Direct digital construction: Technology-based operations management practice for continuous improvement of construction industry performance

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A B S T R A C T

Construction operations suffer from fragmented structures and loose coupling among project actors. Building on direct digital manufacturing (DDM), we describe direct digital construction (DDC) as a technology-based operations management practice aiming to improve construction performance through design reuse and diminished human interpretation. We develop the operational principles, describe the operations in practice, and identify alternative implementation paths based on case examples of partial implementations. The core principle of the practice is to direct the value-adding operations over the building's lifecycle through the digital design model, resulting in increased reusability, project-specific differentiation, and automation of designs and processes across projects. Three implementation paths are identified: (a) as-built modeling-driven path, (b) modular product architecture-driven path, and (c) algorithmic and parametric design-driven path for the incremental transformation of the construction industry.

1. Introduction

The fragmented structure of construction projects has inhibited the construction industry's development in terms of efficiency and productivity [1]. Construction projects are loosely connected to other projects, leading their own life, with limited past or future coordination and learning between projects [2]. As a result, the reuse of project designs and plans remains an untapped source in performance improvement. Furthermore, construction tasks within individual projects are also loosely coupled with one another, undermining the performance of many projects [3]. This loose coupling of tasks and participants from different domains is partially due to the fragmented structure of the construction industry on the one hand [4] and the operational practice of time-limited involvement of actors in task-specific work on the other. Each of these actors relies on his or her own interpretation of how to move the project forward from one stage to another [5]. Improvisations in the construction process are frequent, emanating from unplanned, emergent situations [6]. Improvisations occur because limited time is allocated to secure additional planning resources when something unexpected happens [7]. However, improvisations also occur because certain tasks and task interfaces are intentionally left un-designed. Moreover, because of their different backgrounds, the actors involved in the project can interpret the designs differently, leading to improvised alignment actions and outcomes that are different from the original intention.

When designs allow interpretation, the actors concerned are required to have special skills and commit efforts to interpret what has been designed correctly [5]. Even when human interpretation and the resulting improvisation are considered appropriate [8], relying on expert and tacit knowledge often creates problems in the future [9]. Merschbrock and Wahid [10] document a case where an improvisation in the use of building information modeling (BIM) technology in a loosely coupled system later resulted in errors, costly production, and additional working hours. By contrast, industrialized construction is characterized by rigorous planning and control of the construction process, increasing upfront costs, and requiring tightly coupled design and management of the operations [11]. Well-prepared operations with complete design from the beginning lead to the smooth execution of operations and decreased defects [12]. Thus, there is an opportunity to improve the efficiency and productivity of construction through direct digital control of the construction operations based on the complete design.

The purpose of this paper is to develop a new operations management practice—DDC—based on a combination of technology-based operations practices from the construction industry and manufacturing. We elaborate on the application of this practice in the construction

Table 1
Forming DDC from existing technology-based practices—commonalities and differences of existing practices and DDC.

Operational practice elements	BIM	VDC	DDM	Required new operations management practice
Digital design	Yes	Yes	Yes	Yes
Design-based production	Yes, but limited	Yes	Yes	Yes
Cyber-physical control of production	No	Yes, but limited	Yes	Yes
Design-based operations beyond production	No	Yes	No	Yes
Cyber-physical control of operations beyond production	No	No	No	Yes
Reuse and improvement of digital designs and cyber-physical controls	No	No	No	Yes

industry through different implementation paths to enable continuous improvement. The remainder of this paper is structured as follows. First, we establish the requirements for the new operations management practice by analyzing the commonalities and differences of the existing technology-based operations management practices. Next, we justify and describe our research approach, design science research [13]. We then present our case examples to introduce the specific problems by the new solution development, and describe the elements of the operations practice design already implemented in the construction industry. We use design theory [14] to structure and report the design of the novel operations practice and its alternative implementation paths. The conclusion section will present the theoretical contribution, explain the limitations of the research, and recommend directions for further research.

2. The need for DDC: commonalities and differences of technology-based operations management practices

Before we describe DDC in detail, we review the technology-based practices on which the novel operations management practice builds and investigate their commonalities and differences (Table 1). As a technology-enabled operations management practice, DDC builds on Building Information Modeling (BIM), Virtual Design and Construction (VDC), and Direct Digital Manufacturing (DDM). The gap in current research concerns the absence of an operations management practice that combines the unique practice elements of VDC and DDM. DDC relies on digital design and design-based production, which are common for both VDC and DDM. Besides, DDC draws on the unique practice element of cyber-physical control of production from DDM and the extension of design-based operations beyond production from VDC. 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 [15]. Attempts have been made to apply the CPS approach in construction to real-time bi-directional coordination and communication between virtual models and physical construction [16]. We extend this research by focusing on a technology-based operations management practice that not only coordinates the virtual and physical worlds but in which a digital design prevents harmful interpretations and improvisations in future operations. Also, the new elements of DDC missing in both VDC and DDM are cyber-physical controls on operations beyond production, which include logistics and lifecycle operations in use phase and the purposeful reuse and improvement of digital designs and controls of operational processes.

Digital building models can be used as information stores in the design and construction phases and in the use and maintenance phases without using either design-based production or cyber-physical control. However, when an operation is carried out in an improvised manner without been specified in the digital design model, the succeeding operations in the use and maintenance phases begin with inaccurate information and inadequate initial conditions that had been left undocumented. A digitalized operation relying on BIM leads to differences between as-designed [17,18], as-planned [19], and as-built [20–22]. Creating virtual buildings through BIM promises that the design models can replicate real buildings. However, very few examples in the

industry relying on BIM suggest that this has been achieved. BIM can be developed for the as-designed status; however, it will not reflect the details of the as-built reality [21].

Similar to the fragmented construction industry characteristics, BIM is a multifaceted approach that involves multiple stages of implementation and many different capabilities; it is also affected by project networks and supply chain interdependencies [23]. The challenges include problems with information exchange and integration, data interoperability, and computability [24]. Construction projects often undergo changes during their lifecycles, resulting in differences between the intended design and end product [24]. Information about the project is typically recreated between five and eight times during the various phases of the project [25]. This indicates that simply increasing design resources is hardly a solution to human interpretation and reuse challenges. Without design-based production and cyber-physical control, the design models are not kept up to date while production and operations are being carried out. Therefore, there is a need for an operations management practice where operations are both planned and carried out based on the digital design model.

