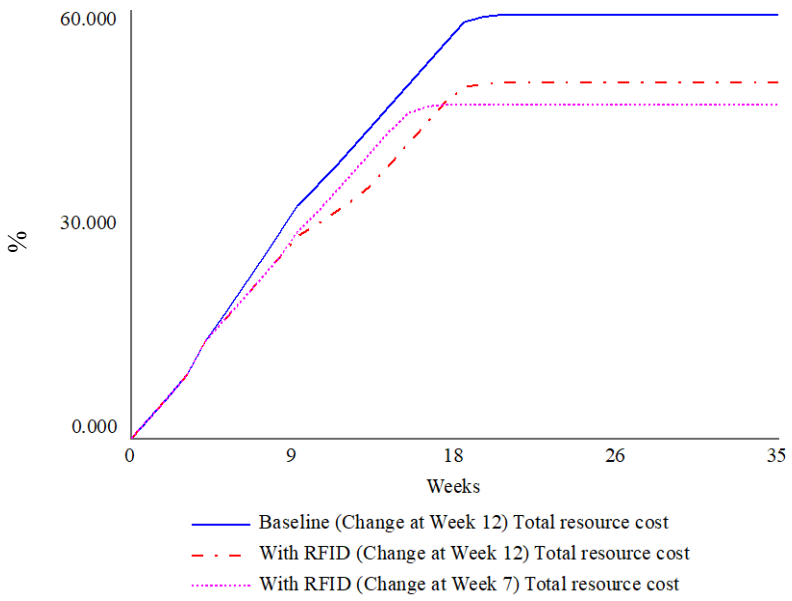

Figure 7.8: Effect of RFID on resource

Consequently, for the RFID implementation to the rest of the depicted strategies, according to the initial values of Baseline scenario 1, the cost overrun decreased to 24% and the project duration to 27.5 weeks with 1.4 uncompensable delays. Noting that the technology increased the speed of decision-making for error correction for production and construction processes as well.

As the final benefit of RFID, it was observed that the supply duration decreased by one week since the missing material percentage was reduced by 50%, according to the feedback of Expert 3. Considering the parallel link between supply and production, this reduction in delay contributes to the overall project duration. Moreover, this benefit of RFID can be influential considering the unstable market conditions for material supply.

5. Integration of Non-ERP Tools for Safety

As the last strategy testing, the experts purposed to increase the safety of the construction site. In fact, although safety is primarily dependent on immeasurable factors such as the well-being of employees, and the reliability and reputation of the company, in this research, Health & Safety management was evaluated over its impact on productivity. The experts indicated there were no non-ERP Tools of safety at the beginning. For strategy testing, it was assumed to integrate new tools (e.g., sensors, enterprise level digitalization for safety, warnings for high-risk tasks). Similar to the previous strategy, the experience of Expert 3 was used to clarify the impact of the technology on the formulation, as stated before. It should be noted that again, for this scenario, the cumulative effect of technologies was considered since the other technologies decreased the required resource level reducing the crowding effect that may indirectly reduce the chance of accidents as well. The resource level for construction is given in Figure 7.9.

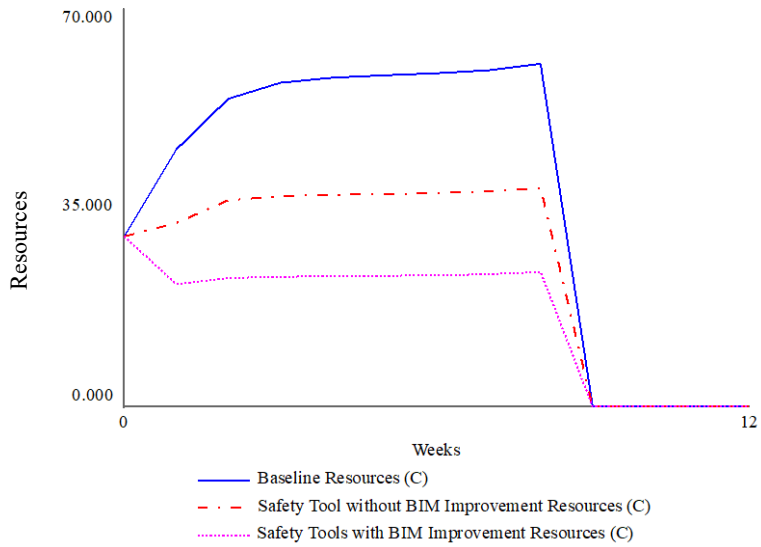

Figure 7.9: Effect of safety tools on construction resources

According to the results of the Model-based Collaboration effect on communication and non-ERP tools on Health& Safety Management, the existing construction efficiency increased by 89%, which majorly reduced the Resource level. Moreover,

as can be seen from the figure, the effect of safety tools exceeds when the strategy is combined with the BIM.

