Integrating the construction project process with the supply chain: Exploring disruptive and incremental solutions

Müge Tetik
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Abstract

Construction industry is characterized by low performance and generically different multiple problems, on-site issues and project process related problems. Construction product is mostly an engineer-to-order product, where the focus of project actors is usually shortsighted; the whole lifecycle of a building is not considered by the most actors. The industry’s productivity is suffering from poor integration of the project process and the supply chain.

Intricate problems have been ongoing, degrading the productivity of construction operations such as material flow issues, delays, improvisations and lack of coordination. The motivation of this study is to find out how the problems encountered in different phases of project process, productivity and coordination issues could be relieved by a better integration of supply chain and project process. To tackle this, two approaches were investigated as disruptive and incremental practices. Multiple partial and complete case studies were conducted to understand the current best practices, present potential solutions, evaluation and testing. Design science was used for solution development. Comparative case studies, scenario analysis and design theory were utilized.

One disruptive solution developed during this work is Direct Digital Construction (DDC); an operations management practice aiming at directing all value-adding operations over a building's lifecycle via a complete digital design model, tackling improvisation and reuse challenges. Another disruptive solution is 3D concrete printing (3DCP). Findings suggest that 3DCP is competitive on cost and completion time to conventional techniques. The incremental practices include material kitting and logistics maturity model. Proper logistics improve construction project performance.

Findings inform managers on design-based control of construction operations. Improving construction projects’ productivity via direct digital control of the operations is possible with complete design model. The dissertation raises awareness on potentials of 3DCP in construction.

For construction and logistics practitioners, the research provides deep insights on how to implement specific solutions. The impacts of material kitting on on-site production were explored. Labor productivity is improved for certain tasks with kitting. Companies can navigate through logistics maturity model to gradually improve their practices.

Change will probably not come to the construction industry overnight. While it is possible for a practice to disrupt the supply chain and project process operations, in the meantime, incremental practices improve the current situation to advance operations performance. The industry’s adaptation of proposed solutions requires increased effort from individual organizations and existing company networks for overcoming shortsightedness and recognizing the long-term benefits.

Keywords Construction operations management, construction supply chain, construction logistics, construction project process
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Contents

1. Introduction ............................................................................................. 1
  1.1 Research context and practical motivation ................................ 1
  1.2 Research objectives ...................................................................... 4
  1.3 Methodology and philosophical assumptions ............................ 5
  1.4 Contribution ................................................................................. 6
  1.5 Thesis structure ............................................................................ 8

2. Theoretical foundation .................................................................... 9
  2.1 Defining the key concepts ............................................................ 9
  2.2 Construction supply chain and project process problems ...... 10
  2.3 Efforts to integrate the construction project process with the supply chain ............................................................. 12
    2.3.1 Technological practices for integrating construction project processes with supply chains............................................. 13
    2.3.2 Management practices aimed at integrating the construction project process with the supply chain .................................................. 16
  2.4 Summary of the theoretical background .................................. 19
    2.4.1 The gap in existing knowledge .................................................. 20

3. Method ............................................................................................ 21
  3.1 Design science research ............................................................. 23
  3.2 Case study research .................................................................... 24
  3.3 Data collection............................................................................... 25
  3.4 Data analysis................................................................................. 27

4. Results ............................................................................................ 30
  4.1 Disruptive approach – Direct digital construction ............... 30
    4.1.1 Case 1: As-built modeling contractor ........................................ 31
    4.1.2 Case 2: The school developer .................................................... 31
    4.1.3 Partial case examples ................................................................. 32
    4.1.4 Direct digital construction ......................................................... 35
    4.1.5 Alternative paths of implementation for DDC ......................... 37
4.2 Incremental approach – Material kitting......................... 40
4.3 Disruptive approach – 3D concrete printing..................... 44
4.4 Incremental approach – Logistics maturity model.............. 46
4.4.1 The construction logistics maturity model ..................... 49
4.4.2 Case 1: Large developer .............................................. 52
4.4.3 Case 2: Medium-sized contractor .............................. 53
4.4.4 Case 3: Large Nordic contractor ................................. 54
4.4.5 Answering the guiding questions ................................. 55
5. Discussion ............................................................................. 57
5.1 Theoretical contributions ................................................. 58
5.2 Managerial implications ................................................. 60
5.3 Limitations ....................................................................... 63
5.4 Future research ............................................................... 64
References .............................................................................. 67
List of Abbreviations and Symbols

3DCP 3D concrete printing
AEC Architecture, engineering, and construction
AM Additive manufacturing
BIM Building information modeling
BOM Bill of materials
BOQ Bill of quantities
CPS Cyber-physical systems
DDC Direct digital construction
DDM Direct digital manufacturing
DT Digital twin
h hours
IC Industrialized construction
JIT Just in time
LOD Level of detail
SC Supply chain
SCM Supply chain management
TPL Third-party logistics
VDC Virtual design and construction
VMI Vendor-managed inventory
This doctoral dissertation consists of a summary and of the following publications, which are referred to in the text by their numerals.


Author’s Contributions


This paper develops an operations management practice to direct value-adding operations over the building’s life cycle through the digital design model, leading to decreased human interpretation and improvisation, increased reusability, and automation of designs and processes across projects. The data for one case study were collected by one of the co-authors. The paper was written by the author and reviewed by the co-authors.

Publication 2: Kitting logistics solution for improving on-site work performance in construction projects

The paper is a case study analyzing a material kitting intervention in a general contractor and logistics service provider, comparing four renovation projects in the indoor construction phase with and without the solution. The author’s contribution was to gather half the case study data, conduct all the data analysis, and carry out the scientific writing and editing. The paper was reviewed by the supervisor and advisors.

Publication 3: Additive manufacturing in the construction industry: The comparative competitiveness of 3D concrete printing

The paper investigates the application of 3D concrete printing in the construction industry by a cost and schedule analysis of two different house designs and comparing that approach to traditional construction methods. The data collection and analysis were jointly conducted with author Khajavi. The author wrote the following sections: part of the introduction, theoretical background, research gap, part of the methodology section, part of the discussion, and the conclusion. The author also conducted the cost and schedule analysis of conventional construction methods and reviewed the rest of the sections.

Publication 4: Defining the maturity levels for implementing industrial logistics practices in the construction industry.

The paper develops a maturity model for construction logistics to serve as a roadmap for construction companies to develop their logistics-related capabilities. The author did all the data collection and analysis, developed the model, and wrote the paper. The paper was reviewed by the co-authors.
1. Introduction

1.1 Research context and practical motivation

Construction is characterized as one-of-a-kind manufacturing using temporary project organizations (Koskela 2000). The construction industry has a fragmented structure, and actors involved in projects often have conflicts of interest (Dave et al. 2008). Construction usually produces an engineer-to-order product, with the focus of project actors typically shortsighted, and the building’s entire life cycle not considered by most project participants.

Like these characteristics, the challenges the industry faces are highly specific and require sophisticated approaches for solution development. The construction industry is lagging behind other sectors in terms of productivity (Tran and Tookey 2011). Only about half of working time directly adds value, with supportive work coming in at around 34% (Kalsaas 2010). In one case study, workers were present in the workplace only 25–36% of the time (Zhao et al. 2019a). The main direct reasons for the low productivity in the construction industry include absence of materials, insufficient supervision, a lack of proper tools and equipment, and incomplete design and specifications (Hasan et al. 2018). Inefficient management practices lead to lengthened schedules, increased costs, and decreased quality (Cox and Ireland 2002).

Problems in projects can be approached from multiple directions, one of which is the supply chain (SC) perspective. The construction SC comprises all the activities regarding producing an end product from raw materials. Problems encountered on-site are usually due to a lack of appropriate SC orientation (Thunberg et al. 2017), which is defined as a shared value system that helps understand how a company should strategically manage its SCs (Esper et al. 2010) and has implications for tactics used in managing various flows in SCs (Mentzer et al. 2001). Problems related to a lack of SC orientation involve improper development of schedules and plans disregarding material flows (Thunberg et al. 2017; Thunberg and Fredriksson 2018) and other material flow issues (Bankvall et al. 2010).

Problems related to material flows comprise a great deal of the obstacles encountered on-site. Only around 40% of material deliveries are made to the correct location at the designated time (Thunberg and Persson 2014). Variabilities in material supply and demand directly affect project performance, decreasing
quality and safety and increasing cost and project duration (Arbulu and Ballard 2004). To prevent a lack of material on-site, costly intermediate storage is often used (Dallasega et al. 2016). Large material buffers lead to congested areas on the job site (Elbeltagi et al. 2004), where materials can prevent workers from moving or unloading in its limited spaces (Levaniemi 2018), and labor wasted in time spent looking for materials (Arbulu and Ballard 2004); both of these challenges result in delays. The most frequent causes of construction project delays arise from issues related to management and the project environment (Abdullah and Koskela 2008). These problems also lead to other problems; a delay in one operation can cause subsequent operations to be delayed, creating a vicious circle. Project overruns increase project costs. According to one study (Assaf and Al-Hejji 2006), only 30% of construction projects are completed on time.

The construction project process is used to undertake project activities such as needs assessment, conceptual planning, building design, detailed design, procurement, production planning, construction, and handover. The value and all relevant information for planning and management of SCs are delivered to SC partners through this process. From the construction project process perspective, the typical problems are on-site emergencies that are dealt with by improvised solutions (Bankvall et al. 2010), a lack of communication (Demirkesen et al. 2019), project uncertainties (Dubois and Gadde 2002), and technological problems (Thunberg et al. 2017). Large amounts of construction waste are due to design changes, procurement errors, and mistakes in design and detailing (Faniran and Caban 1998), all of which cost time to fix. Since the construction product—a building—is highly complex and consists of multiple sub-systems, the project process is highly fragmented.

There are also productivity and coordination problems that stem from the poor integration of SC operations and the process of a given project. Client representatives and project managers often integrate activities into the project process but do not integrate them with the SC. This task is typically delegated to sub-contractors who are responsible for purchasing and ordering specific materials and products and installing them on the job site. The responsibility for integration of the project process and the SC is usually delegated to these subcontractors. Typically, the materials are ordered and handled by the individual subcontractors. Subcontracting practices increase the fragmentation of the construction production process (Dainty et al. 2001), with projects regarded as a set of isolated operations in which the project actors do not assign enough importance to the long-term success of the building (Briscoe and Dainty 2005). Construction tasks are loosely coupled with one another, hampering the performance of projects (Wegelius-Lehtonen 2001). The design phase and the construction of the built object are kept separate (Vrijhoef and Koskela 2000). Thus, it is essential to better integrate the construction SC with the construction project process, because such integration could significantly improve performance, reduce waste, and lower costs along the entire SC (Papadopoulos et al. 2016).
Innovations that improve an industry are either incremental or disruptive. At this point, it is necessary to differentiate between disruptive, incremental and radical innovations. Radical innovations can become disruptive in the future. Not all the radical innovations are disruptive (Dan and Chieh 2008). Technological discontinuities do not always have a disruptive impact on the industry (Ehrenberg 1995). Disruptive technology can be a facilitator for an innovation if it is successfully embedded in a business model. In this study, the term “disruptive” is used, representing the changes in the activities of an organization leading to a large departure from existing practices (Leifer et al. 2001). Construction industry ecosystem includes multiple organizations. With disruptions the business model and the roles of the multiple players in the construction ecosystem would change.

Incremental innovations are those made within an existing frame of solutions; namely, “doing better with what we already do,” whereas disruptive innovation demands or creates a change of frame: “doing what we did not do before” (Norman and Verganti 2014). However, radical innovations are illusionary because the learning process is always incremental (Lindblom 1959). In the incremental phase, practices are developed over time. Lewis et al. (2001) refer to this phase as the period of consolidation phase development, with its series of sustaining incremental improvements moving toward maturity. Acquiring knowledge is more effective for incremental innovation than for disruptive innovation (Ritala and Hurmelinna-Laukkonen 2013). Thus, during the incremental phase, knowledge is accumulated, and insights build linearly on previous insights (Wheelwright and Clark 1992).

The disruptive moment occurs when the benefits are pulled together from the incremental phase. Figure 1 shows this framework, in which the two phases take place in sequence, which is also the framework used in this research. The development of capabilities is cyclical, namely companies would encourage radical innovation attempts first, followed by periods of incremental innovation performance (Burgelman 2002). Disruptive innovations are not a single discrete event; they are dynamic and ongoing processes (Ringberg et al. 2019). The process of disruptive innovation consists of searching and selecting, exploring, and experimenting (Assink 2006). When a certain competence level is achieved by a company or industry, the transformation of research and development effort is more efficient (Hacklin et al. 2004). This thesis investigates these successive phases of incremental and disruptive practices that can help solve construction industry performance issues.

![Figure 1. Conceptual framework of the study.](image)

In summary, the overall motivation of this study is to find out how multiple generically different problems encountered in different phases of construction project processes and productivity and coordination problems on-site could be relieved by a better integration of the construction SC and the project process.
That process and the SC are intimately connected to and affect each other (Thunberg et al. 2017). A particular SC practice can generate a better operational performance than another for a given product design (Pero et al. 2010). Hence, better efforts are required to integrate the construction SC with the construction project process to improve overall project performance. To tackle this, two approaches can be taken: incremental practices to improve the current situation by better aligning the SC with the project process, or disruptive practices in which the new integrated solution would replace the existing project process and SCs. The innovation literature suggests that a disruptive technology is at first new to the world and slowly brings performance gains that are then followed by more efficient performance gains when a certain level of competence is achieved by an industry (Hacklin et al. 2004; Raurich 2004). Thus, to obtain a more comprehensive solution, this thesis investigates these two approaches as solutions to the persistent challenge of low construction industry performance.

1.2 Research objectives

In this thesis, the integration problem of construction project processes and SCs are investigated, and possible solutions are proposed. The work aims at identifying ways to improve construction performance by developing practices to integrate the construction project process and SC through both disruptive and incremental approaches.

This section of the study specifies the research focus areas and related research questions. The thesis focuses, in part, on disruptive operations management practices in integrating construction SCs and project processes. The research question investigated in this regard is:

I. What are the disruptive practices that successfully align the construction supply chain with the construction project process?

More specifically, solutions in the following two areas are investigated: the first involves developing a comprehensive operations management practice in which value-adding SC operations are directed based on the digital design model created at an early phase of the project process. The second involves analyzing new production technologies—namely, additive manufacturing (AM)—and their impacts and opportunities to disrupt current construction practices and integrate the SC with the project process.

The second focal area of this thesis is the incremental practices used in construction operations. For instance, logistics operations are used as supporting activities in the construction project process. Thus, it is relevant to examine the role of logistics activities in integrating construction project processes with construction SCs, and the second research question is:

II. What are the incremental practices that successfully align the construction supply chain with the construction project process?

This part investigates specific logistics solution combinations and their effects, along with the impacts of logistics capabilities. It provides a roadmap for
companies aiming to improve their performance through logistics capabilities that are based on the integration of the SC with the construction project process.

1.3 Methodology and philosophical assumptions

Epistemology is the philosophical study of knowledge, answering the question of how to know (a phenomenon). The synthesis of new knowledge created in this study includes dialectical thinking. Synthesis involves integrating opposite aspects through a dynamic process of dialogue and practice (Nonaka and Toyama 2015), as it comprises the interactions among individuals, organizations, and the environment (Nonaka and Toyama 2002) and the dialogical relationships among theory, observation, and the situation on the ground (Pikas 2019). In this study, two pragmatically different approaches are taken to reach the end goal. Integrating the construction project process with the SC through two different approaches has been chosen. One improves the existing SC structure, while the other proposes using a production process that is substantially different from conventional construction. While these two approaches may appear to be separate, they are positioned on the same path (see Figure 1); in other words, with this approach, one actor can develop its operations using both approaches in the development life cycle.

Design means the conscious and justified shaping of our environment in ways that satisfy our needs and bring meaning to our lives (Heskett 2002). Design science is a problem-solving paradigm (Hevner and Chatterjee 2010). In this study, the following two parts of design science research (Peffers et al. 2007) have been used: 1) solution development and 2) solution evaluation and testing.

Design theory (Gregor and Jones 2007) has frequently been used for solution development. Design theories comprise knowledge of a practical character (Goldkuhl 2004). Thus, in this study, design theory is used to solve a real-life problem faced by practitioners in the industry. In this way, knowledge is generated through attempts to understand the impacts of the interaction between an artifact and a problem domain in particular cases (Wieringa 2010). Unlike the natural sciences, organizational problems require novel, creative, and innovative solutions which can be more effectively addressed through a paradigm shift (Hevner and Chatterjee 2010). This methodology is suitable for developing new knowledge in the form of disruptive practices to integrate the construction project process and the SC. This study combines knowledge created through both theory and practice. A detailed description of how the methods were selected is provided in the Method chapter.

The solution evaluation and testing portion of this study was conducted through empirical case studies. Disruptive and incremental practices used in the construction industry and aimed at integrating construction project processes and SCs were studied through partial and complete industry case examples. In the multiple case study approach, cases are systematically compared with each other to reframe a new theoretical vision (Eisenhardt 1989). Furthermore, cause-and-effect relationships (i.e., the induction of explanatory hypotheses) are used (Niiniluoto 1999) by inducing explanatory principles from observations in the case studies (Losee 2001), which can be applied in the future to
similar problems. In the case studies in the publications, both constructivist qualitative and positivistic quantitative methodological approaches are used. A qualitative methodology provides an understanding of a social phenomenon within its context (Van Maanen 1979), whereas quantitative approaches are deeply rooted in our daily lives and used to systematically analyze basic social phenomena, using methodological rules and complex patterns of standards (Scholl 2008). Qualitative approaches are interpretive techniques that help arbitrate the meaning of a certain phenomenon in the social world (Van Maanen 1979) and have been used intensively in this research. However, a quantitative methodology has also been employed where appropriate. Quantitative methodologies include methods involving systematic investigation of a social phenomenon by using statistical or numerical data (Watson 2015). The quantitative approach was used in this research to understand the impacts of certain solution approaches on construction performance, with several examples compared in the case studies.