VDC uses the digital design model to model and plan the multidisciplinary execution of design-construction projects, enabling achieving explicit and public business objectives [26]. Luth [27] states that VDC is the process of utilizing accurate three-dimensional (3D) building information models for facilitating visualization, simulation, communication, coordination, estimation, purchasing, and scheduling. This concept allows all actors to access a project's shared data. On the advanced maturity levels of VDC, cyber-physical control of fabrication and building of subassemblies in a factory have been added [26]. However, in the construction industry, project orientation of design and delivery limits the benefits from investments in design-based production and operations to individual projects. Moreover, BIM focusing on building elements of VDC model can bring disadvantages due to management issues requiring process interactions (see Table 1) [26]. Furthermore, VDC as an operational practice does not explicitly aim to reuse the designs and process controls to prevent improvisations and improve productivity across projects. Therefore, integrated project delivery (IPD) and partnering have been suggested as appropriate contractual forms to incentivize actors to invest in VDC [28]. VDC together with IPD would increase the use of construction knowledge upstream in the design process and development of detailed design at an earlier stage [29], both of which are needed for more automated design and construction. The challenge of introducing VDC is that it requires firms to invest in the operational practice more than the value they can capture in a single project [26]. Therefore, we argue that new, technology-based operations practices that focus on the continuous improvement of the firm- and supply chain-level operational performance need to be developed; this calls for the reuse of design and operating models beyond a single project lifecycle.

In DDM, the focus is on using the digital design model for the efficient production or fabrication of customized design of parts. The direct cyber-physical control of manufacturing offers a potential solution element to minimize improvisation while improving efficiency and customization in the construction value chain. In manufacturing industries, the concept of DDM is popular because of its ability to resolve customization and reusability issues by combining digital design with

cyber-physical control of production [30]. DDM is a technology-based operations management practice where the 3D computer-aided design (CAD) models are used directly to manufacture end-use parts with additive manufacturing [31], for example. DDM uses additive manufacturing, computer-numerical-controlled (CNC) machines, computer-aided manufacturing (CAM), and computer-aided engineering (CAE) [32]. DDM reduces the time and cost required for the design and manufacturing of individual items, eliminates the need for tooling, and offers customization possibilities to satisfy different customers' requirements effectively [30,33].

DDM is an important operational practice in implementing the vision of Industry 4.0 and Construction 4.0, as its potential counterpart in the construction industry [34]. However, because of the highly variable maturity level of digital manufacturing in the construction industry, adapting the practice poses several challenges. The cyber-physical control and reuse of designs need to be supported by operational practice elements from both BIM and VDC. Actors in construction need to address many issues, such as data security, implementation costs, and process changes [34], the resolution of which takes time. Here, BIM is available to address the collaboration, integration, and interoperability issues [35]. VDC is available to align the design model with different operations and actors within the project and building lifecycles [36].

As DDM has been developed in manufacturing industries with stable product design and supply chains, the development of a new practice such as DDC should allow handling higher levels of customization and assembly activities on customer sites in construction. Partial implementations of DDC involving combining digital design and BIM-based automated construction for structures, i.e. [37], are available. However, the holistic design of the technology-based operational practice of DDC construction is needed to support the paradigm shift from a project orientation to solution orientation in architectural design and construction [38]. For this task, we will adopt a design science approach [39].

3. Methods

Building on the existing technology-based operations management practices, this research aims to design and describe a new operations management practice for construction. Closely working with the practice in steering the design toward providing a solution to real-world problems, design science research is a suitable approach to develop and evaluate solutions to organizational and operational problems [39]. We chose the design science approach because design science identifies the problems that practitioners usually face, defines the objectives of a solution by asking what would a better artifact accomplish, and then designs and develops the artifact to use it to solve the problem in a proper context [39]. It then observes the effectiveness of the artifact in solving practitioners' initial problems. We adopted this approach to solve the fundamental issues concerning limited productivity improvement, excessive improvisation, and lack of learning in the construction industry.

Designs in design research can be operational concepts and practices, implementation methods, and example artifacts [39]. In our research, DDC, as a new technology-based operations management practice, proposed solutions to the problems that construction industry practitioners face, such as common interpretation, improvisation, and lack of reuse. The development of the DDC concept requires describing its design and implementation components based on the design science approach. While design science seeks to generate new knowledge on solving organizational problems, design theory offers to codify and generalize aspects of the created knowledge [40]. Gregor and Jones' [14] design theory posits that the design of a new concept or practice can be structured using the components listed and described in Table 2. We apply this model by focusing on the purpose and scope of the new practice, its constructs, principles of its form and function, implementation principles, and expository instantiations, which are the case examples.

In our research process, we utilized the four phases of research for design exploration and theory building in operations management research [13]. These phases (see below) represent the movement from new to tested ideas, mid-range theory, and formal theory:

1) We first framed the problem and collected fragments from practice for a potential solution design;
2) The initial proposal for a solution design was then subjected to further development using inputs from cases which adopt required operational elements of the new operations management practice;
3) The findings were generalized, and a theoretical contribution was demonstrated in terms of novel insights in the research literature; and
4) The findings were presented more formally as design theory.

Fig. 1 illustrates our research process more closely: In the first phase, two case examples of the state-of-the-art BIM practices from the field are analyzed to frame the problem, determine the issues requiring new solutions, and propose the purpose for a new practice. In the second phase of our research process, six partial case examples are explored to develop a solution proposal, namely the DDC operational practice. The six cases partially implement the required operational practice elements (Table 1) beyond the mere digital design and design-based production in specific firms or supply chains. Our research process investigates what these partial solutions are; it also investigates what the approaches to solve the issues identified in the problem-framing phase are. In the third and fourth phases, design theory [14] is utilized to frame the opportunities and problems in the six cases; this is followed by formalizing the proposed operational practice. The last part of our research process corresponds to generalizing the findings, demonstrating its theoretical contribution, and presenting the design theory for the DDC concept.

According to Denscombe [41], case studies are suitable for understanding the complex relationship between various factors that operate in a specific social setting. To understand the current level of implementation of technology-based practices in the industry and observe our rudimentary solution design in a real-life context, we chose a case study method as part of our design science research approach, conducting eight case studies in total.