The simulation shows that safety does not have a major impact on the construction duration, thus the total project duration. Since the actual construction duration was already 8.08 weeks, nearly the same as the planned duration. Hence the managerial actions for this step solved the delay problem.

Consequently, after combining each strategy and reflecting it into the model, the total project cost overrun decreased to 21% and the total project duration to 27 Weeks, with 1.4 uncompensable delays. It was understood that since the work increased by nearly 50% due to the external requests, there was a nearly 50% cost overrun from the initially planned budget at the beginning. However, the stated technology integrations reduced this percentage nearly to 20% and enabled significant savings in case of external changes.

Since the increase in production work usually has to be compensated by the company itself, as stated before for their contracts (e.g., resource allocation requests are not accepted, the owner's additional payment does not meet market conditions in terms of material), such a cost overrun occurred at the baseline. Nevertheless, the technologies allow it to be overcome by both reducing errors and increasing productivity.

7.4 Discussion of Simulation Tests

After finishing the simulations, it was asked to the company experts in GMB-7 whether the simulation helped them to identify the benefits of digitalization for project dynamics. Their verbal statements revealed that the group modelling sessions and simulation results enhanced the strategic decision-making for different digital technologies. In particular, it was found effective in analysing the effects and interrelations of the main parameters of projects by evaluating the increase in existing technology maturity levels and new ones in different scenarios. Moreover,

re-thinking the existing processes and management dynamics with technologies help them configure the different options according to their objectives and performance criterion. Each strategic test has different implications and is discussed with the company experts during GMB-7.

Firstly, it was observed that in the first strategic test, although the interoperability increased for model-based collaboration among different departments and models, the “competency of the technology team” limited this benefit both in the model simulation and in real life. Hence, to complete the automation of the design process, the capability of this team should be considered. Moreover, it was discussed with the experts that the competency of the technology team could be considered as the interface management capability of the company and the departments' adaption of technologies at the design stage. Hence it is an important conclusion inferred from the model and should be considered by the company to increase the maturity level of BIM.

Moreover, the model indicated that the maturity level of BIM, as model-based collaboration is one of the most important technology integrations considering its effect on all the processes and causes a considerable decrease in cost and duration. Since the experts indicated that the speed of decision-making for realizing reworks was low for the design process due to the inability of every department to adapt BIM, the Model-based Collaboration increase makes an important contribution to this problem, and the detection of clashes reduced the design errors by automation. Therefore, for this scenario is implied that the interoperability should be increased in line with the competency of the technology team. The level of detail of the object-based models lays the foundation for this.

Secondly, the Network-based Integration increased to a moderate level (to 60%) to make a realistic scenario for the case company. It was observed that the integration of processes by models and IoT sensors majorly affected the error parameters. Especially since the case company indicated a relatively larger error ratio for production processes in the base scenario, it can be helpful to decrease the chance of

production errors (e.g., incorrect material use, inadequate quality controls, errors due to lack of tracking/management in the factory). Moreover, for construction, the real-time information regarding the resources and status of tasks is assumed to decrease the error ratio during the conceptualization stage, and its dynamic effect is monitored during construction duration. However, as the model equations between the network-based integration and errors indicated, the technology couldn't resolve the errors, considering there will always be a "human factor". To overcome these errors, other technologies of Construction 4.0 can be considered, such as Robotics and CPS. Consequently, Network-based integration is especially important to decrease the errors but to overcome the major external changes; there is a need for additional technologies that directly increase productivity.

For the ERP scenario, the simulation findings are discussed with the company experts, and it was concluded that although the ERP has an important contribution to inventory management and reduces excessive material, in case of order increase, it cannot prevent the increase in material cost. Nevertheless, the enterprise-level collaboration through the technologies for ordering and supply decreased the delays (time to adjust orders).

Besides, it was realized that the production planning and control features of ERP decreased the schedule pressure and errors due to this pressure among the workforces. Since this decreases the errors due to poor management, it reduces the delays and total project duration.