1.4 Contribution

The overall contribution of this thesis is identifying successful ways to integrate the construction project process with the SC through different approaches and investigating their impacts on performance. The contribution is presented in four publications that focus on different elements that together capture the overall theme of the thesis through their own approaches. This study investigates both incremental and disruptive practices that can be used to help solve the problem of integrating construction project processes and SCs by providing a comprehensive view. Figure 2 illustrates the construction operations management including the focus areas of the publications. The intersection of the SC and construction project process presented by Olsson (2000) has been modified to best fit the focus of this research.

Publication 1, on direct digital construction (DDC), focuses on developing an operations management concept that integrates all construction project processes and SCs, starting from the design process and continuing through the construction and post-completion phases, such as maintenance. It is a comprehensive concept favoring innovative approaches to integrating the SC with the construction project process. This technology-intensive approach also covers information flow and production operations. DDC was regarded as a disruptive approach because it is a novel concept that changes the way operations are conducted. Partial solutions included in this publication provide examples for the different parts of the SC and different ways of implementing the DDC concept.

Publication 2 focuses mainly on a logistic practice that stabilizes on-site assembly operations, which are an important phase of the construction project process. Kitting practice also has implications on detailed design and procurement in the construction project process. It improves overall project productivity. This practice is not technology-intensive; it is more like a production innovation that also focuses on information flow. The practice belongs to the incremental approach to integrating the construction project process and the SC.
Publication 3 focuses on 3D concrete printing (3DCP) in construction, which is a sophisticated and promising production technology. This is a system innovation that makes model-based operations possible. 3DCP can radically change the logic, principles, and practices of construction operations. Thus, this technology is explored in the context of the first research question, which addresses disruptive practices.

Publication 4 focuses on logistics maturity in the construction industry. It aims to provide a maturity model as a roadmap for companies to improve their logistics abilities and, in so doing, integrate logistics practices into the construction project processes. The study engages in the information flow aspect of the construction SC. Construction logistics maturity has been investigated as part of the second research question, which deals with incremental practices.

Figure 2 shows that this thesis focuses on the entire problem of integrating construction SCs and project processes through publications that focus on these two areas either partially or as a whole. While the focus of publications 1 and 3 is on the beginning—the design phase—of the end product, the focus areas of publications 2 and 4 are on the next phase: planning. Logistics encompasses some of the operations shown in Figure 2 such as procurement, assembly, transportation and unloading.

Figure 2. Focus areas of the publications in construction operations management including project processes and supply chains.1

1SCs include more upstream activities, such as supplying raw materials to component manufacturers, that are not included in the scope of this thesis.
The scope of this thesis includes the implications of technology and process-based innovation taking place in construction operations. Since the thesis does not really focus on one organization and the dynamics within one company but it approaches the situation from a rather comprehensive view of the overall construction operations, human behaviors and leadership aspects were not given much emphasis.

1.5 Thesis structure

The rest of the thesis is structured as follows. All sections build on data and findings from the several publications. Section 2 begins with generic definitions that are central to this work. Then, detailed information on the theoretical foundations, which consist of the two research streams of a) construction SC problems, and b) efforts to integrate the construction project process and the SC, is presented. Integration efforts are divided into two subsections: technological practices for integrating construction project processes with SCs and operational practices aimed at integrating construction project processes with SCs. Section 3 offers a detailed description of the research method, while Section 4 presents the results of the study. Section 5 contains a discussion of the findings and offers theoretical and practical implications and areas for future research, along with the study’s limitations.
2. Theoretical foundation

Before reviewing the specific theoretical foundations of the two research streams, we need to define certain general concepts related to this work, such as SC and construction logistics.

2.1 Defining the key concepts

Supply chain management (SCM) is defined as the integration of key business processes from the end user through original suppliers who provide products, services, and information that add value for customers and other stakeholders (Lambert and Cooper 2000). Construction end products are complex, and many stakeholders are involved during the life cycle of any built object. The construction factory is set up around a single on-site product (the building), in contrast to other production systems in which products pass through the factory (Vrijhoef and Koskela 2000). Thus, the construction projects involve many companies working on the same product and interacting throughout the project.

Construction logistics comprises significant practices that support site operations:

Logistics is the process of strategically managing the procurement, movement and storage of the materials, parts and finished inventory (and the related information flows) through the organization and its marketing channels in such a way that current and future profitability are maximized through the cost-effective fulfillment of orders. (Christopher 2011)

Logistics is performed within a given supply chain at multiple locations. While logistics is more tactical and operational, supply chain management is more strategical (Lummus et al. 2001).

Construction logistics means managing the material flows that are delivered to the project location; in other words, supplying the right materials to the right customer and construction site (Janné 2018). Logistics is a vital part of construction operations management. The success of a construction project depends on the coordination of on-site and external logistics (Ying et al. 2014).

The construction process begins with an assessment of project needs. Then, conceptual planning and architectural design are developed and detailed. The next operation is planning the material procurement, procurement activities,
followed by planning and conducting the assembly operations. The construction project process is a continuous reduction of uncertainty over time (Winch 2001), as uncertainty is high at the start of a project and declines toward the end.

Supply chain integration is defined as strategically collaborating with the supply chain partners and managing intra- and inter-organizational processes to have advanced and efficient product and information flows (Flynn et al. 2010). For a construction company to achieve supply chain integration would mean effective information and material flows among project partners and delivering the highest value to the clients rapidly with a competitive price. Supply chain integration impacts the performance of the operations as well as cost and efficiency (Bagchi et al. 2005). Integrating the construction supply chain can also mean for the actors of a supply chain to collaborate on different projects for longer periods of time improving their relationships among each other (McDermott and Khalfan 2006). Integration in this sense and in the sense of effective information and material flows has not been completely achieved by the construction industry.

Integration significantly improves the cost efficiency (Richey et al. 2010). It can be said that the competition is no longer among the companies but rather between supply chains (Näslund and Hulthen 2012). Finnish companies hesitate in sharing information apart from order processing and scheduling operations in their supplier-buyer relationships (Kemppainen and Vepsäläinen 2003). Richey et al. (2010) states that the supply chain management integration is more comprehensive than within-company or only between supplier-customer integration in one layer. It rather covers suppliers’ suppliers and customers’ customers. This fits to the construction industry due to the ongoing common subcontracting practice.

After defining the core concepts around which this study revolves, it is necessary to investigate the problems encountered during the construction project process and the SC-related issues, along with the actions taken so far to tackle them.

2.2 Construction supply chain and project process problems

Studies reveal that productivity and the flow of assembly work in construction is low (Fulford and Standing 2014), with 25% of rework costs caused by problems related to on-site construction management (Josephson et al. 2002). Other causes of on-site waste have been identified as complex assembly operations, unnecessary transportation of materials, large stocks, inadequate production plans, waiting (Gerth et al. 2013), rework (Durdyev and Ismail 2016), and double handling of materials (Donyavi and Flanagan 2009).

Problems encountered due to SCM issues include ordering too many materials, failing to deliver the right materials at the right time (Donyavi and Flanagan 2009), a loss of productivity due to change orders, and delays in material deliveries (Durdyev and Ismail 2016). Furthermore, problems during the reception
Theoretical foundation

11

of materials and builders’ merchant issues also relate to SCM (Thunberg et al. 2017).

According to Thunberg et al. (2017), there are four categories for the project process and SC issues encountered in the construction industry. On-site problems that are related to material flows affect all parts of the SC, including construction on-site. Internal communication issues arise during the design and pre-construction phase of the project process. External communication issues are linked to the integration of the SC and construction project process, as smooth communication between suppliers and subcontractors is required for successful production. Issues of complexity are linked to the whole project (Thunberg et al. 2017).

The construction industry suffers from loose coupling among the actors involved in projects and a fragmented project structure. People, processes, and information management are only lightly integrated (Alhava et al. 2015), and projects exist in limited periods during which project actors work on a specific task and move on to future projects. Construction projects are only loosely connected to other projects; each leads its own life, with limited past or future coordination and learning between projects (Dubois and Gadde 2002). As a result, the reuse of project designs and plans remains an untapped source of performance improvement. This short-term project focus with temporary project networks has negative effects on learning and innovation (Gadde and Dubois 2010). There are complex interdependencies between firms, tasks, and parts, leading to a lack of SCM advances in construction (Bankvall et al. 2010).

Incomplete design models also constitute problems in subsequent operations in the construction project process and SCs. When design models are incomplete, improvisations and on-site actors’ interpretations are used, and relying on expert and tacit knowledge may create problems in the future (Johnston and Brennan 1996). Improvisations that are made in the use of building information modeling (BIM) technology in a loosely coupled system can result in subsequent errors, costly production, and additional working hours (Merschbrock and Wahid 2013).

Improvisations also occur due to the limited time that is allocated to secure additional planning resources when something unexpected happens (Hamzeh et al. 2012), but the needed redesign is not made, or when the design or some tasks and task interfaces are intentionally left undesigned. Furthermore, because of their different backgrounds, the actors involved in projects can interpret even complete designs differently, leading to improvised actions and outcomes that stray from the original intention.

There are also problems regarding a lack of proper material logistics management on-site, such as untimely material deliveries, ambiguity of material arrival times, and the waste of labor spent on looking for materials on the site (Donyavi and Flanagan 2009). Workers spend their time on non-value-adding tasks such as collecting required tools and materials (Sarhan et al. 2017). A fully efficient flow means that a given process does not lose time to waiting (Reddy 2015). If flow efficiency is increased without reducing variation, the material resources need to be increased exponentially. Ordering more materials may seem like a
solution, but it is effectively impossible in practice. Procuring materials in large quantities without complying with the production needs of the site could lead to a waste of resources in stocking, handling, and transporting materials (Agapiou et al. 1998). On the other hand, when material stocks are too low, production can slow down or even come to a complete halt (Cheng and Kumar 2015).

Proper logistics solutions may mitigate the problem of high variation. However, most construction companies have not yet realized the benefits of logistics practices and SCM (Fadiya et al. 2015). Proper logistics management is not adopted by most practitioners because of its demand for detailed data (Said and El-Rayes 2014). It requires a detailed design phase in the project process to obtain precise data. Practitioners could also be unwilling to adopt logistics innovations because they might not understand how exactly those solutions work (Tanskkanen et al. 2015). The contemporary construction industry is not fully aware of construction SCM and logistics efficiency, with most of the available operational tools and techniques to improve SC and logistics management not fully internalized (Ying et al. 2013).

2.3 Efforts to integrate the construction project process with the supply chain

Many initiatives have been undertaken to overcome the problems encountered during the construction project process. This section reviews these concepts and practices to provide a better understanding of what is needed to integrate the construction project process and the SC. Most of these practices are incremental.

Improvements in the construction supply and demand management are possible through integration, collaboration, information sharing, and trust (Papadopoulos et al. 2016). SCM tries to determine the interdependencies in the SC and advance its configuration through integration (Vrijhoef and Koskela 2000). Previously, information sharing has been proposed to achieve a high level of collaboration and integration between customers and suppliers (Hill and Scudder 2002). Information visibility and data availability are important factors for a design-to-order SC (Lee 2004). However, knowledge and information sharing are limited in the construction industry because of its fragmented structure (Na et al. 2007).

Integrating product design and SC improves the position of a company in the industry, SC resilience, and responsiveness due to better alignment with suppliers, becoming more vertically integrated, and being transparent (Khan et al. 2012). The early involvement of suppliers in product development decreases the time needed to design and manufacture a product (Mikkola and Skjøtt-Larsen 2006). By proactively planning the unique and complex construction operations through preparation and information sharing, it is possible to realize improvements in construction time (Hildreth et al. 2007).

In the next two subsections, practices that can relieve the integration issue of construction project processes and SCs are reviewed. These efforts are examined in two streams: technological practices for integrating the construction
project process with the SC and management practices aimed at the integration of the construction project process with the SC.

2.3.1 Technological practices for integrating construction project processes with supply chains

Reviewing technology-based practices is beneficial for developing a novel approach to integrating the project process and the SC. There have been many attempts to address the problems encountered during the project process, some of which achieved relatively wide adoption rates; many others, though, require extra efforts for wider adoption. Training and motivation are required to successfully implement new solutions in companies. Processes such as BIM and virtual design and construction (VDC) are examples of these solutions and are reviewed in this section.

Digital building models can be used as information stores in the design and construction phases and in the use and maintenance phases of a building, without requiring any connection to production or SCs. However, when an operation like construction is carried out in an improvised manner without being specified in the digital design model, operations in the use and maintenance phases begin with inaccurate information and inadequate documentation. Creating virtual buildings through BIM offers design models that can replicate real buildings. However, the fact that there are very few examples in the industry relying on BIM suggests that this has not been achieved. BIM can be developed for the as-designed status; however, it will not reflect the details of the as-built reality (Tang et al. 2010), and there are always differences between as-designed (Akinci et al. 2006; Chen and Luo 2014), as-planned (Golparvar-Fard et al. 2009), and as-built structures (Bosché 2010; Tang et al. 2010; Han and Golparvar-Fard 2017).

BIM is a multifaceted approach that involves several stages of implementation and many capabilities; it is also affected by project networks and SC interdependencies (Ahmed and Kassem 2018). The challenges include problems with information exchange and integration, data interoperability, and computability (Azhar 2011). Construction projects often undergo changes during the life cycle, resulting in differences between the design and the end product (Azhar 2011). Information about a project is typically recreated between five and eight times during its various phases (Davis 2007). This indicates that simply increasing design resources is hardly a solution to human interpretation and reuse challenges. Without design-based production, design models are not kept up to date as assembly operations are carried out. Therefore, there is a need for practices in which operations are both planned and carried out using the digital design model.

VDC employs that model to conceive and plan the multidisciplinary execution of design construction projects, enabling the achievement of explicit and public business objectives (Kunz and Fischer 2012). Luth (2011) states that VDC is the process of using accurate 3D building information models to facilitate visualization, simulation, communication, coordination, estimation, purchasing, and scheduling. This concept allows all actors to access a project’s shared data. In
the advanced maturity levels of VDC, cyber-physical control of the fabrication of subassemblies in a factory has been added (Kunz and Fischer 2012). However, in the construction industry, the project orientation of design and delivery limits the benefits of investments in design-based production and operations to individual projects. Moreover, BIM focusing on building elements of the VDC model has disadvantages due to management issues requiring process interactions (Kunz and Fischer 2012). Furthermore, VDC as an operational practice does not explicitly aim to reuse designs and process controls to prevent improvisations and improve productivity across projects. Therefore, integrated project delivery and partnering have been suggested as appropriate contractual forms to incentivize actors to invest in VDC (Zhang and Wang 2009). Combining VDC and integrated project delivery would increase the use of construction knowledge upstream in the design process and the development of detailed designs at an earlier stage (Sacks et al. 2010), both of which are needed for more automated design and construction. The challenge of introducing VDC is that it requires firms to invest more in its operational practices than the value they can capture in a single project (Kunz and Fischer 2012).

Cyber-physical control refers to cyber-physical systems (CPS), which are physical systems whose operations are monitored and controlled by a computing and communication core (Rajkumar et al. 2010). Attempts have been made to apply the CPS approach to construction using real-time bi-directional coordination and communication between virtual models and physical construction (Sutrisna et al. 2015). The cyber-physical control of production is present in direct digital manufacturing (DDM) while the extension of design-based operations beyond production is possible through VDC. DDM is an important operational practice in implementing the vision of Industry 4.0 and Construction 4.0, its potential counterpart in the construction industry (Oesterreich and Teuteberg 2016). However, because of the highly variable maturity levels of digital manufacturing in the construction industry, adapting the practice poses several challenges. Cyber-physical control and the reuse of designs need to be supported by operational practice elements from both BIM and VDC. Actors in construction need to address many issues, including data security, implementation costs, and process changes (Oesterreich and Teuteberg 2016), the resolution of which takes time. Here, BIM is available to address the collaboration, integration, and interoperability issues (Ilhan and Yaman 2016). VDC is available to align the design model with different operations and actors within the project and building life cycles (Dave et al. 2015).

As DDM was developed in manufacturing industries with stable product designs and SCs, the development of a new practice like DDC should enable higher levels of customization and assembly activities on customer job sites. Partial implementations of DDC involving a combination of digital design and BIM-based automated construction for structures are available (Ding et al. 2014). However, the holistic design of technology-based operational practices of DDC construction is needed to support the paradigm shift from a project orientation to a solution orientation in architectural design and construction (Labonnote et al. 2016).
Industrialized construction (IC) is another concept in which processes are thoroughly planned, structured, and systematized, while the flow of materials and information is integrated into the design, manufacturing, and building processes (Lessing 2006). It demands integration of the SC to achieve stable and ongoing processes (Erikshammar 2011), which also require continuous improvement (Meiling et al. 2014). The development of manufacturing methods and technical solutions is required for the establishment of industrial housing, and constructs must be strategically integrated at the company level (Lessing et al. 2015). IC is characterized by rigorous planning and control of the construction process, increasing upfront costs, and the tightly coupled design and management of operations (Lessing et al. 2015). In IC, the technology aspect is more about product design and production technology (Razkenari et al. 2019) rather than information management.

Digital twin (DT) is a new concept that refers to the virtual representation of objects that can also be used for buildings. While the BIM model can include current and historical data about the built object, the DT can be used to assess the current state and to forecast the future state of a digital duplicate of the built environment (Posada et al. 2015). A DT is a kind of CPS in the conceptual sense; it simply focuses more on the data aspect (Zheng et al. 2019). DTs require understanding technologies such as the Internet of Things (Greif et al. 2020) and point clouds. Broad adoption of this concept could also improve operations after the on-site assembly phase, as with renovation projects. This practice can help prevent information loss on the models and, in so doing, avoid interpretations and improvisations.