First, we analyzed two different leading-edge attempts to have the match between as-designed models and as-built models; we also described the benefits and shortcomings of each. This was done to gain insights into the state-of-the-art attempts to create a constructible design model that can be followed in construction without allowing improvisations intending to achieve an accurate as-built model in the end. One of the authors conducted a field study, which included interviews and site visits to the two case companies.

Following these two in-depth case studies, we analyzed six case examples to elaborate on DDC's design theory components. The six cases were selected based on their partial physical implementation of the required six operational practice elements (Table 1) required for the new technology-based operations management practices. We used an exploratory approach, selecting cases with different settings via theoretical sampling [42]. The cases do not represent any countries or building types; however, they all exhibit some exceptions from the traditional fragmented practices and are selected purely based on their elements related to the required new operations management practice, such as the cyber-physical control of production and the reuse and continuous improvement of digital designs. The analysis of the six cases was performed to understand how the identified weaknesses of the leading-edge as-built modeling practices were solved in the cases and to identify implementation principles for the DDC elements.

We used multiple data sources in our cases, including interviews, observations, official documents, and public sources concerning the case companies and their solutions. In the case studies, semi-structured

Table 2
Design theory components and their descriptions [14].

| Component	Description
Purpose and scope	Describe what the system is for; state the requirements and specify the type of entity to which the design theory applies along with various scope elements
Constructs	Comprise representations of the object of interest
Principles of form and function	Present the abstract blueprint that describes the structure and functionality
Principles of implementation	Describe the processes used to implement the theory in a certain context
Expository instantiation	A physical implementation that helps illustrate the theory as an example or for testing purposes
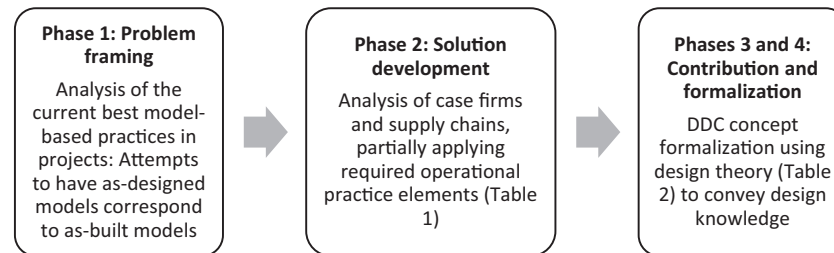
Fig. 1. Research process.

interviews were conducted to collect data on solutions as well as their development, features, effects, and challenges. According to Brinkmann [43], semi-structured interviews allow data to contain more spontaneous descriptions. Thus, the interviews with the company managers of the state-of-the-art practices included semi-structured questions to obtain a profound understanding of the level of application of the concept and suggesting further implementation possibilities. In the six partial solution cases, we interviewed solution developers and managers. We also utilized the available video materials, webinars, documents, and news articles in professional journals to obtain a comprehensive view of the solutions and validate our interview data. Finally, the concept was validated along with its novelty and usability in a focus group discussion with 12 professionals from the architecture, engineering, and construction (AEC) industry. More information about the collated data from the cases is presented in Appendix A. Finally, the design principles and implementation paths of the DDC concept and inherent operational elements were presented by discussing the findings related to the best as-built modeling practices and partial solutions of the six cases in light of the existing literature.

4. Problem framing: state-of-the-art practices in matching the as-designed model with the as-built reality

The exploration to match the as-designed model with the as-built reality started with interviewing the managers from the two state-of-the-art projects. To achieve a design-based production, these companies followed two different sophisticated processes, as described below.

4.1. Case 1: As-built modeling contractor

Our first case company is a general contractor. This contractor updates models during projects so that the design models can be built without improvisation and the final updated 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. It has a sophisticated process of documenting the as-built and controlling the as-built reality against the design model. The operations are as follows. The external design companies develop the models to a level of detail (LOD) of 290, meaning that each element is designed with an approximate shape, location, size, and orientation without precise information, such as the model number, supplier, or exact location. Thus, the designers do not have to specify the exact dimensions and location information—precise detailing is the contractor's responsibility. Then,

the contractor makes the models buildable with his or her detailing team. This yields a construction model that is accurate, coordinated, and leaves no room for improvisation. The contractor can build the design model using a systematic controlling process, modify the designs immediately if there are deviations from the design, and follow these modified designs closely. Not only does this approach to securing accurate modeling at the outset of the process minimize the chances of interpretation in later designs and operations, but it also decreases iterations, which often arise when the design is not sufficiently complete at the beginning.

To ensure that the construction model is adhered to in the field, drawings are extracted from the 3D model, and the quality of the on-site work is controlled every day. A full-time surveyor checks the field using a robotic total station with up to 600 measurement points per day and compares it back to the model before and after the installation. Any deviations are checked against the drawings, and corrections are made either in the model or in the field, depending on the severity of the issue. All subcontractors must control the quality of their work. If they lack surveying capability (most do), they can purchase surveying services from the case company. Since the case company does not seek profit on providing this service, it is the most affordable solution for the subcontractors. In the end, surveying does not incur costs for the case company.

The case company does not change the design model if there is only a minor deviation in the as-built reality that would not matter in subsequent processes, such as centimeter differences in areas where there is no requirement for small tolerances. The company shifted considerable design scope from the designers to the case company's detailers and shifted work from the subcontractors to the detailers. In this way, the case company could assure a high-quality construction model to ensure that it could be built as designed. 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 reduced, the 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. Moreover, the subcontractors also profited from the practice. Furthermore, the process led to increased quality and saved hours in the subsequent phases of the project. The owner paid for the 10,000 h because it would be saved 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. However, the company experienced challenges in convincing the owners and subcontractors to invest more money earlier in the process, hoping that the money would be saved later. Owners were convinced by learning about the benefits of having an accurate as-built model. The savings, profits, and quality enhancements of the previous projects increase the credibility of the practice and hence convince the prospective project stakeholders.