The RFID integration scenario testing revealed that this technology especially increases productivity, which decreases the requirement of resource allocation and project cost overrun. However, it was observed from model simulations that the external conditions are determinant of project duration, and RFID cannot completely overcome the delays in case of that. For example, compared to the case of a change in Week 7, when there is a change in Week 12, RFID may be slightly inadequate in managing. This means that the technology cannot resolve the delays caused by external changes but rather increases productivity and positively impacts the project

management actions and their consequences. Additionally, from the model results, it was concluded that combining the RFID technology with the rest of the strategic digitalization options is more beneficial, especially for cost overruns.

For the last strategic test, since the case company stated that their Health Safety Management competency is moderate and may induce productivity problems on construction sites, new safety technologies can be considered. Expert 3 is indicated as “Non-ERP Tools” in the conceptualization stage since it is an enterprise-level integration for keeping the labours safe, predicting the situations, and providing preventive management. The simulation results indicated that considering the existing situation of the case company, the integration of these technologies increased productivity and reduced the number of required construction resources significantly.

CHAPTER 8

CONCLUSION

8.1 Summary

Current studies show that digitalization will soon be the next normal in the construction industry. This shift expects to change the business processes, value chains and entire ecosystem of the companies. Standardization, integration, product-based processes, and informed decision-making are the driving forces for digitalization. However, it is a well-known fact that in the case of innovation, the construction industry has some shortcomings, such as the tendency to continue with the "traditional", the uncertainty of project conditions and environment, and the interrelatedness of different processes and many stakeholders. Despite these barriers in the industry, in line with the increase in the application of BIM, construction companies started to embrace information exchange through digital models. Moreover, in recent years, Construction 4.0 technologies have started to be considered. Construction 4.0 is a concept started the industry 4.0 that introduces the digital value chain and integration of processes. Moreover, the concepts encompass the different aspects of digitalization such as economic, social, technical, and in a way that combines processes and people.

Hence this study proposed that digitalization should be considered a strategic decision-making problem, and there is a need for a holistic approach to understanding the existing and future dynamics of business processes. Thereafter, this project seeks to evaluate technology integrations using a system dynamics approach to unravel different dynamics of processes and integrate people into the picture by implementing the strategic decisions into the model.

For model development and simulation, a demonstrative case study was conducted with an experienced Turkish construction company, especially working in the field of modular construction. Model development and strategy testing were utilized to discuss how different technologies contribute to project goals and how they are integrated with existing managerial actions.

Firstly, to understand which technologies can be integrated into the business processes and create value for project-level objectives, a comprehensive literature review was conducted on Construction 4.0 and digitalization. Then, an initial session was conducted with the company experts to understand the strategic position and goals of the company. Accordingly, it was concluded that the case company needs digital technologies for process-level improvements. Hence with the methodology of business process engineering, the as-is and future process chains were drawn for the company, and the strategic roadmap was developed for the project-level digital integration. Then in the conceptualization stage, the selected technologies of digital ecosystems as BIM, RFID and ERP and their different maturity levels were considered to understand which processes and performance indicators may be influenced. For this step, the project characteristics, managerial actions, causalities and specifically the feedback loops were created. In the next part, the computerized model was created with Stella Architect software and iteratively validated with both structural and behavioural validation tests. The computerized model encompasses four processes design, order/supply, production, and construction. For each process, several assumptions have been made for both the initial dynamics, external factors and anticipated technology impacts. In the final step, firstly, the baseline scenario was tested in two steps for different external dynamics and discussed with the experts to confirm the reliability of the model. Then, the strategic road map was followed to simulate different technology impacts on existing project dynamics. For the research, project objectives such as cost overrun, time, errors, and productivity were considered. According to the simulation results, it was concluded that considering its benefits for each process, the interoperability, “model-based collaboration”, has a major impact on digital improvement. It decreases the time that is spent on

discovering errors in the design process by coordinated models of different activities. Moreover, it contributes to productivity through interoperable production modelling and construction by enhancing communication on site. These impacts influence the resource allocation that is needed to respond to the external work increase requests. Especially this technology integration (i.e., increase in the maturity level of BIM) decreases both the cost overrun and time delays. Moreover, the 4D/5D models are also determined as model parameters which influence the schedule pressure of design and construction processes through better planning and management. Likewise, the model depicted that production planning with an ERP system can decrease the pressure on production resources. It was concluded that the decrease in schedule pressure reduces the errors.