AM is a disruptive technology (Barnes and Slattery 2021) that has been defined as “a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” (ASTM F2792-10, 2010). In contrast to conventional manufacturing methods, such as molding or computer numerical control machining, AM creates part geometry using a layer-by-layer process that adds rather than subtracting material. Additionally, AM differs from conventional manufacturing methods because it does not need molds for printing walls, making the AM process much faster than tool-based conventional manufacturing processes for the first part of a production run. Being a toolless process, economies of scale only apply to AM parts until the production chamber is full; thereafter, the cost per part remains constant, independent of production volume. In the construction context, one of the applications of AM is 3DCP; it can be seen as an approach to simplifying the construction SC and contributes to digital transformation in the manufacturing and construction sector.

AM produces components directly from a digital design file and prints the special raw material layer by layer. Today, AM technology is explored intensively in the construction industry since it allows designs to be developed and manufactured rapidly (Ituarte et al. 2016). It can also shorten SCs in the construction industry by autonomously manufacturing components directly from a digital design model with the least possible human intervention (Ghaffar and Mullet 2018). Regarding concrete structures, 3D printing technology enables concrete
to be printed at the desired location and speed by pumping the concrete toward the printing head (Bos et al. 2016). New sorts of structures with dimensional accuracy and evaluation of the morphologies of the structures are made possible by 3DCP (Allevi et al. 2019). Using a concrete mix that satisfies several design and operational constraints, 3DCP can be employed without using formwork (Malaeb et al. 2019). Elimination of formwork can shorten the construction process and decrease building cost.

AM provides construction opportunities such as design flexibility (Camacho et al. 2018; Krimi et al. 2017), automation (Ghaffar et al. 2018), digitalization (Nerella and Mechtcherine 2019), and high precision (Hager et al. 2016). Studies have shown that novel shapes can be manufactured via large-scale 3D printing (Bhooshan et al. 2018). Using 3D printing for construction reduces the labor, capital investment, and formwork (Tay et al. 2017) demanded by traditional construction. Table 1 illustrates the existing technology-based practices and their characteristics as to the integration of project processes with SCs.

Table 1. Existing technology-based practices and their characteristics.

<table>
<thead>
<tr>
<th>Practice</th>
<th>Characteristics of integration of project process with the supply chain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building information modeling</td>
<td>Digital design models are used while design-based production is limited. Cost estimates, drawings, and quantities can be extracted.</td>
</tr>
<tr>
<td>Virtual design and construction</td>
<td>Use of digital design models and design-based production with limited cyber physical control of production. Design-based operations beyond production.</td>
</tr>
<tr>
<td>Cyber-physical systems</td>
<td>Operations are monitored and controlled by computing and communication core. Coordinates between physical and computational elements.</td>
</tr>
<tr>
<td>Industrialized construction</td>
<td>Digital design models and automated production processes are used. Digital designs can be reused at the project or component level.</td>
</tr>
<tr>
<td>Digital twin</td>
<td>Digital design models, performance monitoring, and reuse opportunities.</td>
</tr>
<tr>
<td>Additive manufacturing</td>
<td>Digital design models with design-based production. Possible reuse of digital design models at the project or component level.</td>
</tr>
</tbody>
</table>

2.3.2 Management practices aimed at integrating the construction project process with the supply chain

Having reviewed technology-based practices, it is also necessary to review the literature on practices that incrementally improve the current SC to have a comprehensive view of ongoing practices in the construction industry. The progress of a project and productivity require punctual material deliveries and reliable production on-site (Kiljunen 2009). Mismanagement of materials is one of the most highly ranked issues influencing construction productivity (Naoum 2016). Logistics operations support on-site activities to avoid these problems. Issues related to the execution of tasks on-site or in the SC often result from communication issues (Vrijhoef and Koskela 2000). Many issues can be solved through effective planning, and SC planning can be employed for communication and coordination issues because it can serve as a facilitator (Thunberg et al. 2017).

How a product is designed can impact the success of the logistics operations (Mather 1992). Logistically friendly product designs would help decrease complexity. A third party logistics provider (TPL) could be utilized at an early phase in construction projects to plan the site layout and logistics to facilitate operations (Skjelbred et al. 2015). Logistics provider could be involved in the design phase, and together with the main contractor, design the logistics routes or
openings in the building for better logistic operations in the construction phase. For projects with space limitations, for example a construction project in a city center, planning the layout carefully for logistics purposes would ease the operations at later stages of construction. Since this concept may require use of TPL and temporary storage, the additional implementation cost is considered high at first. More quantitative research is needed to clarify the benefits.

Buffer management, which companies often employ to manage uncertainty, prevents wasting time waiting for materials to be delivered. The requirements for implementing buffers in construction determine project schedules and require identifying reasonable estimations for each activity (Jan and Ho 2006). However, if inventory buffers are much larger than the material required, performance may actually decrease (Horman and Thomas 2005). This can be avoided by accurate scheduling of material orders in the project plan from the outset (Bertelsen and Koskela 2002).

Just-in-time (JIT) delivery means that when materials are delivered to construction sites, they are installed immediately, without having to be stored (Tommelein and Li 1999). JIT delivery can partly decrease the need for on-site storage areas (Jaillon and Poon 2014) and can increase overall quality and efficiency (Pheng and Hui 1999). Materials are less prone to being damaged because on-site waiting times are eliminated. Waste is reduced by delivering the required materials exactly when they are needed. JIT can be applied to both engineer-to-order and make-to-stock products. The schedule of the task that will use the specific materials must be known in advance to implement JIT delivery.

Consolidation centers are logistics solutions for consolidating deliveries from suppliers and producers. Consolidation facilities keep materials for a certain period until delivery by logistics workers to stores or sites on a JIT basis (Sullivan et al. 2011). Hamzeh et al. (2007) state that consolidation centers can be configured for purposes such as assembly and “kitting” (detailed below), along with consolidation, sorting, and breaking bulks. Some of the requirements for implementing consolidation centers are the availability of real-time schedule information at the task level, specific project requirements, shipment types, and information on transportation capacity and peak seasons (Song et al. 2008). The project schedule must be available to ensure complete pre-planning of material deliveries.

Material kitting packs different parts into a package based on an assembly schedule and supplies these kits to the production (Limère et al. 2012). In kitting, materials are packed according to a specific floor or even apartment and are ordered to the site during a specific time window (Riihimäki and Palolahti 2011). This practice connects delivered material batches to site activities in specific locations. To successfully apply a kitting solution, the information requirements include material type, quantity, unit, supplier, kitting date, delivery date, kit name and number, task, and the location where the kit will be used (Zheng et al. 2020). When companies use this solution, which they can apply together with consolidation centers and JIT delivery, on-site workers save time by not searching for materials, since they are delivered to the task location as pre-sorted kits. Figure 3 illustrates the material kitting process.
Takt production (derived from *Taktzeit*, the German word for “cycle time”) is a lean concept in which users attempt to tune the rate of work output to the rate of customer demand (Frandson and Tommelein 2014). Its requirements include having an estimated lead time for consuming all materials involved in the materials requirement planning and the required material list calculations (Segerstedt 2017). These plans ideally should be made with the trades involved. The required work of every trade must be completed during the allocated “takt beat” (Haghsheno et al. 2016). Takt time needs to be determined to implement takt production, while determining the takt areas is required to identify the takt time. Capacity buffers and the work density of each team are used when planning with takt (Frandson et al. 2015). Takt production brings clear benefits to projects and it suits repetitive work like construction (Binninger et al. 2018). The necessary know-how to implement the technique is easy to obtain, as are any additional resources necessary to implement takt. The use of takt does require a planning phase, during which takt areas and takt schedules are determined.

Takt results can be improved even more when implemented with specific logistics solutions such as kitting, JIT delivery, and consolidation centers (Tetik et al. 2019). The benefits of takt include reduced completion time and lower project costs (Vatne and Drevland 2016). This method can bring more benefits when it includes several additional steps, such as explicitly considering material logistics, garbage collection, and real-time data collection (Heinonen and Seppänen 2016).
Vendor-managed inventories (VMIs), another logistics solution that can be used in construction projects, is an on-site inventory system in which the material supplier manages the levels of materials. In a VMI partnership, the supplier makes the main inventory replenishment decisions for the consuming organization and provides continuous replenishment (Waller et al. 1999). Some of the requirements for this practice to work include having customer-specific material information records, including reorder levels and minimum delivery quantities (Tanskanen et al. 2015). The system also depends on information technology platforms, communications technology, and product identification and tracking systems (Waller et al. 1999). VMI is a good example of how collaboration could work well (Näslund and Hulthen 2012).

Third-party logistics (TPL) refers to activities carried out by a logistics service provider on behalf of another company. At a minimum, TPL involves the management and execution of transportation and warehousing and can also include inventory management, secondary assembly, and material tracking (Berglund et al. 1999). The use of TPL often leads to more centralized logistics, because not all contractors handle their materials themselves. Hence, the use of TPL not only outsources but also centralizes activities, which should lead to smoother coordination. The ability to work collaboratively with customers determines the success of TPL providers (Tian et al. 2010). Using TPL has been shown to reduce construction costs, and the benefits of using TPL for material handling have been shown to exceed the costs of doing the handling in-house (Lindén and Josephson 2013).

Tracking materials can be used to improve productivity and decrease material waste. Wi-Fi-based tracking systems can be used to monitor the locations of different construction resources (Woo et al. 2011). Materials can be physically located in the construction site, to be assigned when workers request them for installation (Song et al. 2006). Wi-Fi- and Bluetooth-based tracking methods can be used to locate workers to improve their production efficiency and management (Zhao et al. 2019a). The same methods may also be used for material tracking. Some preconditions to using tracking include having the floor plan available to install the tracking devices and ensuring their connectivity, including power connections and a sufficient supply of charged batteries (Zhao et al. 2019b).

2.4 Summary of the theoretical background

The previous two subsections of the theoretical background outlined existing attempts to integrate the construction project process and the SC. The first subsection focused on the technological practices used in the construction industry for this integration, while the second focused on the available operational practices designed to achieve the same purpose. Together, these perspectives provide the background for understanding the need for integration solutions. Taking these concepts and practices into account, this summary seeks to provide a comprehensive approach to integrating the construction project process with the SC.
Disruptive innovations benefit new technologies that can create new markets or radically change, or disrupt, the status quo in existing markets (Bower and Christensen 1995). Technological solutions that aim at integrating construction project processes with SCs appear to require fundamental changes in the system, whereas operational practices with the same aim can be used within the existing system. For instance, deciding to use a combination of logistics solutions does not necessarily change the status quo, but it does require having the knowledge about how to implement those solutions.

The construction industry has been slow to adopt the new technologies and has never gone through a disruptive transformation (Gerbert et al. 2016). Difficulty in implementing SC planning in complex SCs is one possible reason for the low levels of SC intervention adoptions (Jonsson and Holmström 2016).

Many of the suggested solutions are only individual attempts that do not provide an overall comprehensive solution; nor are they widely adopted. Inefficiencies during operations and industry-specific complexities are still common. Construction is an inherently project-based industry. The short-term focus of construction projects narrows the perspective of managers and inhibits the possibilities for optimization and innovation. The implementation of individual solutions in isolation on single projects contributes to this situation. However, combining some of these solutions may provide more benefits. Both expertise and experience are needed during the planning phase when deciding which solutions are to be used in a project.

2.4.1 The gap in existing knowledge

On-site problems encountered during construction projects usually stem from the lack of SC orientation among construction companies (Thunberg et al. 2017). Since there is no standardized process for SC planning, problems related to the planning phase of the construction projects are common (Thunberg and Fredriksson 2018). There is a synchronization problem between the construction project process and its SC, which could be approached from an integrative view.

It is true that there are novel operations management practices such as VDC, DDM, and CPS. However, construction companies have still not achieved the integration of digital technologies to keep up with their counterparts in manufacturing (Hampson et al. 2014). There is no operations management concept in the construction sector that combines and extends the unique practice elements of these practices. There is a gap in the literature on how on-site problems encountered in construction projects can be mitigated through an SCM perspective (Tennant and Fernie 2014). So far, there has not been a solution to the issue of integrating the project process and the SC. Thus, solutions to integrating project processes with SCs and their impacts on performance in the construction industry is investigated in this dissertation.
3. Method

In this chapter, the methods used in this research are presented and justified, followed by descriptions of the data collection and data analysis methods used in the publications.

Publication 1 uses a design science approach, while a comparative case study approach was adopted for publication 2. In publication 3, case studies with scenario analysis, a suitable method for future studies (Alcamo 2008), have been used. Publication 4 features a literature review and case studies. Table 2 illustrates the overall research design of each publication, including research questions or purposes, short descriptions of the research process, and the methods used.

Table 2. Overall research design of each publication

<table>
<thead>
<tr>
<th>Publication</th>
<th>Publication 1</th>
<th>Publication 2</th>
<th>Publication 3</th>
<th>Publication 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research question or purpose</td>
<td>To develop a new operations management practice (direct digital construction) based on a combination of technology-based operations practices from the construction and manufacturing sectors.</td>
<td>To evaluate the applicability of a material kitting logistics solution by focusing on its impact on work performance and requirements for management.</td>
<td>To compare the performance of conventional construction methods with that of 3D concrete printing technology for different design solutions and supply chain configurations.</td>
<td>To determine and propose an order of gradual logistics developments in construction by using the maturity level approach.</td>
</tr>
<tr>
<td>Methods used</td>
<td>Case study with design science approach</td>
<td>Case study</td>
<td>Case study with scenario analysis approach</td>
<td>Case study</td>
</tr>
<tr>
<td>Short description of the research process</td>
<td>The problem is framed, with fragments from practice for a solution design collected. The initial solution design is subjected to further development with inputs from cases that adopt required operational elements of the new operations management practice. Findings are generalized and presented.</td>
<td>Performance measurement data of using and not using kitting practice are compared through case studies in four construction tasks.</td>
<td>Cost and time analyses are conducted for seven scenarios to compare conventional and 3D printing methods for building a small house.</td>
<td>Based on a literature review, logistics maturity levels are proposed. A recommended order of implementing logistics practices is devised. The proposed model is validated through case examples from the industry.</td>
</tr>
</tbody>
</table>
Table 3 illustrates the approaches used in this research to fulfill its purpose. The incremental approach provides empirical and conceptual improvements to the SC to integrate the construction project process with the SC. Similarly, the disruptive approach proposes different production techniques and practices to radically change current SC processes both conceptually and empirically.

Table 3. Approaches to integrating the construction project process with the supply chain.

<table>
<thead>
<tr>
<th>What are the disruptive practices that successfully align the construction supply chain with the construction project process?</th>
<th>What are the incremental practices that successfully align the construction supply chain with the construction project process?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Digital Construction – Publication 1</td>
<td>Material kitting – Publication 2</td>
</tr>
<tr>
<td>3D Concrete Printing – Publication 3</td>
<td>Logistics maturity model – Publication 4</td>
</tr>
</tbody>
</table>

Building on existing technology-based operations management practices, publication 1 designs and describe a new operations management practice for construction. For this purpose, the four phases of research for design exploration and theory building in operations management research from Holmström et al. (2009) are used. First, the problem was framed and fragments from practice for a potential solution design were collected. The initial proposal for a solution design was then subjected to further development using inputs from cases that adopt the required operational elements of the new operations management practice. After that, the findings are generalized and a theoretical contribution demonstrated in terms of novel insights in the research literature; finally, the findings are presented formally.

To provide an incremental approach to the issue of integrating the construction project process with the SC, the impacts of a material kitting logistics solution are investigated in publication 2. Kitting has been suggested for use in the construction industry (Tanskanen et al. 2009), and proper logistics is a step toward integrating construction project processes and SCs, as logistics support on-site operations. To investigate kitting logistics solutions and their effects on on-site labor productivity and schedules, four projects are investigated. Two were conducted conventionally; the other two implemented material kitting logistics solutions.

In publication 3, to provide a disruptive approach to the integration problems of construction project processes and SCs, the impacts of using 3DCP are investigated. 3DCP is another practice that changes the construction SC. Thus, the impact of production innovations in construction for tackling the same problem is investigated via another approach; namely, 3DCP, a new production technology in the construction sector. The construction industry is one of the least automated industries, and its productivity has been stagnant until recently, but a digital transformation due to the emergence of new tools like 3DCP promises to change the status quo (Ghaffar and Mullet 2018).

The construction industry, which is among the industries with the least amount of digitalization, can significantly benefit from digitalized solutions. 3DCP technology is one digitalization method with significant implications for construction efficiency. To illustrate its benefits, costs and completion times
were calculated for a housing construction project using different methods, SC configurations, and designs; ultimately, seven scenarios were compared.

In publication 4, the available literature was synthesized into five relevant maturity model themes based on previously developed logistics or construction SC maturity models, with existing logistics practices categorized under each theme. Case studies are used to validate the model and determine the proper order of implementing logistics operations in construction by analyzing the development of logistics operations of the case companies. Three guiding questions emerged to guide the data collection and analysis:

1. To ensure performance improvement, what is the optimal order of logistics practices in each theme?
2. Should companies progress in themes to approximately the same extent to ensure good performance?
3. Do higher maturity levels explain better performance in logistics and projects?

Performance was considered in terms of overall project performance, including schedule, cost, quality, and logistics performance. In detail, in publication 1, the performance is considered at the entire construction industry level in terms of cost, quality and schedule. In publication 2, the project performance in terms of schedule and logistics is considered. In publication 3, the performance is based on cost and completion time at project level. In publication 4, the logistics performance of assembly operations in projects is considered.

3.1 Design science research

In addition to description-driven research that helps understand the essence of a problem, prescription-driven research is also needed to produce solutions to management-related issues (van Aken 2004). Information systems have been defined as the effective design, delivery, utilization, and impact of information technology in organizations and society (Avison and Fitzgerald 1995). Design science is an outcome-based research methodology originally developed in the discipline, and design theory is a subfield of design science. The design science approach is used in this study because it identifies the real-world problems that practitioners face, defines the targets of a solution to be achieved and, based on these, designs and develops an artifact to be used to tackle the initial problem (Peffers et al. 2007). Design theory offers guidelines or principles that can be followed in practice (Gregor 2002).