4.2. Case 2: the school developer

Another state-of-the-art case example is a school construction project. In this project, the as-designed model and built reality were ultimately matched. This requirement was driven by the owner developer. The analysis of the interview data shows that the motivation behind this complete match was the desire to omit any inaccuracies in the renovation and maintenance operations of the buildings. The owner developer of the school wanted the designs to exactly represent the building since it was important to avoid information loss; besides, up-to-date information was desired when renovation and annual repairs were 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 that everything was constructed according to the design model. They also participated in the construction management meetings and actively collaborated with the workers on site. The designers were always available in case of a need for a design change. This presence ensured that the contractor did not have to improvise and that the as-built model always followed the as-designed model. The design contract comprised a target/ceiling price and was paid according to an hourly rate. The developer also partnered with several design companies with agreed hourly rates and often asked the partners for estimates. Sometimes, the designers issued change orders to follow the process. The contractor was responsible for assessing the BIM model and giving feedback on its constructability if any issues arose or improvement suggestions were offered. The designers subsequently performed the necessary design changes. They modeled the building to the required LOD so that everything could be installed according to the design model.

The owner developer of the school kept the models up to date and was able to utilize the same design model (from 10 years ago) in the design of a new renovation operation with no deviations from the design model on the construction site. Based on the owner developer's experience, in ordinary projects, many subcontractors 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 analysis of the interview data indicates that no other companies invest in this practice because it is easier to stop updating models. Considerable staff training is necessary to achieve the desired match between the design model and the actual building, which can incur enormous costs. The owner developer of the school emphasized the significance of interaction in the team for keeping the models up to date. Moreover, in comparison with other companies' traditional practices, the developer allocated substantial additional resources to the design phase. However, it was considered that a lack of investment in better design would increase the workload at the subsequent stages on the worksite. Thus, investing in a detailed and complete design model pays off in the construction and maintenance phases.

4.3. Summary of the state-of-the-art solutions

Table 3 summarizes the practices and their purpose and scope elements in the state-of-the-art cases. The state-of-the-art examples show

that design-based production is possible in the fragmented and project-based practice of the current construction industry, although some weaknesses persist. For as-designed models to match the as-built reality, companies need to invest substantial time and labor in the construction project's early phases. Our analyses suggest that both case companies found it useful to have a detailed and complete as-built model as these investments can be recouped in future operations.

The weaknesses identified in these two current best BIM practices mainly relate to the high need for labor and training. In the as-built modeling contractor's case, each project had a new group of stakeholders: different owners, designers, and subcontractors. Although the process is highly transferable across different project types, transferring the process through different project teams requires training. For instance, the contractor's detailers had a different starting point each time in case examples. They could standardize some of the details, although they still had to carry out substantial custom work. In the school developer case, the public owner developer had to select the design teams and contractors competitively. Therefore, they needed considerable training for each new team and project. It is unclear whether any transferable knowledge other than the knowledge related to the training materials had been developed in this organization. Design solutions remain with the design teams; however, each project had a new design team. Therefore, process and design models that could be utilized in other school projects were not purposefully reused.

Fig. 2 presents the DDC logic in the state-of-the-art cases compared to the more traditional construction practice where the design model is not kept up to date. The iterations between the design and construction phases preclude improvising and having to interpret the design models. In practice, both case examples had expanded the role of the design phase and design resources to design the building and assembly work more comprehensively and keep the design model up to date. We call this "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 utilized during the lifecycle of the building, it is not clear whether it could be reused when designing new buildings. Thus, the challenges of the state-of-the-art practices include the additional labor time required to keep the designs up to date and the limited opportunities for reusing the models between projects.

5. Solution development: partial DDC solutions

We next analyze the six case examples to investigate the ways of solving the detected problems with the current best practices explained in the previous section. These six case examples were selected to illustrate the adoption of the required operational practice elements (Table 1) 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 the 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. Fig. 3 illustrates the workflow of construction operations for log house production. In this case example, the software developer developed custom libraries for wooden log house design and fabrication. The log house architects use the program's custom libraries to model log houses in a BIM environment according to the customer requirements. The program automatically decomposes the log house design into building components and their respective locations. In this solution, the set of tasks to be performed on the building is fully specified by the design eliminating the possibility of misinterpretation and improvisation. The design model is directly transformed into a machine-readable file to be

Table 3
Purpose and scope elements of the state-of-the-art cases.

Practice	Purpose and scope
Surveying up to 600 points at the construction site every day to ensure as-designed models corresponded to as-built models	+ Substantial savings on time and quality error costs + Accurate as-built models −/+ Investment in planning to obtain a buildable model that can be constructed without improvisations – Additional man-hours spent on surveying – Difficult to convince owners and subcontractors
Designers involved in the construction phase to ensure as-designed models corresponded to as-built models	+ Accurate as-built models + Savings in construction, maintenance and renovation phases – Increased scope of work for the designers – Need for training

Note: + denotes an advantage; − denotes a disadvantage.

used in CNC production for manufacturing the logs. The design model also defines loads and logistic kits for site deliveries and provides on-site assembly instructions for the parts. The instructions (i.e., the process information) are generated using the digital design model. Hence, in log house production projects, it is possible to use the digital design models directly in many operations and minimize human interpretation in all process interfaces. The solution also automates the work of structural designers and production planners. 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 case 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. The robots produce welds in an automated manner and based on the digital model. Thus, the practice enables the digital designs to be used in different projects in whole or in part. The accuracy level of these operations is extremely high. With this practice, the design model becomes the built reality. Moreover, the same models can be used during maintenance operations. For example, when the sensors detect a malfunction in a structure, the software displays the parts. These parts are used in different areas of the structure in the updated digital design model allowing other malfunctions to be checked and prevented.

The third partial DDC case is a modular building contractor. In this

contractor's solution, the prefabricated modular components fit into one another. The fitting wall system can create different types of room arrangements or partitions, and these can be changed if required. The contractor stresses the importance of the early planning phase and precise service descriptions. Moreover, the contractor standardizes the invisible building components, such as the shell and supporting structure, although it leaves room for individual choices when it comes to the visible components of the building (e.g., the façade). The models for the 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 in assembly, and additional design work can be directed toward improving and optimizing single components.

The fourth partial DDC case is a direct digital timber and steel manufacturer. This manufacturer emphasizes an integrated approach in the early design phase. They use 3D CAM/CAD software, which includes production and logistics information in the design model. This practice reduces the need for costly redesigns and changes. Hence, they insert material properties, such as strength, into the design model only once. The virtual building process used identifies potential geometric and installation issues before construction work, so no material or labor is wasted. With this solution, customized and complex structures are built according to the design model with a high level of accuracy.