Although the automation of design increased with the technological parameters, the model makes an important contribution by limiting this with the competency of the technology team. This concludes that, for the technological integration and improvements for project processes, the internal dynamics of the companies are substantial. Similarly, the model showed that technologies could be insufficient to respond to extreme external changes. In this regard, RFID was also found to be effective, especially in terms of increasing the productivity of resources and creating value by integration with other technologies.

After simulating each strategy of the case company, it was observed the experts indicated that the system modelling enhances decision-making for digitalization goals and its impact on existing project managerial actions.

8.1 Practical Implications

This research expects to contribute to practical applications by enhancing the strategic planning and decision-making of projects in terms of digitalization. Firstly, after simulating the model, it was asked the company experts about their opinion throughout the conceptualization, model development and scenario testing phases.

The experts indicated that the model enables them to think about the causalities and feedback between the decisions and their consequences for technology integration. Moreover, the model provides the computerization of different project management dynamics, which technologies can be integrated into them. The technology integration both compensates for the drawbacks of management actions and creates additional value, which can be simulated under different conditions.

As another important aspect of system dynamics modelling, scenario testing provides different benefits such as creating what-if scenarios under different internal and external uncertainties, observing the response of the entire system for each decision, and evaluating different strategic options with the perspective of "continuous improvement". Hence the modelling sessions facilitate the group decision-making for the digital technology integration. In addition, since the prepared model simplifies a complex project environment as a system, it enables the results of strategies to be observed directly.

Moreover, the presented model has a generic structure that can be used by companies with a similar project flow. Due to the fact that the model involves general strategic parameters such as internal capabilities, external uncertainties, and maturity levels of different technologies that can be used for different projects and companies. Besides, the simulation of the model reveals different outputs for project-level objectives such as productivity, time, cost, and quality, which may be beneficial for other companies' strategic analyses as well. It should be noted that, within the scope of this study, the developed system model focused on project-level technology integration and process improvement. Hence, the model should be used with other case applications by considering this aspect of the research.

The following steps may be followed for other case companies to use the developed system dynamics model. Firstly, with an initial session with a company, the strategic positioning and goals for digitalization can be understood as stated in Chapter 4. Then, according to the strategic goal, the developed causal loop diagrams may be

reconsidered, and feedback loops can be discussed with the experts to improve the brainstorming.

Noting that, the project flow and integrated technologies of the SD model develop considering the modular construction companies. Nevertheless, for other practical applications, the system parameters may be re-evaluated (e.g., the production process can be changed, and other technologies may be considered for different strategic goals).

After that, the computerized model parameters may be reviewed to make it suitable for the company and necessary changes can be done according to the opinions of the experts. Moreover, the experts can evaluate the external uncertainties (e.g., change orders), internal capabilities (e.g., competency of the technology team, resource levels), managerial actions for each process (e.g., overtime for design) and as-is level of technologies (e.g., level of interoperability). Finally, the model can be simulated, and the results can be discussed with the experts for strategic analysis.

According to these steps, the methodology and developed model of this research can be used by a similar company to make a contribution to their project processes with digital technologies. Consequently, the research proposed a holistic picture of the dynamics of the project environment and impacts of scenarios, as digitalization goals, which support strategic decision-making for sectoral partners.

8.2 Limitations and Further Studies

As in every system development research, there are some limitations that can be further investigated in future work. Firstly, as also stated in the validation section, it is not possible to completely validate the system dynamics models since it only considers the "part" of the system and environment. However, it can be stated that the developed model reflects the dynamics with reasonable logic and the model's structure and assumptions meet the purpose.

As a limitation, the validation test number can be increased, and operational validity can also be tested in future research. Moreover, from Stella software, interfaces can be created for inputs, which can be used as a decision-making tool by different users easily.

As another limitation, although the background and experience of the experts contributed to the research a lot, the number of participants can be increased in the company to collect more opinions and reflected into the model as different strategic goals.

Moreover, this research developed a model for the project-level benefits of technologies to take the initial steps for company-based analysis. In future studies, different technologies (e.g., blockchain, robotics) and processes (e.g., outbound logistics) can be integrated into the model by involving the learning and growth of the company for the strategic decision-making of digitalization. For that, other objectives may also be considered at a company level, such as financial and social aspects of technologies.