Design science research approach was adopted for publication 1. A new operations management concept is developed via design theory (Gregor and Jones 2007). Design science tries to develop new knowledge for solving organizational issues, whereas design theory seeks to codify and generalize aspects of the knowledge generated (Piirainen and Briggs 2011). Design theory postulates that the design of a new artifact is structured around the following components: purpose and scope, constructs, principles of form and function, and expository instantiations (Gregor and Jones 2007). These components are defined in
elaborating the DDC concept. Since design science is used for developing solutions to practitioners’ problems, this methodological approach was found suitable.

Design theory suggests that when developing a new concept, its purpose and scope (what the system is for), constructs (representations of the entities of interest), principles of form and function (abstract blueprint of an information systems artifact), artifact mutability (specifying the degree of changeability of the developed artifact), testable propositions (hypotheses), justificatory knowledge (why something works), principles of implementation (the means by which a design is brought into being), and expository instantiations (a realistic implementation of a thing in the physical world) should all be defined for an artifact to be constructed (Gregor and Jones 2007). These components have been used to develop a new operations management concept in this study.

3.2 Case study research

Case studies can be used as a step toward theory (Glaser and Strauss 1967). To develop a validated theory, SC planning interventions need to be identified, and case studies can be used to focus on the outcomes of SC interventions in different contexts and on how to achieve them (Jonsson and Holmström 2015). Case studies have been intensively used in the publications that are part of this thesis. Case studies are suitable for understanding the complex relationships between multiple factors that operate in a specific social context (Denscombe 2014). The case study research method is defined as an empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clear, multiple sources of evidence are used (Yin 1984).

In this dissertation, case studies are used for multiple purposes. On one hand, they are deployed to understand existing best practices and illustrate potential solutions. On the other hand, case studies are used for evaluation and testing proposed solutions. Thus, the setting adopted in this study is a comparative case study design (Yin 2014) and the comparative case studies in this thesis are divided into two groups: I) real-life experiments and II) scenario analyses.

Tellis (1997) suggests that single case studies are especially suitable for revelatory cases where an observer may have access to a phenomenon that was previously inaccessible. It is a misconception that single-case studies cannot contribute to the science and form generalisations (Flyvbjerg 2006). On the other hand, single case study is often too limited for validation and when research resources are limited, Patton (1990) recommends using a multiple case study approach with purposeful sampling. The publications that are used in this thesis use several number of case studies. The candidate had access to some of the case companies through on-site internships lasting 3-8 months.

In publication 1, eight case studies are used to determine the level of implementation of technology-based practices in the construction industry and inspect the initial solution design in a real-life context. The case examples were selected to illustrate the adoption of the required operational practice elements in technology-based construction operations; they are also used to address the issues like the need for labor and training and the lack of opportunities to reuse
a design model. The case examples emphasize the direct use of digital design models in the operations following the design phase, such as manufacturing of parts and maintenance.

In publication 2, four case studies were conducted to examine the effects on renovation project performance of using an assembly kitting logistics solution. These case studies belong to the group of real-life experiments of the comparative case studies. A multiple case study design is used to achieve an in-depth understanding of a particular phenomenon (Zach 2006). To understand the impacts of the material kitting logistics solution, four cases were studied; two used the material kitting solution, and two did not. To understand the impacts of the solution on labor productivity, a quantitative approach was used, whereas a qualitative approach employing interviews and observations was adopted to understand the managerial implications of the solution.

In publication 3, a deductive case study approach with scenario analysis was applied to seven different SC configurations. Thus, the second group of comparative case studies is used in this study for scenario analysis. The complex and multidimensional nature of problems and solution development processes require an integrative approach that includes comparative analyses and scenario approaches, which help with the decision-making processes (Mitchell and Nijkamp 2005). First, seven scenarios were defined based on theory and gaps in existing knowledge; each scenario was then modeled subjected to quantitative analysis to compare them in terms of cost and completion time.

In publication 4, case companies were used to validate the proposed model and to determine the proper order of implementing logistics solutions in the companies’ operations. Three case studies with differences in terms of company size and approaches to logistics have been conducted. The companies were selected based on their different size and history of their logistics practices. Moreover, the fact that the authors had access to reliable data via the selected case companies was a factor in case selection. Case 1 is a large developer that operates in Estonia, Russia, and Finland. Case 2 is a medium-sized contractor operating in Finland, and Case 3 is a large international contractor operating in Europe and the United States; only its operations in Finland were investigated.

### 3.3 Data collection

Different data collection strategies were employed in the various publications to increase the credibility and robustness of the analyses. Both qualitative and quantitative data were collected to achieve data triangulation (Ketokivi and Choi 2014). Applying different techniques can provide more robust results (Mitchell and Nijkamp 2005). For publication 1, semi-structured interviews were conducted for the two case studies. Then, six partial case examples from the industry were used. Interviews, observations, official reports, and public sources concerning the case companies and their solutions were all part of the data. Semi-structured interviews allow for more spontaneous descriptions (Brinkmann 2014). Hence, for the interviews with the case company managers, semi-structured questions were posed to obtain the deepest possible understanding of their operations. For the six partial case examples, interviews were conducted.
with solution developers and company managers. Moreover, video materials, webinars, documents, and articles in professional journals were examined to obtain a broad view of the case examples and validate the data collected in the interviews.

For publication 2, a comparative case study approach was chosen to illustrate the impacts of material kitting logistics solutions. Four cases involving the same contractor were studied. Table 4 illustrates the case projects in this publication. Interviews and empirical observations were conducted, and data were collected by monitoring the workers on-site and measuring the time used for different tasks with a stopwatch on the site and by watching recordings from on-site cameras. The angles of the cameras are shown in Figure 4. Moreover, schedule, material, and material delivery information was obtained from the case company.

Table 4. Research design and case projects in Publication 2.

<table>
<thead>
<tr>
<th>Project and logistics solution</th>
<th>Analyzed work performance aspects</th>
<th>Data collection methods and amount of data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project 1</td>
<td>Daily workplace utilization rate</td>
<td>Camera-based video recordings in bathroom (32 work shifts in 32 days)</td>
</tr>
<tr>
<td>Residential, 16 flats</td>
<td>Schedule compliance</td>
<td>Two site visits and three interviews were conducted with a project manager and site supervisor. Observations were made in the consolidation center.</td>
</tr>
<tr>
<td>Centralized material procurement, material packaging to kits in the consolidation center, JIT delivery of kits to the site</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Project 2</td>
<td>Daily workplace utilization rate</td>
<td>Camera-based video recordings in bathroom (24 work shifts in 12 days)</td>
</tr>
<tr>
<td>Residential, 9 flats</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traditional</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Project 3</td>
<td>On-site assembly work productivity</td>
<td>Researcher observing assembly and logistics activities (14 working days)</td>
</tr>
<tr>
<td>Residential, 96 flats</td>
<td>Share of value-adding time per worker</td>
<td>• Branching-3 days</td>
</tr>
<tr>
<td>Centralized material procurement, material packaging to kits in the consolidation center, JIT delivery of kits to the site</td>
<td></td>
<td>• Tiling-3 days</td>
</tr>
<tr>
<td>Project 4</td>
<td>On-site assembly work productivity</td>
<td>Site manager, workers carrying out the observed tasks, and the manager of the consolidation center were interviewed.</td>
</tr>
<tr>
<td>Residential, 216 flats</td>
<td>Share of value-adding time per worker</td>
<td>Researcher observing activities of assembly workers (11 working days)</td>
</tr>
<tr>
<td>Traditional</td>
<td></td>
<td>• Branching-4 days</td>
</tr>
</tbody>
</table>

26
For publication 3, case data were collected from two experimental uses of 3DCP in the real world, one in Singapore and one in Denmark (Weng et al. 2020). Table 5 illustrates the scenarios used for the analysis. International market surveys and Finnish productivity documents (Ratu cards) were used to obtain material cost data from Nordic countries. Expert opinions from the 3DCP industry were also solicited and employed.

Table 5. Research design and case projects for Publication 3.

<table>
<thead>
<tr>
<th>Supply chain configuration</th>
<th>Production method</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-site</td>
<td>3DCP</td>
</tr>
<tr>
<td></td>
<td>Scenario 1 (On-site printing of round house)</td>
</tr>
<tr>
<td></td>
<td>Scenario 3 (On-site conventional construction of round house)</td>
</tr>
<tr>
<td>Off-site</td>
<td>Scenario 2 (Off-site printing of round house)</td>
</tr>
<tr>
<td>On-site</td>
<td>Scenario 4 (On-site printing of rectangular house)</td>
</tr>
<tr>
<td></td>
<td>Scenario 6 (On-site conventional construction of rectangular house)</td>
</tr>
<tr>
<td>Off-site</td>
<td>Scenario 5 (Off-site printing of rectangular house)</td>
</tr>
<tr>
<td></td>
<td>Scenario 7 (Off-site conventional construction of rectangular house)</td>
</tr>
</tbody>
</table>

For publication 4, which aimed to develop a maturity model for construction logistics, a literature review was conducted and data for three industry case examples were collected to determine the appropriate order of implementing logistics practices in general contractors’ operations. Three case examples were used, with data gathered from interviews with a business development manager, a logistics manager, the logistics service provider’s material flow engineers, and site personnel, supplemented by site observations and public reports. In total ten interviews were conducted, each lasting about an hour. Interviews included semi-structured questions so the interviewees could answer the questions in a more in-depth way.

3.4 Data analysis

For publication 1, a total of eight case studies were conducted. The recorded case company interviews and observations from site visits and a field study were all analyzed. First the problem was framed by assessing the current best practices in projects in attempts to have as-designed models correspond to the as-built models. Then, in the solution development phase, case companies and SCs were
analyzed, after which the DDC concept was formalized using design theory. The concept developed proposes a match between the design model and the building when it is built. Leading-edge attempts to have the match between as-designed and as-built models were investigated, and descriptions of their benefits and deficiencies are presented. Then, the DDC concept was developed using a design theory approach. Three implementation paths are defined. To increase the validity, novelty, and usability of the designed operations management concept, a focus group discussion with 12 design, development, and business managers from the architecture, engineering, and construction (AEC) sectors was carried out.

For publication 2, four case studies were conducted to investigate the impacts of assembly kitting logistics solutions on work performance. The value-adding and non-value-adding times of the workers were calculated for four work phases of projects where the kitting solution was used and those where it was not. Moreover, document analysis was conducted to determine compliance between planned and actual schedules of a renovation project in which the kitting solution was used. As focus of this empirical research is on the impact of kitting on on-site work performance, four operational and time-related measures were selected to guide the data collection and analysis. Other aspects not directly connected to work performance, such as cost, safety, or material waste, were not primarily considered. Following Sacks (2016)’s idea of project, product, and trade flows, the four selected performance aspects included (1) stabilized assembly work, which was measured by schedule compliance (i.e., how well assembly work followed the plan); (2) product flow, which was measured by the share of value-adding time in one bathroom per day; (3) labor productivity, (i.e., at the single assembly task level, how much of a worker’s time was used on each task); and (4) trade flow (i.e., share of value-adding time per worker).

For publication 3, scenario analysis was conducted on seven different scenarios with different SC configurations, such as on-site 3DCP, off-site 3DCP, on-site conventional construction, and off-site conventional construction. The cost and schedule of each scenario were calculated. Two different house designs were used for the analyses to determine and assess the differences in design geometries. The rectangular design represented a typical design solution for conventional in situ concrete work using molds, whereas the round design represented a more flexible design option. The cost model considered the following parameters: construction machinery and equipment, raw materials, transportation, and labor.

In publication 4, a logistics maturity model for the construction industry is developed. Previously developed maturity models related to construction logistics and current industry examples were reviewed to identify the most suitable themes for construction logistics, such as planning, organizing, operating, technology utilization, and information flow. A thorough literature review was conducted to determine the practices for construction logistics; their interdependencies were determined to outline a roadmap for construction companies. Moreover, case studies were used for validating the proposed model in real life
context, maturity levels of the case companies have been determined for different themes based on the logistics practices they use.
4. Results

This section provides answers to the dissertation’s two research questions. The first two subsections include the key results from the publications that answer the first research question, which involves the disruptive approach. Correspondingly, the last two subsections present findings from the publications to answer the second research question, which involves incremental changes.

4.1 Disruptive approach – Direct digital construction

A novel operations management concept can be used for integrating construction SCs and project processes. Based on the theoretical background, it was concluded that technology-based operations practices that focus on the continuous improvement of firm- and SC-level operational performance need to be developed; this calls for the reuse of design and operating models beyond a single project life cycle. DDC is an operations management practice aiming at directing all value-adding operations over a building’s life cycle through a complete digital design model. Figure 5 illustrates the difference between the logic of traditional construction practices and the DDC concept.

![Figure 5. The logic of DDC compared to traditional construction practices (Tetik et al. 2019).](image)

The iterations between the design and construction phases preclude improvising and having to interpret the design models. In practice, the role of the design phase and design resources has been expanded to design the building and
assembly work more comprehensively and keep the design model up to date. This is called “as-built modeling-driven DDC,” whereby the workload increases in the design phase but decreases in the construction phase. The most notable benefits may be achieved during the use and maintenance phases because the models are only useful in these phases—provided they are accurate. However, even if the as-built model could be used during the life cycle of the building, it is not clear whether it could be reused when designing new buildings.

4.1.1 Case 1: As-built modeling contractor

The contractor updates models during projects so that the design models can be built without improvisation and the final as-designed models correspond to the as-built reality. The company invests several thousands of man-hours in the design and construction phases to achieve this goal. The operations are as follows. External design companies develop the models to a level of detail (LOD) of 290, meaning that each element is designed with its approximate shape, location, size, and orientation, though without highly specific information, such as the model number, supplier, or exact location. Then, the contractor makes the models buildable with its detailing team. This yields a construction model that is accurate, coordinated, and leaves no room for improvisation. Not only does this approach to securing accurate modeling at the outset of the process minimize the need for interpretations in later designs and operations, but it also decreases iterations, which often arise when a design is not sufficiently complete at the outset.

To raise the design to the desired LOD and quality before construction, the case company’s detailers spent roughly around 10,000 h on a project worth $150 million: the project was a 300,000 square foot residential apartment building. By committing these additional hours to the design phase, the case company reported that work in the field had been reduced, quality had increased, and the number of requests for information had decreased significantly. The results of the practice included $2.5 million savings for the owner and a 20% increase in profit for the company. The owner paid for the 10,000 h because that investment would be recouped later in the process due to the lower number of change orders, as the model could be used to produce dimensionally accurate shop drawings. As an additional deliverable, an accurate as-built model was obtained. The savings, profits, and quality enhancements from previous projects increased the credibility of the practice, and hence can convince prospective project stakeholders. Overall, besides having the accurate as-built model, substantial savings on time and quality error costs have been achieved.

4.1.2 Case 2: The school developer

The second state-of-the-art case example is a school construction project. In this project, the as-designed model and built reality were ultimately matched. The analysis of the interview data shows that the motivation behind this complete match was the desire to avoid any inaccuracies in the renovation and maintenance operations of the buildings. The owner-developer of the school wanted the designs to represent the building exactly since it was important to avoid
information loss; in addition, up-to-date information was desired when annual repairs and renovations were to be carried out in the building. In practice, the engagement of the designer was increased on-site, and the project did not proceed to the construction phase until the design model had been completed; this meant that there was no room for improvisation during the installation phase. The designers supervised the process to ensure everything was constructed according to the design model. They were always available in case a design change was needed, and their presence ensured that the contractor did not have to improvise and that the as-built model always followed the as-designed model.

The owner-developer of the school kept the models up to date and was able to use the same design model (from 10 years earlier) in the design of a renovation operation with no deviations from the design model on the construction site. Based on the owner-developer’s experience, many subcontractors in ordinary projects do not even ask for the design model in advance, as it is not usually updated; instead, it has already become outdated in the construction phase. The owner-developer of the school emphasized the significance of interaction among the team for keeping models up to date. Moreover, in comparison with other companies' traditional practices, the developer allocated substantial additional resources to the design phase. However, its view was that a lack of investment in better design would increase the workload in subsequent stages on the job site. Thus, investing in a detailed and complete design model pays off in the construction and maintenance phases. Overall, besides having the accurate as-built model, savings in construction, maintenance and renovations phases have been achieved.

4.1.3 Partial case examples

The other six case examples were analyzed to investigate ways of solving the problems with current best practices explained in the previous section. These six case examples were selected to illustrate the adoption of the required operational practice elements in technology-based construction operations; they were also used to address the issues of the need for labor and training and lack of opportunities for reusing the model. The case examples emphasize the direct use of digital design models in operations following the design phase, such as manufacturing of parts and maintenance.

The first case is a log house design and construction solution. The flow of operations begins with the architectural design phase, which is followed by the planning and manufacturing of log house parts. In this case, the software developer created custom libraries for wooden log house design and fabrication. In this solution, the set of tasks to be performed on the building was fully specified by the design, eliminating the possibility of later misinterpretation and improvisation. The design model is directly transformed into a machine-readable file to be used in computer numerical control production for manufacturing the logs. The design model also defines loads and logistics kits for site deliveries and provides on-site assembly instructions for the parts. Hence, it is possible to use digital design models directly in many operations and minimize human
interpretation in all process interfaces. Moreover, the design models, in whole or in part, can be reused in different log house fabrication projects.

The second partial DDC case focuses on producing steel structures. In this example, a model-based software solution for steel structures is used for automatic welding operations. The position of the welds and welding robots, relative to the materials and all other information on the welding operations, is stored in the digital model. This information is used directly during the manufacturing operation by the welding robots. The practice enables the digital designs to be used in different projects in whole or in part. With this practice, the design model becomes the built reality. In case of a malfunction, it is possible to find the same parts that are used in different areas of the structure in the updated digital design model, allowing them to be checked and perhaps preventing other malfunctions.

The third partial DDC case is a modular building contractor. In this contractor's solution, the prefabricated modular components fit into one another. The contractor stresses the importance of the early planning phase and precise service descriptions. Moreover, the contractor standardizes invisible building components like the shell and supporting structure, although it does leave room for individual choices when it comes to the visible components of the building such as the façade. The models for invisible building components are reused and continuously improved in new projects. Computer-controlled operations do not diminish human interpretation. Instead, standard interfaces between the components rule out improvisation at the assembly stage.