A similar approach is also adopted for the customized interior architecture area. The fifth case is a company that produces customized
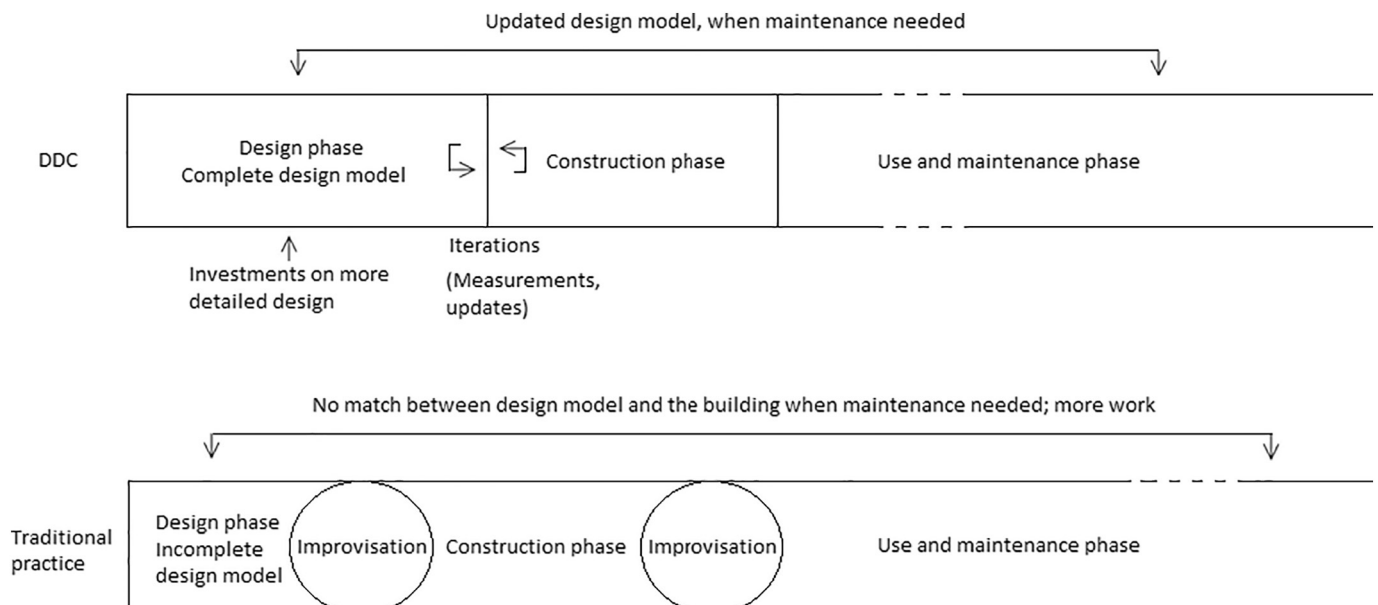

Fig. 2. DDC logic in the state-of-the-art modeling cases in comparison with the traditional practice—the first version of as-built modeling-driven DDC.
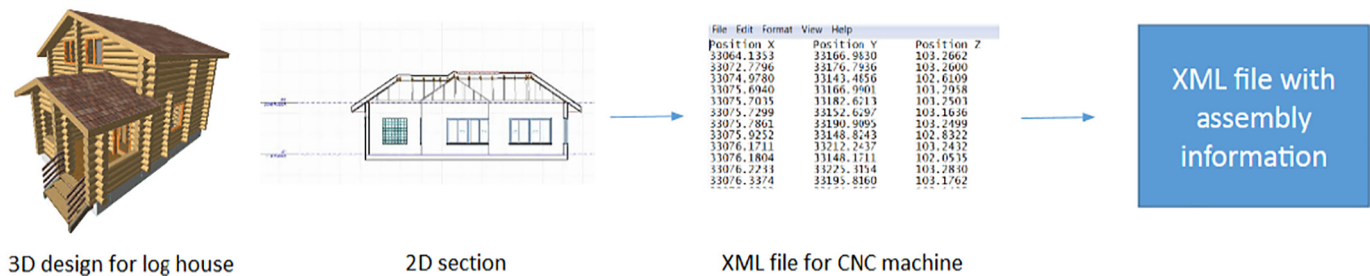
Fig. 3. Construction workflow of a log house company.

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 then increases the control over what is being built mainly because no worker is required to interpret the installation drawings. The used software platform enables the company to build exactly what has been designed. Moreover, the design, engineering, manufacturing, and installation operations are tracked on the same platform.

The sixth case is a platform-based building designer who works as an integrated design and operations consultant and uses earlier components and models for guiding the construction of future buildings. The company has developed three open design platforms for different building types, which include 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, the production can be automated on the site. The company aims to refine and improve the common elements by reusing the 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. The same components and manufacturing process can be used for different project types and sizes. Thus, the company develops assets that include repeating components that fit into specific locations and architectural designs. Having a detailed design model that comprises component designs makes it possible to achieve a complete match between 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. Table 4 shows the advantages and disadvantages of 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, we propose that the required operational practice elements are applicable to the construction environment and that the partial solutions have addressed the problems of the state-of-the-art cases. Reuse of the designs and process information are possible in most of the case example. Increased specifications of design models result in increased constructability of models and ensure high accuracy levels. However, albeit for a few of the aforementioned 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 to ensure design-based and computer-controlled operations. However, because the same models in both building design and the cyber-physical system 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 utilizing the same operations technology.

The first five partial solution examples were driven by the company responsible for the delivery of building components and installation

work. In the last one, the designer was driving the process; it works in a project environment and creates unique products with a standard platform. In contrast, the state-of-the-art cases were driven by the owner or general contractor in a project environment with multiple stakeholders. Furthermore, the cases illustrate that the DDC concept can be utilized by companies with vertically integrated supply chains that drive their own product range and designs for controlling construction operations directly from a digital design model, such as in the modular building case.

6. Concept formalization: the DDC components

Building on the findings from the eight case examples, the concept of DDC and its principles are presented in Table 5 using design theory [14]. 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 lifecycle of the buildings or building subsystems. All operations including maintenance and renovation can be conducted based on the same, accurate and complete model. Based on the case studies presented in this paper, these complete design models would also increase the opportunity for reusing the entire or partial product and process models in different construction projects. Design patterns in the architecture field involve different ways of building. Although they are different in detail, they are similar in their general outline [44]. Thus, although the buildings are unique, the processes needed to build them can be similar, partially the same or the same. Therefore, the design and process models can be reused between the projects. Similarly, standardized components, component interfaces, and sub-product structures can be reused between the projects. In addition, by repetitively reusing and improving the previous solutions that have been proven to be efficient, the quality and efficiency of the products and processes can be improved over time with the refined design model in each iteration. Since with DDC, everything 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 best designs enable continuous improvement over time.