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APPENDIX

		Model Equations and Values for Baseline Testing	Units
Technology Ratings	Level of detail in object-based models	4	1-5
	Level of integration of time and cost data into the models	2	1-5
	Level of interoperability	3	1-5
	Level of integration of processes and models (Integration of interfaces)	2	1-5
	Competency of technology team (design team)	4	1-5
	RFID	N	Yes or No
	ERP	2	1-3
Design Sector	Actual design completion time	IF (Design time required>0) THEN (TIME)+Design time required ELSE PREVIOUS (SELF, 1)	Week
	Actual design errors ratio	IF (Automation of design) =1 THEN 0 ELSE IF Automation of design>=0.6 THEN Initial design error ratio*0.8*Effect of schedule pressure on design errors ELSE Initial design error ratio*Effect of schedule pressure on design errors	Dimensionless
	Actual design productivity	Design efficiency*Planned designer productivity*"Overtime (D)"	Buildings/Week/ Team
	Automation of design	0.56	Dimensionless
	Change orders	IF((TIME)=Time of change orders) THEN INIT (Design work) *(Design change percentage)/DT ELSE 0	Buildings/Week
	Design change percentage	0.15	Dimensionless
	Design completion rate	Design team*Actual design productivity*(1-Actual design errors ratio)	Buildings/Week
	Design efficiency	IF (Automation of design>=0.6 AND Automation of design<1) THEN 1.20*Fatigue ELSE IF Automation of design=1 THEN 1.5*Fatigue ELSE Fatigue	Dimensionless
	Design error generation	Actual design errors ratio*Design team*Actual design productivity	Buildings/Week

	Design errors(t)	Design errors (t - dt) + (Design error generation - Design rework) * dt INIT Design errors=0	Buildings
	Design rework	IF (Design work>1) THEN Design errors/Design rework discovery time ELSE Design errors/DT	Buildings/Week
	Design rework discovery time	Design rework discovery time= IF (Model-based Collaboration)>0.6 THEN Initial Rework Discovery Time*0.75, ELSE IF Model-based Collaboration=1 THEN 1 ELSE Initial Discovery Time=2	Week
	Design team	1	Team
	Design time required	IF (Remaining design work)>0 THEN Remaining design work/(Planned designer productivity*Design efficiency*Design team) ELSE 0	Week
	Design work(t)	Design work (t - dt) + (Change orders + Design rework - Design completion rate - Design error generation) * dt INIT Design work=4	Buildings
	Effect of schedule pressure on design errors	GRAPH ("Schedule pressure (D)") Points: (1.000, 1.000), (1.100, 1.000), (1.200, 1.000), (1.300, 1.000), (1.400, 1.150), (1.500, 1.200), (1.600, 1.250), (1.700, 1.300), (1.800, 1.350), (1.900, 1.400), (2.000, 1.500)	Dimensionless
	Fatigue	GRAPH (DELAY ("Overtime (D)", 1, 1)) Points: (1.0000, 1.000), (1.1000, 0.980), (1.2000, 0.900), (1.3000, 0.850), (1.4000, 0.830), (1.5000, 0.800)	Dimensionless
	Finished design(t)	Finished design (t - dt) + (Design completion rate) * dt INIT Finished design=0	Buildings
	Initial design error ratio	0.3	Dimensionless
	Initial design work	4	Buildings
	"Model-based Collaboration"	0.6	Dimensionless
	"Overtime (D)"	GRAPH ("Schedule pressure (D)") Points: (1.000, 1.0000), (1.200, 1.1000), (1.400, 1.3200), (1.600, 1.4300), (1.800, 1.4800), (2.000, 1.5000)	Dimensionless
	Planned design duration	3	Week
	Planned designer productivity	1.3	(Buildings/Week)/ Team
	Remaining design work	Total design work-Finished design	Buildings
	"Schedule pressure (D)"	IF (Actual design completion time>0) AND (Effectiveness of project management>=0.5) THEN (Actual design completion time/Planned design duration) *0.5 ELSE (Actual design completion time/Planned design duration)	Dimensionless
	Time of change orders	2	Week