The fourth partial DDC case is a direct digital timber and steel manufacturer that emphasizes an integrated approach in the early design phase. It uses 3D CAM/CAD software, which includes production and logistics information in the design model. This practice reduces the need for costly redesigns and changes. The virtual building process identifies potential geometric and installation issues before construction begins, so no material or labor is wasted. With this solution, customized and complex structures are built according to the design model to a high level of accuracy. A similar approach is adopted for the customized interior architecture area.

The fifth case is a company that produces customized interiors via modular and prefabricated solutions. The company uses 3D design and manufacturing software, which automatically updates the information used in the factory for production operations, thereby leaving no room for interpretation. It thus increases the control over what is being built mainly because no worker is required to interpret the installation drawings. The software platform it uses enables the company to build exactly what has been designed.

The sixth case is a platform-based building designer that operates an integrated design and operations consultancy and uses earlier components and models to guide the conception and construction of future buildings. The company has developed three open design platforms for different building types; each includes detailed designs for standardized components. While each project remains unique, significant aspects of the design from previous schemes are retained. For the sake of standardization, production can be automated on-site.
The company aims to refine and improve the common elements by reusing common parts in the projects to enhance the quality and efficiency of the production of design information. The company standardizes the manufacturing process and connection interfaces. Having a detailed design model that comprises component designs makes it possible to achieve a complete match between the as-designed and as-built models.

In summary, solution opportunities from real-world examples show that by integrating the product and operations information into the design model, design-based operations and cyber-physical control of operations become possible with different kinds of materials, construction practices, and product offerings. The reuse and improvement of digital design models in whole or in part are also possible between projects. Finalizing the design model early or keeping it updated, and by so accurate, along the construction and maintenance phases contributes to efficient information flows and collaboration between the project actors. It would mean improved integration between the supply chain and construction project process.

Table 6 shows the advantages and disadvantages of the partial case examples. These practices illustrate how the operational practice elements of the DDC concept are used in different environments. Based on the six case examples, publication 1 proposes that the required operational practice elements are applicable to the construction environment and that the partial solutions have addressed the problems of state-of-the-art cases. Reusing designs and process information proved possible in most of the case examples, and increased details in the specifications of design models resulted in increased constructability of models and ensured high accuracy levels. However, except for a few of the state-of-the-art projects, the technology-based elements require investments in the early stages of the parallel design and development of the products and operations, as the design model must be detailed enough to enable design-based and computer-controlled operations. However, because the same models in both building design and the CPS can be reused, the additional investments in design and operations and controlling technology are shared by multiple projects. Thus, return on investment can be evaluated based on a series of projects reusing the design and using the same operations technology.
Table 6. Advantages and disadvantages of partial case examples.

<table>
<thead>
<tr>
<th>Case companies</th>
<th>Advantage (denoted by +) /disadvantage (denoted by –)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log house design and construction</td>
<td>+ Computing-based automated engineering and manufacturing + Design-based loading, delivery, and assembly + Investment in the design phase can be recouped in future operations – Constrained by manufacturing technologies</td>
</tr>
<tr>
<td>Model-based software solution for steel structures</td>
<td>+ Cyber-physical control of welding and maintenance operations + High level of accuracy due to model-based automated process + Investment in the design phase is recouped through reuse – Constrained by manufacturing technologies</td>
</tr>
<tr>
<td>Modular building contractor</td>
<td>+ Design-based configuration and assembly + Continuously optimizing design through reuse and adaptation of component designs + Efficiency improves as investments are directed to component development rather than interface management – Limited cyber-physical control but likely implementation in future</td>
</tr>
<tr>
<td>Digital timber and steel manufacturer</td>
<td>+ Cyber-physical control of engineering and manufacturing + Design-based delivery and assembly information + Investment in the design phase is paid back through reuse – Constrained by manufacturing technologies</td>
</tr>
<tr>
<td>Interior manufacturer</td>
<td>+ Cyber-physical control of interior product manufacturing + Design-based installation + Investment in the design phase is paid back through reuse – Constrained by manufacturing technologies</td>
</tr>
<tr>
<td>Platform-based building designer</td>
<td>+ Cyber-physical control of site operations through automation and robotics in assembly + Reuse of design components, faster design process, and unique products – Limited reuse of designs to date; requires committed owners or developers to become scalable</td>
</tr>
</tbody>
</table>

4.1.4 Direct digital construction

The concept of DDC and its principles are presented in Table 7, using design theory (Gregor and Jones 2007). The purpose and scope elements of DDC suggest making the as-designed model correspond to the as-built model. This leads to increased efficiency over the life cycle of a building or its subsystems. All operations, including maintenance and renovation, can be conducted based on the same accurate and complete model. These complete design models also increase the opportunity for reusing entire or partial product and process models for future construction projects. Even though each building remains unique, the processes needed to build them can be similar, whether in whole or in part. Therefore, the design and process models can be reused between the projects. Similarly, standardized components, component interfaces, and sub-product structures can be reused in other projects. In addition, by regularly reusing and improving previous solutions that have been proven efficient, the quality and efficiency of the products and processes will improve over time, as the design model is subtly refined in each iteration. Because everything with DDC is digital and up to date, it is possible to scale up the benefits from reused designs. Continuous elimination of problematic designs and reuse and improvement of the best designs enable steady improvement over time.

The constructs represent the elements that are used to achieve the targets of the proposed concept. In light of the state-of-the-art cases and partial cases, having complete, detailed, and up-to-date digital design models with embedded operational instructions represent the most significant constructs of DDC design theory, but to achieve this goal, design models must have a high LOD. The
design models should be complete before the start of the operations and be kept up to date. Operational instructions should also be embedded in the design model. Product information (e.g., LOD 300) and instructions on how to produce the product or its parts (e.g., LOD 350) should also be part of the digital design model. To accurately describe and define the processes that are directed and controlled by the design object, specific investments are needed in process and technology interfaces. Table 7 presents the principles of function and implementation elements for the practice of DDC. A fully implemented DDC approach enables all value-adding operations over the life cycle of a building, from design to use, to be directed and controlled by the digital design model. This increases efficiency in the planning and control of the operations and promotes the industrialization of construction operations (Lessing 2006).

Table 7. The components of the DDC concept.

<table>
<thead>
<tr>
<th>Design theory component</th>
<th>DDC concept</th>
<th>Evidence from case studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purpose and scope</td>
<td>As-designed corresponds to as-built.</td>
<td>Based on state-of-the-art case analyses, as-designed corresponding to as-built leads to improvements in the later phases of buildings' life cycles.</td>
</tr>
<tr>
<td></td>
<td>Increased efficiency over the life cycle of buildings and building subsystems.</td>
<td>Based on the state-of-the-art and partial case examples, using the same design in whole or in part increases quality and decreases project cost.</td>
</tr>
<tr>
<td></td>
<td>Increased reuse of designs and process control models in different projects.</td>
<td></td>
</tr>
<tr>
<td>Constructs</td>
<td>Complete, detailed, and up-to-date digital design model.</td>
<td>Limits improvisations and enables the use of the same model in every operation.</td>
</tr>
<tr>
<td></td>
<td>Embedded operational instructions in the digital design model.</td>
<td>Increases control over later operations through cyber-physical systems.</td>
</tr>
<tr>
<td>Principles of function and implementation</td>
<td>Direct use of the design model when carrying out operations: engineering, manufacturing, logistics, installation, use, and maintenance.</td>
<td>Using the same digital model in design, logistics, and assembly operations in partial DDC examples and state-of-the-art case examples.</td>
</tr>
<tr>
<td></td>
<td>Design model, including operation instructions, can be reused, adapted, and continuously improved at both the building and building subsystem levels.</td>
<td>The original investment in the design model and cyber-physical control systems are recouped through reuse in multiple projects.</td>
</tr>
<tr>
<td></td>
<td>Operations and buildings evolve incrementally evolve toward DDC.</td>
<td>Alternative implementation paths toward DDC are available.</td>
</tr>
</tbody>
</table>

Figure 6 compares the operations under traditional construction practices and the DDC concept. It shows that with DDC and its detailed and complete design model, there is no distinction between the as-designed, as-planned, and as-built models since the design model is identical to the built model. To minimize interpretation and improvisation in operations, not only are the connections between the design model and operations bi-directional (Sutrisna et al. 2015), but complete design models from previous projects, including operational instructions, are also reused to reduce the need for project-specific changes. Models can be reused for both product designs and process control designs by using CPS.
in operations. Designers can customize their work at the project level either through component configuration or by changing parametric values.

The concept helps integrate the construction project process with the SC by centralizing the design-based operations in the SC. Figure 6 shows that with the DDC concept, processes are more centrally controlled rather than being linear, as is the case with traditional construction practices. The relationships within the different operations are bidirectional with changes being updated to the design model, rather than being linear. This would contribute to continuously improved supply chain integration with construction project process via creating and sustaining efficient product and information flows. With this concept, control of operations is based on the complete digital design model. Since the design model is constantly updated, it is refined. This refined model can be reused in future projects.

4.1.5 Alternative paths of implementation for DDC

After developing the design theory elements for DDC, this section identifies alternative paths of implementation. Table 8 presents three identified implementation paths, their relevant elements and constructs, and case examples following each path. Achieving similarity between the design model and the built reality (design-based production) is the common element among the paths. However, different initiators of the partial solutions, different application areas, and different emphases in the purposes may cause variations in the specific ways that DDC is implemented. Based on the practices (both common and different)
in the case examples and in the literature, we argue that DDC can be approached using three alternative implementation paths:

1. As-built modeling-driven DDC
2. Modular product architecture-driven DDC
3. Algorithmic and parametric design-driven DDC

The as-built modeling-driven DDC implementation path enables the development and maintenance of unique engineered-to-order buildings. BIM objects can be used for engineered-to-order component production, supporting the workflow between design and manufacturing operations and generating automated activities, as suggested by Hamid et al. (2018). This approach validates the intended design before passing it to the manufacturer; it supports DDC by highlighting the importance of having complete and detailed digital design models.

Table 8. Direct digital construction elements of case examples and implementation paths.

<table>
<thead>
<tr>
<th>Implementation path</th>
<th>Direct digital construction purpose and scope elements</th>
<th>Direct digital construction constructs, functions, and implementation</th>
<th>Case examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-built modeling-driven direct digital construction</td>
<td>As-designed corresponds to as-built. Increased efficiency over the life cycle of a building.</td>
<td>Complete, detailed, and up-to-date digital design model.</td>
<td>As-built modeling contractor School developer</td>
</tr>
<tr>
<td>Modular product architecture-driven direct digital construction</td>
<td>As-designed corresponds to as-built. Increased reuse of design and process models between projects in construction. Increased efficiency over the life cycle of buildings and building subsystems.</td>
<td>Complete, detailed, and up-to-date digital design model. Design-based operations: embedded operational instructions in the digital design model.</td>
<td>Modular building contractor Platform-based building designer (partially)</td>
</tr>
<tr>
<td>Algorithmic and parametric design-driven direct digital construction</td>
<td>As-designed corresponds to as-built. Increased reuse of design and process models between projects in construction. Increased efficiency over the life cycle of buildings and building subsystems.</td>
<td>Complete, detailed, and up-to-date digital design model. Embedded operational instructions in the digital design model. Cyber-physical control of operations: direct use of the design in carrying out automated operations (e.g., engineering, manufacturing, and installation).</td>
<td>Log house design and construction Model-based software solution for steel structures Digital timber manufacturer Interiors manufacturer Platform-based building designer (partially)</td>
</tr>
</tbody>
</table>

Modular product architecture-driven DDC can be implemented by using make-to-stock or assemble-to-order items and modular building blocks that are designed, fabricated, and installed according to the design model’s specifications. When producing a design based on a digital design model, the control information needed to assemble the product from its components can be embedded in the design model (Främling et al. 2007). With product modularity-driven DDC, the interfaces between product subsystems are standardized, thereby increasing continuous improvement and control and minimizing interpretation and improvisation. This enables the use of permanent design rules in the building design and engineering phases. The focus shifts from designing and
planning the project to the continuous development of scalable modules and module interfaces. These interfaces are then used from project to project and even when updating the existing building. In the case of the modular building contractor, the contractor owned the component designs and interface solutions and developed them throughout the company’s project portfolio. Modular solutions can be an appropriate way of developing innovative design solutions and reducing the cost and improving the quality of buildings (Peltokorpi et al. 2018). Thus, although a modular product architecture may limit some design features, as the number of module and interface variants are finite, it can also provide a cost-efficient path for DDC implementation because the modular product architecture simplifies project management even before it is embedded into the digital design model.

Algorithmic and parametric design-driven DDC relies on the integration between the early design phase and the engineering and production phases up to the level at which some operations—previously requiring human interpretation—are now automated. Parametric design is an algorithm-aided process where various parameters are used to control the design properties (Lalla and Pirhonen 2018). Automating the process of generating construction drawings saves a significant amount of time in the design phase (Manrique et al. 2015). These parametric designs on either the component or building level can be reused; this supports the reuse principle of function and implementation of DDC. Moreover, designers can automatically generate and assess design solutions through parametric design and genetic algorithms (Turrin et al. 2011). This method would generate unique and efficient buildings; however, it would also require investments in systems integration and algorithm development. Moderating the expected investments requires beginning implementation with comparatively simple buildings or the sub-products of those buildings. The partial case examples of log houses, steel structures, furniture, and timber products represent approaches in which focusing on certain materials helps simplify the development of algorithms. The platform-based building developer, by contrast, adopted a whole building solution in which component designs can be used partially or fully in other projects, on the one hand, and modified according to the specific needs of future projects on the other. In summary, it is possible to benefit fully from this practice once the required investments are made in manufacturing technologies, such as assembly and welding robots, or automated computer numerical control operations.

The implementation paths differ from one another according to the required investments. As-built modeling-driven DDC requires major early investments of time and labor at the project level. At the product level, there is also early investment required, although its level is lower. Since DDC includes constant updates on the design model based on changes made during construction, it will also increase the overall quality due to regular checking of the design model’s compatibility with the built reality. As-built modeling-driven DDC enables a single building to be continuously improved over time. However, benefits across buildings are limited if the number of embedded operations instructions remains low.
As-built modeling-based DDC appears to emerge most readily in companies that integrate other companies’ products, while modular product architecture-driven DDC and algorithmic design-driven DDC are typically scaled up by companies with independent manufacturing capacities. Fully modular product architecture-driven DDC in complex products can be achieved with either a vertical integration strategy or a network/SCM strategy, where the construction processes are flexible enough to accommodate the modular DDC approaches.

As-built modeling-driven DDC is flexible enough to be applied to various environments. The state-of-the-art practices show that DDC is possible with both owner-driven and general contractor applications. Broadly speaking, in contractor-driven applications, newly added subcontractors and the need for training can be seen as disadvantages. Moreover, continuous improvement can be constrained due to limited reuse opportunities. The modular building contractor is an example illustrating that the concept can also be applied by a single integrated actor. Modular product architecture-driven DDC is feasible in terms of reuse and continuous improvement; however, problems can arise in terms of the uniqueness of the product when considering the perspective of the end user. Algorithmic and parametric design-driven DDC, by contrast, focuses more on investments in processes and their cyber-physical control instead of product architecture. It is a powerful approach to reduce human interpretation and increase opportunities for reuse. Yet, technically, it can limit the scope of the product and become constrained by the available direct manufacturing technologies.

4.2 Incremental approach – Material kitting

This section is based on “Kitting logistics solution for improving on-site work performance in construction projects” article. The interview results indicated that the overall experience of the actors with kitting logistics solution was positive in terms of the workers’ time when compared with the projects using traditional logistics. Thus, the case company used plans to continue using the practice in its future projects with its partnering logistics service provider. Respondents mentioned that the solution saved workers’ time because they could perform the tasks for which they were hired instead of searching for materials. Even if the costs were not analyzed thoroughly, the interviews indicate that there was no cost difference between Projects 1 and 2.

Daily utilization rates for case Projects 1 and 2 are shown in Figure 7, and Table 4 illustrates the case specifications. The average daily workplace utilization rate for Project 1 with kitting was 38.5%, whereas it was 31.5% for Project 2 with traditional logistics. Because a higher workplace utilization rate suggests better product flow, the logistics solution appeared to improve the product flow, although that could be partly due to random variation. Project 1 was planned to be completed in two weeks; however, it took longer due to customer requirements that were added after the renovation work started.
Figure 7. Distribution of daily workplace utilization rates for Projects 1 and 2.

Figure 8 shows the distribution of the standard deviations of the projects. Standard deviation distribution for Project 1 is between 30% and 50%, whereas it is between 20% and 40% for Project 2. Thus, it can be said that kitting practices may stabilize and improve workplace utilization rates. The standard deviation of the workplace utilization rate for Project 1 was 14.3%, whereas it was 15.5% for Project 2. This indicates that kitting may not only accelerate but also smooth out the daily workflow.

In Projects 3 (with kitting) and 4 (without kitting), branching, tiling, ceiling, and fixtures tasks in the bathrooms were observed. The activities considered value-adding work including necessary work outside the bathroom, treating material outside the bathroom, and value-adding time spent inside the bathroom. The category of treating material outside the bathroom was mainly cutting and forming materials, such as pipes, tiles, gypsum boards, and wooden panels, and dismantling and assembling fixtures. When the worker was getting the required items, the time was counted as fetching materials/tools/both materials and tools, based on the items fetched. Non-value-adding activities might have been conducted in the bathroom; however, the observer could have
distracted the worker by trying to observe these activities inside the tight space of the bathroom. Because the work phases differed from one another, the results were relative to the work content. Furthermore, only one researcher observed the work phases of the projects; due to this limitation, the number of observed bathrooms ranged between two and three per task.