The constructs represent the elements that are utilized to achieve the targets of the proposed concept. Considering the state-of-the-art case examples and partial cases, having complete, detailed, and up-to-date digital design models with embedded operation instructions represent the most significant constructs of DDC design theory. To achieve this goal, design models must have a high LOD. The design models should be complete before the start of the operations and should be kept up to date. Operation instructions should also be embedded in the design model. Product information (e.g., LOD 300 level) and instructions on how to produce the product or its sub-part (e.g., LOD 350) should 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 interfaces and inherent technology interfaces. Table 5 also presents the principles of function and implementation elements for DDC practice. A fully implemented DDC enables all value-adding operations over the lifecycle of

Table 4
Advantages and disadvantages of partial case solutions.

Case companies	Advantages/disadvantages
Log house design and construction	+ 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
Model-based software solution for steel structures	+ Cyber-physical control of welding and maintenance operations + High level of accuracy due to model-based automated process + Investment in the design phase is paid back through reuse − Constrained by manufacturing technologies
Modular building contractor	+ Design-based configuration and assembly + Continuously optimizing design through reuse and adaptation of component designs + Efficiency improves as investments are directed to component development, not interface management − Limited cyber-physical control but likely implementation in future
Digital timber and steel manufacturer	+ 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
Interior manufacturer	+ Cyber-physical control of interior product manufacturing + Design-based installation + Investment in the design phase is paid back through reuse − Constrained by manufacturing technologies
Platform-based building designer	+ 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

Note: + denotes advantage; − denotes disadvantage.

a building, from its design to its 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 the construction operations [12].

Fig. 4 compares the operations of traditional construction practice and DDC concept. It shows that in the case of DDC with a detailed and complete design model, there is no distinction between the as-designed, planned, and built models since the design model is identical to the built model. To minimize interpretation and improvisation in operations, not only is the connection between design model and operations bi-directional [16] but complete design models from previous projects, including operations instructions, are also reused to reduce the need for project-specific changes. Models can be reused both at the level of product designs and process control designs by utilizing cyber-physical systems in operations. Designers can customize designs at project level either through component configuration or through changing parametric values. Effective customization is enabled by open design platforms as in the cases of the platform-based building developer and the log house developer whereby designers can utilize detailed component designs from the platforms to come up with unique building design.

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 the design in further projects, the value of reusability may be lost. On the other hand, if the owner, contractor, or designer has access to design model and they utilize it in further operations, this would lead to increased efficiency over the lifecycle of both building and supply chain when potential mistakes are prevented by the up-to-date design model in future operations. Continuous improvement can eventually lead to automation in all the operation phases, including engineering, manufacturing, logistics, installation, and maintenance.

The effectiveness and applicability of the concept were validated by a focus group session with 12 design, development, and business managers from AEC companies. In the session, the components of the DDC concept (Table 5), benefits and disadvantages of the partial case solutions (Table 4), and comparisons between the traditional construction practice and the DDC concept (Fig. 4) were first presented to the participants. After that, the following three questions were debated:

- Are you familiar with similar concepts? *(the novelty of the concept)*

Table 5
The components of the DDC concept.

| Design theory components	DDC concept	Evidence from case studies
Purpose and scope	• As-designed corresponds to as-built • Increased efficiency over the lifecycle of buildings and building subsystems • Increased reuse of designs and process control models between projects	• Based on state-of-the-art case analyses, as-designed corresponding to as-built leads to improvements in the later phases of buildings' lifecycles. • Based on the state-of-the-art and partial case examples, utilizing the same design in whole or in part increases quality and decreases project cost
Constructs	• Complete, detailed, and up-to-date digital design model • Embedded operation instructions in the digital design model	• Limit the improvisations and enable the use of the same model in every operation • Increase control over later operations through cyber-physical systems
Principles of function and implementation	• Direct use of the design model when carrying out operations: Engineering, manufacturing, logistics, installation, use, and maintenance • Design model, including operation instructions, can be reused, adapted, and improved continuously at both the building and building subsystem levels • Operations and buildings incrementally develop toward DDC	• Utilizing the same digital model in design, logistics, and assembly operations in partial DDC examples and state-of-the-art case examples • The original investment in the design model and cyber-physical control systems are recouped through reuse between projects. • Alternative implementation paths toward DDC are available
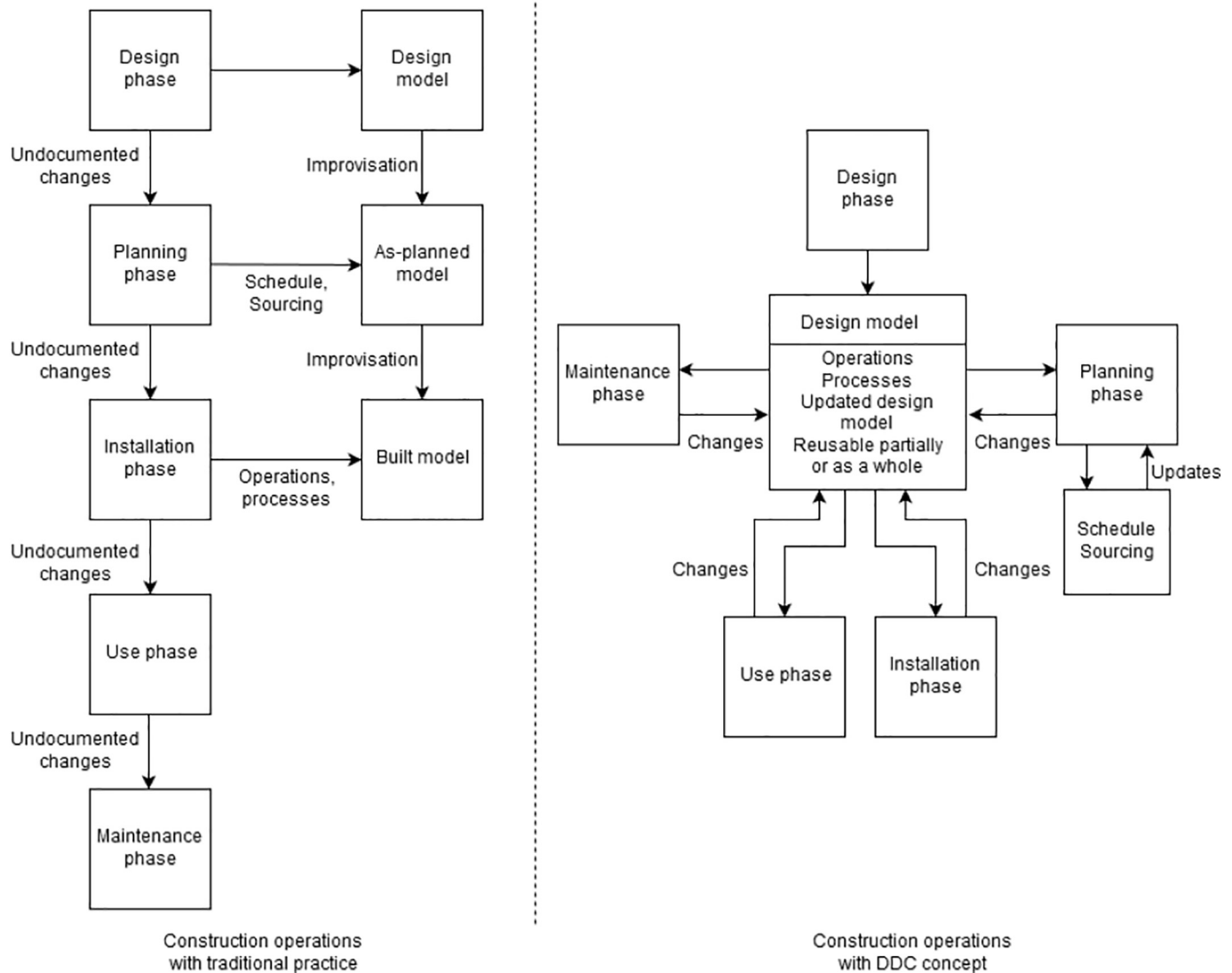
Fig. 4. Comparison of traditional construction practice and the DDC concept.