	Total design work	Initial design work+ STEP ((Initial design work*Design change percentage), Time of change orders)	Buildings
Supply Sector	Accuracy of material quantities	IF (ERP in projects=3) THEN 1 ELSE IF (ERP in projects=2) THEN 0.7 ELSE 0.4	Dimensionless
	Actual supply completion time	IF (Desired material inventory>Material inventory) AND Supply rate>0 THEN TIME+ ((Desired material inventory-Material inventory)/Supply rate) ELSE PREVIOUS (SELF, 1)	Week
	Demand increase time	7	Week
	Desired material inventory	Total production work*Raw material per unit	Tonnes
	ERP in projects	2	Dimensionless
	Inventory gap	IF (TIME=Demand increase time) AND (Desired material inventory-Planned material supply>0) THEN Desired material inventory-Planned material supply ELSE 0	Tonnes
	Material inventory(t)	Material inventory (t - dt) + (Supply rate) * dt INIT Material Inventory=0	Tonnes
	Missing material	IF (RFID=1) THEN 0.15 ELSE 0.30	Dimensionless
	Order Contingency	IF (Accuracy of material quantities>=0.7) AND Accuracy of material quantities<1 THEN 0.15 ELSE IF (Accuracy of material quantities=1) THEN 0.1 ELSE 0.30	Dimensionless
	Order increase	DELAY (Inventory gap/DT, Time to adjust order)	Tonnes/Week
	Order rate	Design completion rate*Raw material per unit*(1+Order Contingency) *Units per Building	Tonnes/Week
	Orders (t)	Orders (t - dt) + (Order rate + Order increase - Supply rate) * dt INIT Orders=0	Tonnes
	Planned material supply	Raw material per unit*Units per Building*(1+Order Contingency) *(Total design work)	Tonnes
	Raw material per unit	2.8	Tonnes/Units
	RFID	0	Dimensionless
	Supply duration	5	Week
	Supply rate	(Planned material supply*(1-Missing material))/Supply duration	Tonnes/Week
	Time to adjust order	IF (Accuracy of material quantities=1) THEN 0.5 ELSE IF (Accuracy of material quantities>=0.7) THEN 1 ELSE 2	Week
	Units per Building	250	Units/Buildings

Production Sector	"Max. production capacity"	130	Units/Week
	Actual production completion time	IF (Production time required>0) THEN (TIME)+Production time required ELSE PREVIOUS (SELF, 1)	Week
	Actual production error ratio	IF ("Network-based integration”) =1 THEN 0.05 ELSE IF "Network-based integration">= 0.6 THEN Initial production errors*0.4*Effect of schedule pressure on production errors ELSE Initial production errors*Effect of schedule pressure on production errors	Dimensionless
	Actual productivity	Planned resource productivity*Production efficiency	Units/Week/ Resource
	Crowding effect on productivity	GRAPH ("Resources (P)"/"Upper limit of resource (P)") Points: (0.000, 1.000), (0.500, 1.000), (0.700, 0.990), (0.900, 0.980), (1.000, 0.960), (1.200, 0.920), (1.500, 0.900), (2.000, 0.880)	Dimensionless
	Demand increase percentage	0.3	Dimensionless
	Effect of schedule pressure on production errors	GRAPH ("Schedule pressure (P)") Points: (1.000, 1.000), (1.100, 1.000), (1.200, 1.100), (1.300, 1.120), (1.400, 1.140), (1.500, 1.150), (1.600, 1.200), (1.700, 1.350), (1.800, 1.450), (1.900, 1.480), (2.000, 1.500)	Dimensionless
	Finished products(t)	Finished products (t - dt) + (Product completion rate) * dt INIT Finished products = 0	Units
	Initial production errors	0.2	Dimensionless
	Initial production work	1000	Units
	"Network-based integration"	0.4	Dimensionless
	Planned production duration	12	Week
	Planned resource productivity	1	Units/Week/ Resource
	Product completion rate	IF ((Actual productivity*"Resources (P)"*(1-Actual production error ratio))>="Max. production capacity") THEN "Max. production capacity" ELSE (Actual productivity*"Resources (P)"*(1-Actual production error ratio))	Units/Week
	Production efficiency	IF (RFID=1) THEN 1.5*Production modelling*Crowding effect on productivity ELSE Production modelling*Crowding effect on productivity	Dimensionless
	Production error generation	(Actual production error ratio) *"Resources (P)"*Actual productivity	Units/Week
	Production errors(t)	Production errors (t - dt) + (Production error generation - Production rework) * dt INIT Production errors=0	Units
	Production inventory(t)	Production inventory (t - dt) + (Production rework + Supplied work rate - Product completion rate - Production error generation) * dt	Units