Table 9 displays the average branching time for one bathroom in Projects 3 and 4. For most activities, the amount of time required to complete the task was considerably longer in Project 4, the one without a kitting solution. In terms of labor productivity, considering the total time for which output work was the same for each project, the input of Project 4 was around 1.89 times that of Project 3 with kitting. Thus, it can be concluded that assembly kitting has a major potential to improve productivity during the branching phase. Moreover, the value-adding time required to complete branching in a bathroom was 123% greater when traditional logistics were used, indicating that many necessary but not core assembly activities could be minimized by the kitting solution. Even when the kit collection and on-site delivery times were considered, the project with kitting showed better completion times for bathroom tasks.

Table 9. Average branching time and kit preparation for one bathroom in Projects 3 and 4.

<table>
<thead>
<tr>
<th>Number of bathrooms observed in each project</th>
<th>Project 3 – Kitting</th>
<th>Project 4 – Traditional</th>
<th>Difference (Traditional/Kitting)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total time</td>
<td>4:32:40</td>
<td>8:34:40</td>
<td>+89%</td>
</tr>
<tr>
<td>Value-adding time</td>
<td>2:12:56</td>
<td>4:56:10</td>
<td>+123%</td>
</tr>
<tr>
<td>Share of value-adding time</td>
<td>48.8%</td>
<td>57.5%</td>
<td>+18%</td>
</tr>
<tr>
<td>Time spent in bathroom</td>
<td>1:14:56</td>
<td>3:40:38</td>
<td>+194%</td>
</tr>
<tr>
<td>Treating materials outside the bathroom</td>
<td>0:21:01</td>
<td>0:22:56</td>
<td>+9%</td>
</tr>
<tr>
<td>Fetching materials</td>
<td>0:19:09</td>
<td>0:40:58</td>
<td>+114%</td>
</tr>
<tr>
<td>Fetching materials and tools</td>
<td>0:06:07</td>
<td>0:02:28</td>
<td>-60%</td>
</tr>
<tr>
<td>Number of different activities</td>
<td>220</td>
<td>254</td>
<td>+15%</td>
</tr>
<tr>
<td>Kit collection time in consolidation center</td>
<td>0:36:30</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>On-site kit delivery duration</td>
<td>0:08:25</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

On the other hand, from the worker point of view, the share of value-adding time of the total work time was lower with kitting, indicating that the time saved in material handling was not effectively used in value-adding activities elsewhere. As a proportion of the total time, the time spent on fetching materials was higher in Project 3 than in Project 4. The number of different activities (e.g., how often the worker left the bathroom) indicates there were fewer interruptions to value-adding work when kitting was used.

Table 10 presents the average time spent on tiling activities for one bathroom in Projects 3 and 4. For tiling tasks, Project 4 required 13% more time than Project 3. Assembly kitting was associated with a reduced need for value-adding time and time spent fetching materials and tools, and this saved time for the project as a whole. Furthermore, the number of different activities was lower in Project 3, which indicates fewer interruptions to value-adding activities. On the other hand, on-site delivery of tiling kits took a long time.
Table 10. Average tiling time and kit preparation for one bathroom in Projects 3 and 4.

<table>
<thead>
<tr>
<th>Number of bathrooms observed in each project = 2</th>
<th>Project 3 - Kitting</th>
<th>Project 4 - Traditional</th>
<th>Difference (Traditional/Kitting)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total time</td>
<td>6:23:00</td>
<td>7:11:00</td>
<td>+13%</td>
</tr>
<tr>
<td>Value-adding time</td>
<td>6:00:11</td>
<td>6:19:38</td>
<td>+5%</td>
</tr>
<tr>
<td>Share of value-adding time</td>
<td>94.0%</td>
<td>88.1%</td>
<td>-6%</td>
</tr>
<tr>
<td>Time spent in bathroom</td>
<td>4:24:33</td>
<td>4:30:48</td>
<td>+2%</td>
</tr>
<tr>
<td>Treating materials outside the bathroom</td>
<td>0:38:55</td>
<td>0:42:38</td>
<td>+10%</td>
</tr>
<tr>
<td>Fetching materials</td>
<td>0:23:41</td>
<td>0:25:09</td>
<td>+6%</td>
</tr>
<tr>
<td>Fetching materials and tools</td>
<td>0:01:44</td>
<td>0:07:16</td>
<td>+319%</td>
</tr>
<tr>
<td>Number of different activities</td>
<td>234</td>
<td>303</td>
<td>+29%</td>
</tr>
<tr>
<td>Kit collection time in consolidation center</td>
<td>0:05:36</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>On-site kit delivery duration</td>
<td>0:19:15</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

The average time spent on ceiling activities is presented in Table 11. Project 4 took 3% more time than Project 3 in terms of value-adding time. The results indicate that assembly kitting has a small positive effect on the worker's value-adding time, but that could be due to random variation. The most significant improvement is in the time spent fetching materials. The number of different activities was nearly the same for both projects.

Table 11. Average ceiling time and kit preparation for one bathroom in Projects 3 and 4.

<table>
<thead>
<tr>
<th>Number of bathrooms observed in each project = 2</th>
<th>Project 3 - Kitting</th>
<th>Project 4 - Traditional</th>
<th>Difference (Traditional/Kitting)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total time</td>
<td>3:51:38</td>
<td>3:52:00</td>
<td>+5%</td>
</tr>
<tr>
<td>Value-adding time</td>
<td>2:51:49</td>
<td>2:56:25</td>
<td>+3%</td>
</tr>
<tr>
<td>Share of value-adding time</td>
<td>74.2%</td>
<td>76.0%</td>
<td>-3%</td>
</tr>
<tr>
<td>Time spent in bathroom</td>
<td>1:48:05</td>
<td>1:41:40</td>
<td>-6%</td>
</tr>
<tr>
<td>Treating materials outside the bathroom</td>
<td>0:37:20</td>
<td>0:33:01</td>
<td>-12%</td>
</tr>
<tr>
<td>Fetching materials</td>
<td>0:12:25</td>
<td>0:24:08</td>
<td>+94%</td>
</tr>
<tr>
<td>Fetching materials and tools</td>
<td>0:00:00</td>
<td>0:00:54</td>
<td>N/A</td>
</tr>
<tr>
<td>Number of different activities</td>
<td>181</td>
<td>180</td>
<td>-1%</td>
</tr>
<tr>
<td>Kit collection time in consolidation center</td>
<td>0:38:30</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>On-site kit delivery duration</td>
<td>0:09:46</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

In summary, the analysis revealed that in most cases, kitting improved workers’ productivity; however, when logistics activities were taken into account, productivity gains declined substantially. The kitting practice reduced the number of steps required for the specialized on-site workers to install parts. The interviews revealed that the workers think assembly kitting facilitated their work. The kits were brought to the task location and, based on the workers’ experiences, having the required materials physically closer to the task location allowed them to complete their work more rapidly because they were able to focus on their own tasks. The fixture installers and plumbers in the project with kitting found the practice beneficial because the time spent searching for the right materials was decreased.

Materials listed in the bill of materials (BOM) were identified and classified based on their area of use in the projects with kitting. With the availability of detailed information on the deliveries and the BOM, integrating this information earlier in the planning phase would improve control over subsequent operations. Generating an accurate BOM requires effort from the general contractor and the contractors responsible for purchasing any materials.
Generating an accurate BOM facilitates the kitting solution because information about the kit ingredients and delivery times is readily available.

The general contractor indicated that there was no significant difference in overall project costs when combining a kitting practice along with JIT delivery and a consolidation center versus traditional logistics. Although it was not possible to obtain specific cost data, this general contractor’s statement was noteworthy because there is always some initial cost with kitting, such as collecting the kits and delivering them to the site. Besides the potential decrease in schedule due to improved worker productivity, materials would get damaged less by being delivered as kits when the kitting solution is appropriately applied. Since the solution improves the product flow and requires close collaborations from project partners as well as efficient information flow to be successfully implemented, it can be said that it is a step toward a better integration between construction supply chain and construction project process.

### 4.3 Disruptive approach – 3D concrete printing

This section of this thesis is based on article titled “Additive manufacturing in the construction industry: The comparative competitiveness of 3D concrete printing”. The results illustrated that 3DCP is both time- and cost-competitive with on-site conventional construction. More specifically, it was found that the cost of on-site conventional construction methods for round houses was more than two times higher than that of on-site 3DCP for the same design. This suggests that 3DCP is more cost-effective for the construction of round walls. Similarly, while comparing the cost of the on-site conventional construction methods and on-site 3DCP for a rectangular design, an 80.1% higher cost for the conventional construction method was observed.

Table 12 presents a schedule comparison for all scenarios. The construction process has been divided into three main stages: pre-construction, construction, and post-production. The pre-construction phase in 3DCP scenarios involves all the steps that are required after the architectural design is ready, from construction permits being issued to beginning the actual construction of the building. In the on-site conventional scenarios, pre-construction involves shipping the required steel, timber, and ready-mixed concrete. For scenario 7, the prefabrication scenario, pre-construction involves extracting the concrete component configurations from the design model and the ordering, manufacturing, and shipping time required for these components. On-site 3DCP proved to be significantly more efficient in terms of time than the other scenarios due to the elimination of assembly work. Although a complex design proved to be costly for conventional construction, with 3DCP, it had positive effects on efficiency and process time (Table 12).

The construction stage in the 3DCP scenarios includes the steps related to the printing of the walls and the reinforcement stages of the 3DCP process, which continue until the printing is completed. For conventional on-site scenarios, construction involves formwork, reinforcement, concrete casting, and demolding and cleaning the molds. For Scenario 7—the prefabrication scenario—
construction involves the assembly of concrete wall components and joint concrete work.

The post-production stage in 3DCP scenarios includes disassembly and relocation of the printer, drying the off-site printed wall, transportation to the site, and assembly of the wall modules. For conventional on-site scenarios, the only post-production activity is the drying of the concrete, which can be excluded for estimating the time taken to build 100 houses consecutively. For the S7 prefabrication scenario, post-production involves the drying time of the joint concrete, which is estimated at one day.

As Table 12 shows, off-site 3DCP requires more time for the entire process because of its longer post-production phase.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Pre-construction</th>
<th>Construction</th>
<th>Post-production</th>
<th>Total (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 (ONP-RND)</td>
<td>11 h</td>
<td>21.5 h</td>
<td>3 d</td>
<td>4 d 8.5 h</td>
</tr>
<tr>
<td>S2 (OFP-RND)</td>
<td>8.16 h</td>
<td>21.5 h</td>
<td>14 d 7.5 h</td>
<td>15 d 13.16 h</td>
</tr>
<tr>
<td>S3 (ONC-RND)</td>
<td>2 h</td>
<td>34.4 h</td>
<td>28 d</td>
<td>29 d 12.4 h</td>
</tr>
<tr>
<td>S4 (ONP-RECT)</td>
<td>11 h</td>
<td>27.3 h</td>
<td>3 d</td>
<td>4 d 14.3 h</td>
</tr>
<tr>
<td>S5 (OFP-RECT)</td>
<td>8.16 h</td>
<td>25.3 h</td>
<td>14 d 7.5 h</td>
<td>15 d 16.96 h</td>
</tr>
<tr>
<td>S6 (ONC-RECT)</td>
<td>2 h</td>
<td>35.8 h</td>
<td>28 d</td>
<td>29 d 13.8 h</td>
</tr>
<tr>
<td>S7 (OFC-RECT)</td>
<td>6 months 1 h</td>
<td>30 h</td>
<td>1 d</td>
<td>6 months 2 d 7 h</td>
</tr>
</tbody>
</table>

1 Not fully comparable with other scenarios since these data adopt the subcontractor’s perspective of buying modules from a prefabricated module supplier rather than manufacturing in-house.

Table 13 presents the cost components for all seven investigated scenarios. The percentages refer to the percentage of the cost of the cost items stated in the table to the total cost of a specific scenario. It is notable that the cost of Scenario 3 was about 135% higher than that of Scenario 1, suggesting that 3DCP is more cost-effective for the construction of round houses. This cost saving was due to eliminating formwork by using 3DCP (Sanjayan and Nematollahi 2019). Comparing the costs of Scenario 4 and Scenario 6, a 72.8% cost disadvantage is observed for on-site traditional construction of a rectangular house. While 3DCP was more cost-effective for both round and rectangular designs, this cost advantage eroded when the rectangular design was chosen because it was mold-friendly and less suitable for the size of the AM robot, which needed to be relocated during the process to complete the task. In the conventional scenario calculations (S3 and S6), there was no major machinery cost, and minor machinery costs were included in transportation and labor costs. Hence, there is no separate machinery cost in Table 13 for the on-site conventional construction scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Machinery and production equipment (€)</th>
<th>Material (€)</th>
<th>Labor (€)</th>
<th>Transportation (€)</th>
<th>Total (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 (ONP-RND)</td>
<td>100.27 (2.9%)</td>
<td>1,056.61 (30.4%)</td>
<td>1,934.45 (55.6%)</td>
<td>586.17 (11.1%)</td>
<td>3,477.5</td>
</tr>
<tr>
<td>S2 (OFP-RND)</td>
<td>1,025.71 (20.1%)</td>
<td>1,056.61 (20.7%)</td>
<td>2,165.45 (42.4%)</td>
<td>365 (16.9%)</td>
<td>5,112.77</td>
</tr>
</tbody>
</table>
3DCP in construction can be seen as a step toward a better integration between the construction supply chain with project process as it is cost and schedule-wise competitive to the traditional construction practices and calls for at least vertical integration and managing the inter-organizational processes to have more improved product flow.

### 4.4 Incremental approach – Logistics maturity model

To provide an incremental approach to integrating construction SC with the project process, a logistics maturity model has been developed via publication 4. Companies can use this model to gradually improve their logistics abilities. The model is based on a thorough literature review and validation through industry case examples. Table 14 lists the logistics practices used in the construction industry, along with their benefits, information requirements, the clarity of their benefits, and implementation costs.
<table>
<thead>
<tr>
<th>Logistics practice</th>
<th>Benefits</th>
<th>Information requirements</th>
<th>How clear are the benefits?</th>
<th>Additional implementing cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building design for logistic operations in construction phase</td>
<td>– Temporary openings and logistic routes in the building under construction are considered comprehensively (Skjelbred et al. 2015)</td>
<td>– Finalizing construction drawings at an early stage (Skjelbred et al. 2015)</td>
<td>Somewhat clear</td>
<td>High at first</td>
</tr>
<tr>
<td>Buffer management</td>
<td>– Less time wasted waiting for material delivery (Thomas et al. 1989)</td>
<td>– Bill of materials (Bradley 2015)</td>
<td>Clear (Ballard and Howell 1994)</td>
<td>Medium (storage, insurance costs, etc.) (Bamana et al. 2019)</td>
</tr>
<tr>
<td>Consolidation centers</td>
<td>– Lower inventory costs (Hamzeh et al. 2007)</td>
<td>– Predetermined project schedule (Song et al. 2008)</td>
<td>Somewhat clear (Hamzeh et al. 2007)</td>
<td>Medium</td>
</tr>
<tr>
<td>Material kitting</td>
<td>– Labor performance improvement (Tetik et al. 2020)</td>
<td>– Complete bill of materials (Tetik et al. 2020)</td>
<td>Somewhat clear; more research needed (Tetik et al. 2020)</td>
<td>High</td>
</tr>
<tr>
<td>Takt production</td>
<td>– Reduced completion time (Vatne and Drevland 2016)</td>
<td>– Order of trades’ activities (Vatne and Drevland 2016)</td>
<td>Clear (Vatne and Drevland 2016)</td>
<td>Medium</td>
</tr>
<tr>
<td>Vendor-managed inventory</td>
<td>– Decreased delivery lead time (Fang et al. 2008)</td>
<td>– Contractors’ specific material consumption information records (real-time inventory management system) (Holmstrøm 1998) or kanban cards (pull signals)</td>
<td>Clear (Tat et al. 2013)</td>
<td>High</td>
</tr>
<tr>
<td>Third-party logistics</td>
<td>– Possibility of outsourcing all logistics activity (Bask 2001)</td>
<td>– Assessment of needs determined in the contract (Wagner and Sutter 2012)</td>
<td>Somewhat clear (Ekeskär and Rudberg 2016)</td>
<td>High at first</td>
</tr>
</tbody>
</table>
| Material tracking | – Material visibility (Song et al. 2006) and less loss of materials (Ala-Risku and Kärkkäinen 2006) | – Power or internet connection (Zhao et al. 2019b)  
– Floor plan (Zhao et al. 2019b)  
– Setup and maintenance of the system (Zhao et al. 2019b) | Somewhat clear; more research needed to develop key performance indicators (Zhao et al. 2019a) | Medium; depends on the number of devices and project size (Zhao et al. 2019a) |
|------------------|-----------------------------------------------------------------|-----------------------------------------------------------------|-----------------------------------------------------------------|-----------------------------------------------------------------|
| Results          | – Cost reductions (Lindén and Josephson 2013)  
– Reduced time on material handling (Ekeskår 2016) | – Clear communication throughout the supply chain (Janne and Rudberg 2020) | | |
4.4.1 The construction logistics maturity model

Logistics entails the strategic and cost-effective storage, handling, transportation, and distribution of resources to synchronize SC parties from origin to point of use, taking key times and dates into account (Sullivan et al. 2011). Table 15 presents the definitions of the relevant logistics themes selected for this study. For a construction activity to be completed, it is necessary to plan the resource requirements (planning). The actors who will conduct the tasks must then be determined (organizing). How a specific task is done requires knowledge and capability regarding that task (operations). To keep all participants updated regarding the operations, information flow must be fluent (information flow). For the actors to communicate and the material flow to be controlled, advanced tools must be used (use of technology).

Table 15. Logistics themes determined for maturity model.