- In which situations can the DDC concept be useful? *(application area)*
- How can the current practices be transformed into the DDC way? *(implementation)*

The participants found it useful to conduct construction operations with methods drawing on the DDC concept. Some discussed industry practices that partially resemble the DDC concept, such as laser surveying for MEP installation to match the model with reality. For the application area, one representative mentioned that in tandem with the development of design automation algorithms, the concept could be utilized in solutions that involve prefabrication mainly because it is currently suffering from human errors. They also cited several examples of how DDC could improve construction operations: The concept can enable continuous improvement in design and building phases because it requires performing the installations precisely according to the design model. Thus, when the operations closely follow the design model, hardly any error will occur during the installation phase, and thus, no rework will be required. Since the design represents the exact building, further operations such as use and maintenance tend to begin with more accurate information. The representatives mentioned that during the facility management phase, updating the models is currently very complicated. Utilizing the same model in every operation and then in

another project will help in refining the model, leading to continuous improvements, both in design and subsequent operations. The representatives emphasized that every actor has the model in his or her own server; they added that he or she works like silos while the owners do not value the digital model. They raised questions such as who owns the model and how every actor can access it. They also suggested that the value of having updated and complete model should be communicated to the actors.

7. Alternative paths of implementation for DDC

After developing the design theory elements for DDC, we now discuss the case examples to illustrate their DDC elements and identify alternative paths of implementation. Table 6 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 ways that the DDC is implemented. Based on the various practices (both common and different) of the case examples and literature, we argue that DDC can be approached using three alternative implementation paths:

Table 6
DDC elements of case examples and implementation paths.

Implementation path	DDC purpose and scope elements	DDC constructs, functions, and implementation	Case examples
As-built modeling-driven DDC	As-designed corresponds to as-built Increased efficiency over the lifecycle of a building	Complete, detailed, and up-to-date digital design model	As-built modeling contractor School developer
Modular product architecture-driven DDC	As-designed corresponds to as-built Increased reuse of design and process models between projects in construction Increased efficiency over the lifecycle of buildings and building subsystems	Complete, detailed, and up-to-date digital design model Design-based operations: Embedded operation instructions in the digital design model	Modular building contractor Platform-based building designer (partially)
Algorithmic and parametric design-driven DDC	As-designed corresponds to as-built Increased reuse of design and process models between projects in construction Increased efficiency over the lifecycle of buildings and building subsystems	Complete, detailed, and up-to-date digital design model Embedded operation 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)	Log house design and construction Model-based software solution for steel structures Digital timber manufacturer Interiors manufacturer Platform-based building designer (partially)

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 in [45]. This approach validates the intended design before passing it to the manufacturer. This approach supports DDC by highlighting the DDC construct on having complete and detailed digital design models.

Modular product architecture-driven DDC can be implemented by utilizing make-to-stock or assemble-to-order items and modular building blocks that are designed, fabricated, and installed according to the specifications of the design model. When producing a design that is based on a digital design model, the control information needed to assemble the product from its components can be embedded in the design model [46]. 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 utilized 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 his or her project portfolio. Modular solutions can be an appropriate way of developing innovative design solutions and improving the cost and quality of the buildings [47]. Thus, although a modular product architecture may limit some design features, as the number of module and interface variants are finite, it would also provide a cost-efficient path for the DDC implementation because the modular product architecture would simplify the 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 also automated. Parametric design is an algorithm-aided process where various parameters are used to control the design properties [48]. Automating the process of

generating construction drawings saves a significant amount of time in the design phase [49]. 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 via parametric design and genetic algorithms [50]. 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 rather simple buildings or the sub-products of those buildings. The partial case examples of log houses, steel structures, furniture, and timber products represent approaches whereby focusing on certain materials helps in simplifying the development of algorithms. The platform-based building developer, in 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 in the 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 CNC operations.

The implementation paths differ from each other 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, the required early investment is still present, although it is reduced. Since DDC includes constant updates on the design model according to the changes made during construction, it will also increase the overall quality due to the regular checking of the design model's compatibility and 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 seems to emerge 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/supply chain management strategy, where the construction processes are flexible enough to accommodate the modular DDC approaches.