		INIT Production inventory = 0	
	Production modelling	IF ("Model-based Collaboration">0.6) AND ("Model-based Collaboration"<1) THEN 1.25 ELSE IF "Model-based Collaboration"=1 THEN 1.5 ELSE 1	Dimensionless
	Production rework	IF (Production inventory<1) THEN Production errors/DT ELSE Production errors/Production rework discovery time	Units/Week
	Production rework discovery time	GRAPH (IF (RFID=1) THEN 1 ELSE "Ratio of completed tasks (P)") Points: (0.000, 2.000), (0.200, 1.700), (0.400, 1.400), (0.600, 1.300), (0.800, 1.150), (1.000, 1.000)	Week
	Production time required	IF (Remaining products)>1 AND "Resources (P)">0 THEN Remaining products/Actual productivity/"Resources (P)" ELSE 0	Week
	Production work(t)	Production work (t - dt) + (Production work increase - Supplied work rate) * dt INIT Production work=1000	Units
	Production work increase	IF((TIME+1) =Demand increase time) THEN (INIT(Production work)*(Demand increase percentage))/DT+(Change orders*Units per Building) ELSE (Change orders*Units per Building)	Units/Week
	"Ratio of completed tasks (P)"	Finished products/Total production work	Dimensionless
	Remaining products	IF (Total production work-Finished products) <1 THEN 0 ELSE Total production work-Finished products	Units
	Remaining time for planned production	IF (Planned production duration-(TIME))>0 THEN Planned production duration-(TIME) ELSE 1	Week
	"Required resources (P)"	Remaining products/Remaining time for planned production/Actual productivity	Resource
	Resource adjustment time	1	Week
	"Resource change (P)"	"Resource gap (P)"/Resource adjustment time	Resource/Week
	"Resource gap (P)"	IF (TIME<=2) THEN 0 ELSE IF ("Required resources (P)">="Upper limit of resource (P)") THEN "Upper limit of resource (P)"-"Resources (P)" ELSE "Required resources (P)"-"Resources (P)"	Resource
	"Resources (P)"(t)	"Resources (P)"(t - dt) + ("Resource change (P)") * dt INIT Resources=80	Resource
	"Schedule pressure (P)"	IF (ERP in projects>2) THEN (Actual production completion time/Planned production duration) *0.6 ELSE Actual production completion time/Planned production duration	Dimensionless
	Supplied work rate	IF (TIME> (Demand increase time)) AND Supply rate=0 THEN Production work/DT ELSE DELAY (Supply rate/Raw material per unit, 2, 0)	Units/Week

	Total production work	Total design work*Units per Building + STEP (Initial production work*Demand increase percentage, Demand increase time)	Units
	"Upper limit of resource (P)"	140	Resource
Construction Sector	Actual construction completion time	IF (Construction time required>0) THEN (TIME)+Construction time required ELSE PREVIOUS (SELF, 1)	Weeks
	Actual construction errors ratio	IF ("Network-based integration”) =1 THEN 0.05 ELSE IF "Network-based integration">=0.6 THEN Initial construction error*0.4*Effects of schedule pressure on construction errors ELSE Initial construction error*Effects of schedule pressure on construction errors	Dimensionless
	Actual construction productivity	Planned construction resource productivity*Construction efficiency	Units/Weeks/ Resource
	Communication on site	IF ("Model-based Collaboration")>=0.8 THEN 1.5 ELSE 1	Dimensionless
	Construction completion rate	"Resources (C)"*(1-Actual construction errors ratio) *Actual construction productivity*"Overtime (C)"	Units/Weeks
	Construction efficiency	Health& Safety management*Communication on site*"Fatigue (C)"*Crowding effect on construction	Dimensionless
	Construction error generation	Actual construction errors ratio*Actual construction productivity*"Resources (C)"	Units/Weeks
	Construction errors(t)	Construction errors (t - dt) + (Construction error generation - Construction rework) * dt INIT Construction errors = 0	Units
	Construction rework	IF (Construction work<1) THEN Construction errors/DT ELSE Construction errors/Construction rework discovery time	Units/Weeks
	Construction rework discovery time	GRAPH(IF(RFID=1) THEN 1 ELSE Ratio of completed task) Points: (0.000, 2.000), (0.200, 1.800), (0.400, 1.500), (0.600, 1.200), (0.800, 1.100), (1.000, 1.000)	Weeks
	Construction time required	IF (Remaining construction work)>0 AND "Resources (C)">0 THEN Remaining construction work/ (Actual construction productivity*"Resources (C)") ELSE 0	Weeks
	Construction work(t)	Construction work (t - dt) + (Construction rework - Construction completion rate - Construction error generation) * dt INIT Construction work = 1450	Units
	Crowding effect on construction	GRAPH ("Resources (C)"/"Upper limit of resources (C)") Points: (0.500, 1.000), (1.000, 1.000), (1.100, 0.980), (1.200, 0.960), (1.400, 0.950), (1.600, 0.940), (1.800, 0.900), (2.000, 0.880)	Dimensionless
	Effectiveness of project management	0.6	Dimensionless