<table>
<thead>
<tr>
<th>Themes</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning</td>
<td>Processes for material requirements and delivery planning</td>
</tr>
<tr>
<td>Organizing</td>
<td>Assigning actors to handle specific tasks</td>
</tr>
<tr>
<td>Operations</td>
<td>Practices regarding performing tasks and how each task is done</td>
</tr>
<tr>
<td>Information flow</td>
<td>Practices used in distribution of information and updates</td>
</tr>
<tr>
<td>Technology</td>
<td>Tools and technologies used in resources and information distribution</td>
</tr>
</tbody>
</table>

The first step of each logistics solution starts with activities related to planning, such as determining work locations, lists of materials, and material delivery schedules. Logistics planning involves the coordination of SC and site activities by integrating decision making and recognizing existing interdependencies to minimize the total material management cost (Sait and El-Rayes 2014). Planning is essential if key dates are to be properly aligned.

The organizing theme is key to integrating supply and site decisions. Logistics is related to the distribution of resources and determining the actors and responsibilities that are directly associated with organizing. In its general sense, organizing means “to form into a coherent unity or functioning whole” or “to arrange by systematic planning and united effort” (Merriam-Webster Dictionary 2020), and integration has been a common theme in previously developed maturity models.

Operations management is critical for an organization to succeed (Slack et al. 2010). Transforming inputs into outputs is the fundamental activity of any attempt at production. In an SC, all operations are part of a larger supply network in which each individual contribution serves customer requirements (Slack et al. 2010). Considering the definition of logistics—which means strategically and cost-effectively conducting the required activities from the beginning to the end user—the operations theme is an essential element of the logistics maturity model.

The synchronization of the various parties involved is possible with proper information technology tools and an effective information flow. Inventory, distribution, and return operations must be recorded with the right tools to prevent information and material loss. Construction operations and schedules can be visualized and simulated with commercially available software programs.
Results

50

(Kamat and Martinez 2001). Information technology tools that can be integrated with other project management systems can ease the planning and tracking of logistics operations. Thus, the information flow and use of technology themes were included in the logistics maturity.

Table 16 lists the elements of logistics practice, with increasing maturity in the various logistics themes. The data used in Table 16 were gathered from the literature review.

Table 16. Logistics practice elements listed from low to high in terms of maturity within the themes.

<table>
<thead>
<tr>
<th>Theme</th>
<th>Logistics practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning</td>
<td>Pre-planning of the complete schedule</td>
</tr>
<tr>
<td></td>
<td>Bill of quantities is generated and used in procurement</td>
</tr>
<tr>
<td></td>
<td>Planning of material deliveries is finalized before the start of the project</td>
</tr>
<tr>
<td></td>
<td>Material deliveries are planned together with trade partners</td>
</tr>
<tr>
<td></td>
<td>Design for logistics, layouts and logistics planning finalized at an early stage</td>
</tr>
<tr>
<td></td>
<td>Complete bill of materials manually at the task level</td>
</tr>
<tr>
<td></td>
<td>Complete bill of materials at the task level (generated automatically, using building information modeling)</td>
</tr>
<tr>
<td></td>
<td>Using bill of materials in operations like procurement</td>
</tr>
<tr>
<td>Organizing</td>
<td>Organizing deliveries to the site (e.g., logistics calendar)</td>
</tr>
<tr>
<td></td>
<td>Responsiveness to the changing requirements of material delivery</td>
</tr>
<tr>
<td></td>
<td>Based on project-specific needs, choosing which logistics practices to use</td>
</tr>
<tr>
<td></td>
<td>Centralized procurement of materials</td>
</tr>
<tr>
<td></td>
<td>Third-party logistics services used</td>
</tr>
<tr>
<td></td>
<td>Separate logistics organization inside the company</td>
</tr>
<tr>
<td>Operations</td>
<td>Defined material consumption and delivery quantities</td>
</tr>
<tr>
<td></td>
<td>Determining who handles missing, broken, or extra materials; clear logistics responibilities determined in contract</td>
</tr>
<tr>
<td></td>
<td>Materials arrive using just-in-time delivery</td>
</tr>
<tr>
<td></td>
<td>Preassembly and material kitting</td>
</tr>
<tr>
<td></td>
<td>Moving materials the least possible amount of time on-site</td>
</tr>
<tr>
<td>Technology</td>
<td>Order updates made via phone calls and emails</td>
</tr>
<tr>
<td></td>
<td>Smartphone applications used for material orders and delivery</td>
</tr>
<tr>
<td></td>
<td>Work progress tracking connected with logistics process</td>
</tr>
<tr>
<td></td>
<td>Material delivery tracking using electronic data interchange, radio frequency identfication, cloud, Bluetooth, and/or Wi-Fi for tracking materials</td>
</tr>
<tr>
<td></td>
<td>Material location tracking using electronic data interchange, radio frequency identfication, cloud, Bluetooth, and/or Wi-Fi for tracking materials</td>
</tr>
<tr>
<td></td>
<td>Situational awareness of logistics processes and related work statuses</td>
</tr>
<tr>
<td></td>
<td>Digital product data</td>
</tr>
<tr>
<td>Information</td>
<td>Communication based on one-to-one phone calls and emails</td>
</tr>
<tr>
<td>flow</td>
<td>Mobile chat applications are used with written messages</td>
</tr>
<tr>
<td></td>
<td>Information transparency with third-party logistics</td>
</tr>
<tr>
<td></td>
<td>Information transparency with other actors</td>
</tr>
<tr>
<td></td>
<td>Real-time information sharing systems</td>
</tr>
<tr>
<td></td>
<td>Integrating other information technology tools into on-site logistics calendar</td>
</tr>
<tr>
<td></td>
<td>Automatic order updates and order tracking via special software application</td>
</tr>
</tbody>
</table>

The maturity model in Figure 6 presents the path in each theme: from basic, unmanaged logistics to optimized, industrialized logistics. Table 16 was the primary source for developing the model. The best practice in terms of planning occurs when a company generates a complete list of materials for each task and then uses the list for procurement and the material delivery schedule prior to the start of the project. To execute this practice effectively, companies may start by having the bill of quantities (BOQ) available. Material deliveries should be planned together with project partners. When a complete task-level BOM is available, material deliveries in accurate amounts can be made. It is not always possible to automatically generate a BOM during renovation projects, however,
as the BIM may not be available. Companies can achieve a complete BOM during construction projects by having a complete design model before they begin.

### Figure 9. Construction logistics maturity model.

For the organizing theme, the use of a shared logistics calendar is the minimum practice for integrated logistics. The main contractor can manage the logistics calendar and share it with subcontractors. Organizing which parties are responsible for which logistics practices is crucial for the success of any project. Having a separate unit responsible for logistics decisions or systematically utilizing TPL would be best under the organizing theme.

Regarding the operations theme (which is of course connected to the planning theme), it is vital to decide on delivery quantities based on material consumption. In the basic, unmanaged level, material consumption amounts are simply scattered throughout a project’s subcontractor network; the main contractor does not usually have all this information. The determination of who will handle material logistics should be determined in the contracts. If a company cannot manage JIT delivery, then the benefits from material kitting cannot be fully
realized. Thus, clear logistics responsibilities should be determined in contracts, and JIT delivery, material kitting, and centralized procurement should all be implemented. Material kitting and pre-assembly of materials are considered the best case in this theme due to the high level of information required to implement these solutions.

In the use of the technology theme, the achievement of situational awareness was the best industrialized case, with progress tracked on-site; material delivery fed that progress. Real-time information-sharing systems can aid in achieving maximum situational awareness of material deliveries and work progress. Companies can develop their own material tracking software to increase control over site deliveries or go with commercially available products, with a positive impact on the progress of on-site work.

The most industrialized logistics practice in terms of the information flow theme was having automatic order updates and order tracking via special software applications. The necessary steps to reach this point start with information transparency in terms of materials and delivery among project participants, real-time information sharing, and integrating those tools into a logistics calendar, which is connected to the organizing theme.

The maturity model does have some interdependencies between the items from the different themes, as shown via the arrows in Figure 9. The direction of the arrows indicates the direction from the prerequisite. For instance, for centralized procurement under the organizing theme, a task-level BOM needs to be used, and that is found in the planning theme. Similarly, to be able to integrate a shared logistics calendar with tracking tools, the company first needs to use the shared logistics calendar. To create a BOQ, material consumption quantities need to be available. Overall, the use of real-time information-sharing systems facilitates situational awareness.

The applicability and substance of the proposed model were validated through three industry case examples. The model was first presented to the development and logistics managers of the case companies. Then, they were asked whether their organizations had been following an order of practices similar to what is presented in the model. Based on the collected interview data, the practices of the companies were analyzed to assess the level of compatibility with the proposed model.

4.4.2 Case 1: Large developer

Case 1 operates in Estonia, Russia, and Finland. The company works with a specialized logistics service provider and a logistics labor provider. The logistics service provider focuses on material flow, while the labor provider only provides on-site material-carrying activities. The logistics practices used in projects are determined by the size and location of the project and client-specific requests. For large and challenging projects, the company implements more sophisticated logistics solutions, such as material kitting and takt production.

The company usually does not have BOM information and relies on subcontractors for material information. It tries to enrich its 3D BIM models to have a
more complete BOM and uses a BOQ in procurement. This confirms the best case determined in the model in terms of planning, and the case company is trying to reach this level. The company uses either the TPL’s logistics applications or a simpler version of a logistics calendar in its projects. It also employs an automatized combinatory 3D model system for model updates. At the time of this study, the company did not engage in material or delivery tracking activities. During a project in which the company used takt production, a consolidation center, and TPL, numerous unnecessary material movements were observed on-site.

The most significant lesson from this example was related to avoiding having to move materials on-site multiple times after they were delivered. The root cause of this situation—ordering overly large material buffers—was revealed after interviewing people from a current project and was caused by not using a BOM at the procurement task level. Procuring materials without considering the material needs in a BOM led to the existence of large buffers that then had to be carried back and forth between task locations and inventory. Using a BOM for procurement and thus avoiding unnecessary material movements on-site is important for more efficient material logistics and reducing wasted labor involved in moving materials.

Another observation from this example was the importance of information transparency with the TPL. Several unscheduled deliveries to the site were noted during the observations, which caused problems in the use of the unloading area, as the TPL was not informed about the deliveries. Thus, the material deliveries were not effectively planned with the trade partners. The interviewees mentioned that because of changing project requirements, they had been trying to have a maximum of two weeks of scheduling available at all times. Cooperating properly with the TPL was crucial to avoiding interruptions in ongoing operations.

All in all, the company confirmed that the order of the logistics practices followed in the developed model: it used a BOQ in procurement; a form of shared logistics calendar was used; and it chose which logistics practices were to be combined in the projects. In terms of information flow, it was noted that the material deliveries were handled with a special software solution through the TPL that the company used. In the future, the company will seek to have a complete BOM, available material consumption and delivery quantities, JIT, and material kitting. The company is in the “basic, unmanaged” category and is planning its move to the “advanced, integrated” category.

4.4.3 Case 2: Medium-sized contractor

The second industry example is a medium-sized contractor operating in Finland. At the time of the study, the company had worked for some time with the same logistics provider on its projects and had achieved a centrally coordinated material logistics flow in previous work, including having its TPL provider coordinating consolidation, JIT delivery, and unloading activities. Because many subcontractors preferred to bring their own materials to the site or
consolidation centers, the company was not yet using centralized procurement. In general, communication issues can occur in the use of unloading areas when subcontractors handle their own materials, including unscheduled deliveries.

The company recognized the importance of logistics. It pioneered the material kitting practice with TPL in renovation projects in 2018 (Tetik et al. 2018). Previous research on case projects from the company found that the use of kitting had stabilized assembly work and increased workplace utilization rates and on-site labor productivity (Tetik et al. 2020). It was able to craft a complete delivery schedule during a previous pipe-renovation project in which most of the materials were delivered as kits, which the company achieved by planning with its project partners and then following the plan. Today, the company does not see much value in using the practice for small residential renovation projects, as doing so would require extensive planning, and unexpected events are always a risk due to the demolition that is part of many renovation projects.

At the time of the study, the company was also using takt production in its projects, and TPL had piloted material tracking activities using radio frequency identification tags to track material deliveries. Subcontractors created a BOM during the planning phase, and the company had tried to create a standard list of work orders to have a generic BOM; it would then modify the BOM based on customer-specific requirements. The company used its own application for tracking work progress, although not all site personnel used it effectively. Since it is a medium-size and fairly young company, it is relatively agile and innovative. At the time of the study, the company had experimented with new ways of conducting operations, such as by developing and using its own software applications. Currently, it is taking steps to develop a digital takt production application for monitoring and supporting schedule planning and construction progress. The most significant observation from this case is the effect of the size of its projects (which affects the choice of logistics solutions to be used) and the fact that the logistics solutions that it had pioneered could be discontinued for small renovation projects. The company can be regarded as being in the advanced, toward integrated level, as most current practices fall into this level of the maturity model. The present steps include material delivery tracking, advanced material kitting, complete material delivery schedule, attempts at real-time information-sharing systems, and a systematic use of TPL.

4.4.4 Case 3: Large Nordic contractor

The third example is a large international contractor operating in Europe and the US, although this study only investigated its operations in Finland. The company provides construction and equipment services and residential project development. It values logistics operations (it has had a logistics manager for 13 years) and strives to have its own logistics maturity model. It has piloted all the logistics practices mentioned in Table 4, except for material kitting, which it plans to implement in the near future, along with takt production for building interiors. While the necessary materials are known before construction starts, when exactly these materials will be needed on-site remains unknown.
The company uses a logistics handbook that includes guidelines and best practices for every project. Clear responsibilities are determined in its contracts with subcontractors. The logistics practices intended for each project are determined based on project-specific needs and conditions. For instance, if the project is large, non-residential, inside a city, and facing a tight schedule, then the company uses all possible solutions. It does not use TPL but does have its own logistics manager; also it hires a logistics supervisor for every project.

The company pioneered the use of VMI in the Finnish construction industry. Floor-specific JIT deliveries are used during the structural phase of every project, with a crane lifting the materials in the structural phase before the building envelope is closed. Apart from these differences, the company follows the logical order of the logistics practice elements shown in Table 4. A full procurement plan is based on the BOQ. In some cases, central procurement is used if the subcontractors perform only assembly operations and do not bring their own materials. How the BIM is used depends on the quality and LOD of the model. The company has an initiative to develop an advanced software tool for monitoring real-time takt schedules and sharing schedule performance information between management and employees.

It evaluated the benefits of the various logistics solutions used and decided that the practices were worth implementing due to the resulting savings in costs and time. The problems the company still encounters include incorrectly delivered materials, late or early deliveries, and inappropriate equipment. In addition, the subcontractor may think that every site has a forklift, even if projects normally only have a tower crane, meaning that delivery trucks need to be opened from the top to be unloaded. The company uses logistics calendars and telephone calls to organize material deliveries. Some elements are tracked in real time, from the design phase through to the assembly, and these status data are then compared to the plan. A web-based digital logistics calendar is used in its projects. The company also tries to keep the movement of materials on-site to an absolute minimum.

The most significant observation from this company was that it chose to become competent in using many logistics solutions. Based on project-specific needs, it deployed a combination of the most suitable logistics practices in its repertoire. Its managers felt that having a wide range of logistics capabilities was a key factor in being able to respond effectively, efficiently, and promptly to a project’s unique needs. In interviews, company managers confirmed that the order of the logistics activities presented in the model is logical and that they have largely followed it in their real-world operations. The company is in the advanced, toward integrated level and is approaching the optimized, industrialized level.

4.4.5 Answering the guiding questions

For an optimal order of logistics practices, the companies began their efforts to achieve better logistics by having a fruitful planning phase in which they tried to make schedules available and obtain a complete BOQ. The companies
decided on the logistics practice elements to be implemented based on project-specific conditions, such as project size, the physical conditions of the site, and the distance to the city center. The first logistics practice that Case 3 ever implemented was VMI, meaning that project-specific conditions played a significant role. As such, companies may choose not to follow the logical order reported in this study.

The analysis indicated that the most important theme was planning, followed by organizing. Every project started with the planning phase, with companies putting a great deal of effort into this phase. Based on industry examples, the work did not progress well unless the project and material delivery schedules for the subsequent two weeks were available. It was noted that it was vital to determine which party was responsible for which tasks. Use of technology and information flow were found to be supporting themes. Thus, every theme does not need to reach the same level. That is why there are no strict lines between the basic, advanced, and optimized levels, as the progress in each theme can occur at a different pace. Similarly, a company can be between two adjoining maturity levels. While planning was the most important, even with adequate planning, on-site problems could still occur due to the persistence of traditional construction site culture. Based on industry examples, companies could still regard situations as common occurrences if, for example, some of the labor force did not show up on schedule or if, even though there is no on-site storage, a month’s worth of materials were unloaded on the site without warning.

The company interviewees mentioned that they still use the logistics practices they had tried because they were worth implementing. For instance, Case 3 had long used a form of kitting in the structural phase because it increased the company’s logistics performance. Similarly, Case 1 considered decreasing unnecessary material movements on-site by adjusting the buffer amount. Information on the level of financial gain from the practices was confidential. Thus, this study concludes that continuing to employ the practices meant that better performance was achieved.

Managing logistics operations and forming partnerships with logistics service providers necessitate strategically collaborating with supply chain partners to manage the processes within the company or among project actors. Most of the logistics practices reviewed here intrinsically aim at improving the information and product flows. Hence, improving logistics capabilities contributes to integrating the construction supply chain with the construction project process.
5. Discussion

This chapter discusses the contributions of this dissertation to research and offers managerial implications. An account of the study’s limitations is followed by suggestions for future research.

The aim of this research was to investigate the approaches—and the impacts of those approaches—to find solutions for the multiple generic problems encountered in the construction industry with integrating the project process with the SC. Four approaches were explored in the disruptive and incremental categories. To implement the disruptive solutions studied in this work, a fundamental approach is needed. For instance, the SC when using 3DCP in construction is notably different from the conventional construction SC due to the different production processes that 3DCP uses, entails, and omits. Thus, this new integrated solution replaces existing project process and SCs. At the same time, practices that belong to the incremental category can be adopted by construction companies while sustaining the existing SC structure. These incremental advances can be regarded as short-term solutions to the integration problem. Since the construction industry is known to be slow in adopting new technologies and practices, incremental solutions are also required to treat the integration problem of construction project processes and SCs.

The four publications together reveal a profound understanding of the issues that construction professionals face due to the industry’s integration problems and the solutions to those problems. Research on DDC proposed an operations management concept that impacts the entire life cycle of a building and offered implementation paths for the practitioners. The new concept, DDC, helps address issues related to improvisations, interpretations, incomplete design models, updates of design models, and a lack of reuse. Using 3DCP in construction is another way to move closer to a full DDC implementation. This research investigates the impacts of concrete printing on cost and schedule. Research on kitting investigates the impacts of a logistics solution that improves labor productivity by proper logistics management, thus tackling the stubbornly low productivity found in the construction industry. Finally, publication 4 provides a logistics maturity model for companies to assess where they are on that scale and a roadmap to improve their current level.

Among the four approaches presented in this summary, research on material kitting and 3DCP are largely empirical, whereas the research on logistics maturity model and DDC are relatively conceptual. However, even if DDC is more
abstract as a concept, it has been validated by industry. Evidence from the industry examples that already use its operational practice elements illustrate the feasibility of the DDC concept and its potential to offer a comprehensive solution to the integration challenge. In due course, instantiations of this concept will be more and more visible in industry practices. To give an overview, DDC should not be understood as an extreme solution that focuses only on technologies like AM, which are applicable to a limited range of subsystems and operations. Some of the components of DDC are in fact highly general and can be used in a wide range of projects. Moreover, industry or SC actors can begin by building a subsystem and gradually moving toward a complete design model-directed approach to their tasks.

Previous research suggests that, even as solving the integration problem is an important aim, attention should also be paid to increasing resource utilization (Bankvall et al. 2010). One approach presented in this dissertation focuses on increasing the workplace utilization rate through material kitting and using accurate BOMs for procurement, so that the materials are ordered in appropriate quantities. Research on the logistics maturity model also promotes using BOM for procurement. Hence, these approaches aim at improving resource utilization. Furthermore, research on DDC highlights a major untapped design resource: reusing design models. Thus, this summary addresses the integration problem of the construction project process and the SC by investigating and reporting on both incremental and disruptive solutions that aim at increasing resource utilization.

All in all, although the construction industry may be slow to adopt new approaches, it is necessary to have an open-minded approach about exploring and adopting possible solutions for the integration problem in that sector. While opportunities offered by novel production and operation management practices could be explored, it would also be beneficial to implement incremental practices to both advance the integration issue and develop a knowledge base that can later serve for a disruptive solution. The theoretical and practical contributions of this dissertation are discussed in greater detail in the following sections. The findings of this study could aid construction industry professionals to evaluate the specific problems they encounter and find the most appropriate solution.

5.1 Theoretical contributions

This dissertation contributes to several research streams, including the SCM literature, specifically in construction. Integrating the construction SC with the project process has been discussed in the literature (Dainty et al. 2001; Briscoe and Dainty 2005), but the approaches presented here offer a new view on solving the multiple and generically different problems faced in the construction industry by integrating the construction SC and the project process. This integration decreases costs, improves information sharing, aids responsiveness to changes, and facilitates decision-making activities (Cheng et al. 2010). The approaches presented in this thesis confirm the measurable impacts of integration efforts, such as 3DCP decreasing the cost of building houses or the logistics
maturity model aiding the decision-making activities of construction professionals. Finalizing the design of a built product early as suggested by DDC improves information sharing and decision making.

This research contributes to the four roles of SC in construction (Vrijhoef and Koskela 2000). Research on material kitting and the logistics maturity model relate to improving the SC itself and the interface between site activities and the SC. Logistics operations coordinate the core elements in a project, such as materials, workers, and information, to prevent interruptions to production. Material kitting can stabilize assembly work and improve the workplace utilization rate and on-site labor productivity (Tetik et al. 2021). All four publications relate to the integration of the site and the SC. For instance, DDC provides adaptability for the operations for the full life cycle of a building; when a change is made, the design model is reconfigured. Moreover, logistics practices can help stabilize the SC. Research on 3DCP explores both off-site and on-site production, which relates to transferring activities from the site to other points along the SC.

IC offers meticulous planning and control of the construction process and a tight coupling between design and operations management (Lessing et al. 2015). The DDC concept also increases control over operations and is a step toward more industrialized practices. Industrialized house building relates more to the standardization of the building parts and prefabrication, while DDC’s standardization focus is on processes and design models. The characteristics of industrialized house building include customer and market focus (Lessing 2006), neither of which has been considered in this study. However, both practices aim at continuous improvements of systems and processes.

DDC suggests that a solid connection between design and operations can be formed by embedding operational instructions into the digital design model. The difference between DDC and IC or DT is that DDC aims to solve the issue of integrating the construction project process and the SC from a more comprehensive view. IC is more focused on prefabrication and standardization, while DT usage area needs to be expanded to take the SC perspective more fully into account. In terms of DDC constructs, DT involves a digital design model; however, embedded operational instructions in the digital design model construct are not aligned in these two concepts.

This thesis contributes to production methods in construction, specifically using 3DCP in the construction sector. Publication 3 analyzed the effects of different SC configurations for building small houses with 3DCP and conventional methods in terms of costs and completion time. Although the construction industry is one of the least automated sectors and has suffered from stagnant productivity until recently, the digital transformation due to the emergence of new tools like 3DCP promises exciting, even epochal, changes on the horizon (Ghaffar and Mullet 2018). The research reported here indicates that 3DCP in construction is competitive with conventional construction practices in terms of cost and completion time for two different design options. 3DCP should thus be considered by practitioners in construction in any number of contexts.

This dissertation also contributes to the material logistics literature. Previously, a form of kitting for construction was described by Tanskanen et al.
(2009), with the materials delivered in the right amount at the right time, so that no on-site inventory space is needed to store them. However, the effects of apartment-based kitting practices in the construction industry have not yet been covered by the literature. The research on material kitting detailed in publication 2 and this summary measured the impacts of this logistics practice on the construction context. Kitting was found to stabilize production and align the SC with the project process. Material kitting must be linked to a redesign of the general production model toward a synchronized production system (Tetik et al. 2021). Moreover, having a complete and accurate BOM is important for kitting, because avoiding ordering too many materials is a key pillar of the kitting concept. On-site operations would be in greater harmony with material deliveries when applying kitting solutions.

Publication 4 proposes a logistics maturity model for construction firms. Maturity models exist in construction (Vaidyanathan and Howell 2007; Meng et al. 2011; Zhao et al. 2013), however, they have not focused directly on the logistics aspect. The maturity model that was developed consists of five themes: planning, organizing, operations, technology, and information flow. Building on previously developed maturity models in the logistics field, logistics maturity was evaluated in this model based on similar themes, although it is focused more on themes that are highly relevant to construction logistics. Previously developed logistics maturity models are not domain-specific and lack an overall evaluation of maturity.

5.2 Managerial implications

This dissertation has several practical implications for construction practitioners. First, the findings inform managers about the design-based control of construction operations. The involvement of construction expertise early in the project process is necessary to reduce the risk of creating designs that cannot be efficiently built (Bakti et al. 2011). Improving the efficiency and productivity of construction projects by direct digital control of construction operations is possible based on a complete design model (Tetik et al. 2019). In this way, the construction project process can be more closely integrated with the SC, as all the operations in a building’s life cycle are controlled by a single and comprehensive digital model.

Finding similarities in projects and their internal processes can help in outlining the most common problems and critical factors that would allow projects to be categorized; for example, they could be classified by their challenges and variety of logistics needs (Kiljunen 2009). DDC can increase the reuse possibilities of design models in the operations of different projects, and digital design models are an untapped resource that can be reused between projects.

Research on DDC provides avenues to develop production strategies and inherent technological capabilities that drive quality improvement and more efficient operations. It underlines the need for close integration between design, production, and maintenance operations if such development efforts are to be successful. The DDC concept and its implementation paths suggest how construction practitioners can benefit from DDM principles and cyber-physical
operations originally developed in manufacturing. Publication 1 describes the logic of how investments in design-based operations can be recouped over a building’s life cycle and by investments in future projects. The study also highlights the role of diminished human interpretation, decreased improvisation and reuse, and continuous improvement of designs and control systems as key mechanisms to realize the quality and cost benefits of the DDC concept.

Effective customization is enabled by open design platforms on which designers can use detailed component designs already on the platforms to come up with unique building designs. Effective customization makes the whole design and engineering process faster and more affordable. If the design is not shared openly or initial designers or design owners decide not to reuse a design in further projects, the value of reusability may be lost. On the other hand, if the owner, contractor, or designer has access to the design model and uses it in further operations, efficiency would increase over both the life cycle of buildings and up and down the SC, with potential mistakes prevented by up-to-date design models in future operations. Continuous improvement can eventually lead to maximum automation in all operational phases: engineering, manufacturing, logistics, installation, and maintenance. DDC potentially forms a basis for automating management and design and some assembly activities. It can also require more labor resources to conduct site surveying in As-built modeling driven DDC.

Second, the dissertation raises awareness of the potential of 3DCP for construction. Using 3DCP decreases the labor intensity of construction operations (Chen 2019). Publication 3 confirms this, as building a structure with 3DCP significantly decreased the reliance on labor on the job site. In addition, the analysis in publication 3 revealed that 3DCP is more cost-effective for building complex structures. 3DCP can also be used in areas that are dangerous for humans, such as disaster areas, or during health crises, like COVID-19, that limit the ability of people to gather in close spaces. Houses can be printed with only two workers using 3DCP, and the concrete elements of a house can be produced more quickly. 3DCP can offer a solution for situations that require rapid construction of housing stock. By comparing the completion time and costs of a 3D-printed house with a conventionally built one, practitioners can make more informed choices of production methods.

The construction industry is highly regulated, which is one reason why 3DCP has not yet significantly disrupted the sector. Different national, regional, and local governments have their own construction standards, and approval processes also vary—sometimes to a great degree—by jurisdiction. The use of 3DCP in construction has not yet been incorporated into construction standards (Gaudillière et al. 2020), which poses challenges in terms of regulatory approval. Most building codes and procurement standards still have not assessed 3DCP technology (Elnaeeem and Taglsir 2002); thus, 3DCP companies follow generic, already established construction standards in their respective locations. This makes the 3DCP construction approval process longer than the one used for traditional construction methods. Currently, structural tests are being conducted, and technical recommendations will eventually be made based on...
such empirical findings (Diks 2019). Other 3D printing methods already have established standards, and 3DCP is now moving in the same direction. In the 3DCP field, a global effort is underway to establish new draft standards, such as the 3DCP Standard (ISO/ASTM 529XX PWI Additive Manufacturing for Construction—Qualification Principles—structural and infrastructure) (ISO 2021). Many stakeholders, including materials manufacturing companies, construction firms, and 3D printing providers are working together to develop standards for 3DCP. This standardization can facilitate regulation and streamline the acquisition of construction permits for houses built with AM technology.

For construction and logistics practitioners, this research offers deep insights into how to implement specific logistics solutions. The discussion of the construction logistics maturity model contributes to construction logistics practice by describing how companies can navigate maturity levels to gradually improve their logistics practices. They can first assess their logistics maturity and then use the developed maturity model as a roadmap to improve their capabilities. Logistics operations support on-site activities; in so doing, they contribute to better aligning the SC with the project process.

Research on the construction logistics maturity model indicates that material consumption and delivery quantities are important resources that the companies examined in this study could tap. The case analysis showed that unnecessary material movement on-site should be avoided by having only the proper amounts of material buffers on-site. BOMs must be available and used during operations to determine those adequate buffer amounts. These findings are in line with those in the existing literature on moving materials several times on the job site after they have been unloaded (e.g., Elfving et al. 2010).

Moreover, publication 4 shows that advanced logistics operations may only be conducted based on a complete design model, more specifically a complete BOM. Design models should have adequate LODs to be able to create robust BOQs and BOMs (Mousharbash 2020). Increased LODs in design models could open possibilities for digital product data linked to BIM. Expending efforts under the technology and planning themes associated with increased LODs in design models and complete BOMs could lead to the use of extremely accurate models that leave no room for improvisation. The use of a BIM model with a high LOD completed prior to the start of a project may enable using the same design model in subsequent operations, thus aligning with IC practices such as DDC (Tetik et al. 2019). As an operations management practice, DDC entails the use of a complete digital design model over a building’s life cycle to prevent improvisations and improve the reusability and automation of designs and processes across projects. The present study indicates that the use of advanced and industrialized logistics processes could be a crucial step toward digital operations at the whole-project level.

Another specific contribution to logistics involves the effectiveness of material kitting in facilitating a smooth-running job site. Publication 2 investigates the impacts of material kitting assembly logistics solution on performance. It was found to be most beneficial for construction tasks that have many small accessories and materials. This solution requires careful and detailed planning to be
successful. Thus, practitioners thinking of implementing this solution should compare the costs and benefits of applying it carefully. Furthermore, the material kitting practice is better suited to renovation projects than to conventional building projects.

Change will not come to the construction industry overnight. While holding out the possibility that a practice will disrupt the construction SC, practices that incrementally improve the current situation are useful in the present day for construction companies to enhance their operational performance.

5.3 Limitations

This research is limited due to the number of case studies and their contexts. For instance, in publication 2, the case studies were all renovation projects, so the impacts of material kitting were investigated only in renovation projects. Moreover, the observed case projects are residential buildings. Any potential impacts on non-residential projects were not investigated. Since on-site and camera-based observations are labor-intensive, the number of case studies was limited, given the length of a PhD program. In addition, even if the cost analysis indicated that the benefits of kitting would offset its initial costs, that analysis was approximate because the authors could not obtain all the task-specific cost data from the companies, which regarded those data as confidential information.

Another limitation involves the method of observing the impacts of 3DCP as a disruptive-empirical practice. The first plan to conduct this research was actually printing the houses in real life instead of employing a scenario analysis. The 3D printing machine was in Estonia and, due to COVID-19, traveling between the two countries was not allowed for a lengthy period. Thus, this research needed to proceed with scenario analysis. Furthermore, the research was limited to investigating the effects of only a few house design variations. Finally, gantry-based 3DCP was not studied.

One other limitation is that the validation methods used in publication 1 regarding the DDC concept are mostly conceptual and theoretical. In terms of design science research, the concept is a design proposal and hardly a field-tested and evidence-based design. In addition, when this research was conducted, there was not much information about the actual time and cost savings from the case companies. Moreover, the scope of the partial case examples is limited due to a variety of material and technical factors. On a different but related note, the case studies included cases from different countries. This approach may have introduced country- and culture-specific biases into the findings.

Another limitation is the light emphasis on the human aspect with regards to the supply chain integration with construction project process. The research mostly focuses on process and technology-based solutions and their impacts on operations and performance. Especially for the logistics maturity model and kitting logistics solution, leadership, work culture, motivation of the workers, individual differences and people aspect could have also been explored. For DDC,
the impacts of potential automation on labor needs have not been considered during this research. The scope of this research does not cover these aspects.

5.4 Future research

This dissertation opens several new avenues for further research and practice. Future research should study the proposed disruptive and incremental solutions more thoroughly from the strategic, contextual, and operational perspectives. Moreover, impacts of the four approaches detailed here need to be observed over a longer time horizon. Specifically, the impacts of material logistics must be further investigated in specific project contexts and settings. Using material kitting logistics solutions in construction is beneficial for stabilizing the productivity of on-site assembly. Measuring the impact of this solution requires a more autonomous approach because the methods used for measurements in the kitting logistics solution study reported here—video camera-based measurement and observation—are laborious and thus limited the number of projects that could be observed and analyzed. Thus, Wi-Fi- or Bluetooth-based tracking methods can be explored to investigate the impacts of kitting in a greater number of projects.

In addition, the projects where material kitting was investigated for publication 2 were all renovations, and this solution might be more suitable for that kind of undertaking. The impacts of using kitting in new-build construction projects should be investigated in enough depth to determine whether it is worth implementing in that context, as kitting requires intensive planning. Future research should compare the different assembly kit strategies of several projects and analyze not only work performance but also other aspects: safety, direct and indirect costs, sustainability, kit dwell times, and so on. For example, whether the kits were fully consumed on the job site could further enhance the understanding of the impact of kitting on waste. The results presented here are indicative of the theoretical benefits of kitting, and more controlled experiments should be conducted. During the study, different data collection methods were used for different projects because it was not possible to analyze all aspects in all projects. Future research should invest in more comprehensive data collection strategies, with multiple methods used simultaneously on a single project. Hence, further research should analyze different project contexts and take a more longitudinal approach to develop a kitting solution while examining the different aspects through which kitting practices could affect a construction project.

Second, to investigate the real cost and schedule of printing small houses and building them with conventional and prefabrication methods, a real-life project could be used. The results can be compared to the costs and schedules of the scenarios in publication 3 to assess the accuracy of the scenario analysis. Moreover, based on the material selection, the quality of houses can differ, and this can also be further investigated. Finally, future research can focus on cost and
schedule comparisons of different 3DCP methods and with a wider range of traditional construction methods.

Third, there is a need for in-depth field testing and obtaining empirical evidence of the DDC concept proposed here. Publication 1 only covers the development of the concept and its validation. Applications of DDC can be explored to reveal its real-world costs and benefits. The customer value and architectural perspectives should be considered in terms of reusing the same designs in different projects, because some, perhaps many, customers may prefer original designs. In addition, the ownership issues regarding the product designs and control system in DDC require further research.

The impacts of the technology and process-based innovations on human experience could be explored in the future. Moreover, future research should investigate the human aspects on a company's logistics maturity and implementation of different logistics solutions, including the role of leadership, trust, work safety and motivation.

The construction industry's adaptation of the DDC concept requires increased efforts from individual organizations and company networks to overcome short-sightedness and recognize the life cycle benefits of its implementation. Future research should further analyze existing and emerging examples of DDC applications by using objective data to evaluate the long-term impact of DDC on construction operations. More knowledge is also required concerning the endeavors of traditional AEC companies in moving toward DDC principles in their operations. In general, further research is advised to concentrate on measuring the costs and benefits of the DDC concept.
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