	Effects of schedule pressure on construction errors	GRAPH ("Schedule pressure (C)") Points: (1.000, 1.000), (1.100, 1.000), (1.200, 1.100), (1.300, 1.120), (1.400, 1.140), (1.500, 1.150), (1.600, 1.200), (1.700, 1.350), (1.800, 1.450), (1.900, 1.480), (2.000, 1.500)	Dimensionless
	"Fatigue (C)"	GRAPH (DELAY ("Overtime (C)", 1, 1)) Points: (1.0000, 1.0000), (1.1000, 0.9000), (1.2000, 0.8500), (1.3000, 0.8000), (1.4000, 0.6500), (1.5000, 0.5000)	Dimensionless
	Finished construction(t)	Finished construction (t - dt) + (Construction completion rate) * dt INIT Finished construction = 0	Units
	Health &Safety management	IF ("Non-ERP Tools") =0 THEN 1 ELSE 1.4	Dimensionless
	Initial construction error	0.1	Dimensionless
	"Non-ERP Tools"	0	Dimensionless
	"Overtime (C)"	GRAPH ("Schedule pressure (C)") Points: (1.000, 1.1000), (1.200, 1.1000), (1.400, 1.3000), (1.600, 1.4000), (1.800, 1.5000), (2.000, 1.5000)	Dimensionless
	Planned construction duration	8	Weeks
	Planned construction resource productivity	5	Units/Weeks/ Resource
	Ratio of completed task	Finished construction/Total units	Dimensionless
	Remaining construction work	Total units-Finished construction	Units
	Remaining time for planned construction	IF (Planned construction duration-(TIME))>0 THEN Planned construction duration-(TIME) ELSE 0	Weeks
	"Required resources (C)"	IF (Remaining time for planned construction>0) THEN (Remaining construction work/Remaining time for planned construction/Actual construction productivity) ELSE 0	Resource
	"Resource change (C)"	"Resource gap (C)"/Resource adjustment time	Resource/Weeks
	"Resource gap (C)"	"Required resources (C)"- ("Resources (C)")	Resource
	"Resources (C)"(t)	"Resources (C)"(t - dt) + ("Resource change (C)") * dt INIT "Resources (C)" = 30	Resource
	"Schedule pressure (C)"	IF (Actual construction completion time>0) AND (Effectiveness of project management>=0.5) THEN (Actual construction completion time/Planned construction duration) *0.5 ELSE (Actual construction completion time/Planned construction duration)	Dimensionless
	Total units	1450	Units
	"Upper limit of resources (C)"	40	Resource

Time Sector	Actual project duration	Actual_design_completion_time+Actual_production_completion_time+Actual_construction_completion_time	Weeks
	Planned project duration	25	Week
	Uncompensable delays	Actual_project_duration-Planned_project_duration-(Actual_design_completion_time-Planned_design_duration)	Week
Cost Sector	Construction resource cost	IF ("Overtime (C)">1) THEN "Resources (C)"*Labour unit cost percentage*"Overtime (C)"*Overtime unit cost ELSE "Resources (C)"*Construction resource unit cost percentage	%/Week
	Design resource cost	IF (TIME<=Planned design duration) AND "Overtime (D)">1 THEN Design team*Design unit cost percentage*"Overtime (D)"*Overtime unit cost ELSE IF (TIME<=Planned design duration) THEN Design team*Design unit cost percentage ELSE 0	%/Week
	Design unit cost percentage	1.67	%/Team/Week
	Indirect cost	0.6	%/Week
	Production resource unit cost percentage	0.020833	%/Resource/Week
	Construction resource unit cost percentage	0.03125	%/Resource/Week
	Material unit cost percentage	0.01552	%/Tonnes
	Overtime unit cost	1.2	Dimensionless
	Production resource cost	IF (TIME<=2) THEN 0 ELSE Production resource unit cost percentage*"Resources (P)"	%/Week
	Project cost	Total material cost+ Total resource cost+(Actual project duration*Indirect cost)+(Uncompensable delays*Uncompensable delay cost percentage)	%
	Total material cost	Material inventory*Material unit cost percentage	%
	Total resource cost(t)	Total resource cost (t - dt) + (Construction resource cost + Design resource cost + Production resource cost) * dt INIT Total resource cost = 0	%
	Uncompensable delay cost percentage	1.25	%/Week