As-built modeling-driven DDC is sufficiently flexible to be applied to various environments. The state-of-the-art practices show that DDC is possible with both owner-driven and general contractor-driven

applications. In general, 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 is also applicable 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 end-user perspective. Algorithmic and parametric design-driven DDC, in 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.

8. Discussion

The developed design solution for DDC and the identified alternative paths to implement it suggest that the construction industry can increase the quality and efficiency of operations by adopting various elements of technology-based operations management practices. The practices from the field show that having a complete, up-to-date, and continuously improving design model with embedded operational information and cyber-physical control in operations is feasible in the construction industry.

DDC should not be understood as an extreme solution that focuses on technologies only, such as additive manufacturing, which are applicable only in a limited range of subsystems and operations. Some of the components of DDC are highly general and can be utilized in various building investments and products. Moreover, the industry or supply chain can begin by building a subsystem and gradually moving toward completely design model-directed building investments. The inefficient construction industry can be disrupted, although it is unclear how this can be achieved (i.e., through a technological revolution, with innovations in other fields, market disruption, or another means of change). Thus, this paper explored the potential approaches on how buildings may be built and used more efficiently in the meantime i.e. without any improvisations, rework, and interpretation, and with more reuse activities.

The research identified three alternative paths to implement the concept of DDC, and they can be utilized in sequence. The first level of DDC is the as-built modeling-driven path. Reusing the as-built model in new projects is an appropriate way of obtaining a return on the investment made initially by utilizing the concept. The AEC industry has experienced problems with reusing digital data [51]. Increased reuse through the DDC concept in projects that are partially similar or identical [52] enables the required investment of time and effort to be recouped over many individual project lifecycles. The analysis of the interviews conducted with the state-of-the-art case companies revealed that the process is the same among the projects; however, the content changes from project to project. Thus, solution opportunities must seek the recouping of the initial investment inside a single project along with the reusability of the solution in future projects in whole or in part.

The more advanced level of DDC favors offerings with more productized ways of manufacturing mainly because DDC can be used with modularized product offerings. Introducing modularization in manufacturing when the design requirements are incomplete and fluctuate from project to project is problematic [53]. Our analysis of the case examples yielded similar results. Having a completed representation of the construction product is one of the constructs of DDC. Moreover, similar to the modular production offerings, prefabricated structures can also be used when DDC is applied. The prefabrication of building parts leads to continuous improvements and the industrialization of the construction [11]. Thus, DDC creates opportunities for industrialized construction with the offerings of modular and prefabricated products.

Owners and contractors can use the as-built driven path to gravitate

toward other paths to achieve automation and cyber-physical control possibilities. From as-built modeling-driven logic, a company can develop toward modular product architecture-driven DDC by re-developing its best as-built solutions to achieve standardized solution components and their interfaces. Alternatively, the company can choose to utilize its as-built designs to better direct and control engineering, manufacturing, and assembly operations, thus moving toward algorithmic and parametric DDC logic with computer-based control of operations. Similarly, the modular product-driven path can be extended to cyber-physical operations by developing assembly automation of modules or by utilizing sensors, which are embedded in the physical product when controlling the use phase of the building. This combination requires further development in certain processes and technologies, although it will enable the full use of DDC in future operations.

Regarding the most advanced level of DDC application, this study indicates that the problem of large investments of additional labor in the design phase in state-of-the-art BIM practices can be compensated for with algorithmic and parametric designs. When using parametric systems [54], updating digital design models becomes less labor intensive. Besides, algorithmic architecture [55] can be used in the design phase to create model drawings in a time-efficient way. Design models that are created algorithmically can compensate for labor costs by shortening the design phase and eventually, the project time. Moreover, platforms provide opportunities for reusing designs of components or buildings, which can also bring about savings in the design phase while still providing constructible design models. Thus, the drawbacks of investing in the design phase can be eliminated by exploring the less costly designs created via such technical solutions while implementing DDC. These solutions can be driven by the owners, manufacturers, and general contractors, making sure that the subcontractors and manufacturers have the required production capabilities.

Augmenting the current best practices of partial solutions opens up future automation opportunities for even more complete DDC solutions. Most of the cases represent opportunities for cyber-physical control of building part production based on the detailed design and even the establishment of direct or automated logistics, installation, and maintenance operations. Identifying a malfunction and using that information in quality control and preventive maintenance of all steel products is a notable example of those opportunities. Similarly, the log house design and construction solution are automated until the assembly phase, and manual assembly instructions can be extracted from the program. The solutions can be augmented by directing future investments to areas in which potential benefits are the most promising. For example, the log house solution can be extended to an automated design model-directed installation and collection of status information of log structures in the use phase.

Additive manufacturing and 3D printing present specific opportunities for the expansion of DDC. The 3D printing [56] that uses digital design models, such as 3D CAD models [57], enables manufacturing operations to be directly controlled by the design model. Hence, 3D printing of buildings has potential mainly because the as-built model and reality are the same, as DDC suggests. To further improve this practice, it is necessary to conduct the manufacturing operation *and* other operations (e.g., logistics and maintenance) based on the same digital design model. This would ensure direct and digitally controlled operations. The same 3D design model can be reused in another project. Thus, using 3D printing technology in construction operations constitutes the potential for benefiting from DDC.

The theoretical contribution of this research involves combining previous knowledge of as-built BIM, VDC, and DDM with the operations management of construction projects by developing the concept of DDC. The research broadens the possibilities of using as-built BIM models, VDC practices, and novel design methods (e.g., parametric, algorithm, and modular design) by better connecting the design concepts with all other operations of the building lifecycle. The

contribution and novelty of this study do not lie in the technology but instead in how the proposed technologies, such as Construction 4.0 [27], can be used to improve construction operations management in supply chains and firms' processes that are not project specific. The connection between design and operations can be formed by embedding the operation instructions into the digital design model. In addition, the research shows that novel design methods, such as algorithmic design, can fix labor problems encountered in the state-of-the-art as-built BIM practices.

For practitioners, this research provides avenues to develop production strategies and inherent technological capabilities toward higher quality and more efficient operations. The research underlines the need for integration between design, production, and maintenance operations in such development efforts. The DDC concept and its implementation paths suggest how construction practitioners can benefit from DDM principles and cyber-physical operations originally developed in the manufacturing industry. This study describes the logic of how investments in design-based operations can pay back in buildings' lifecycle and investments of 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 quality and cost benefits of the DDC concept.

9. Limitations and further research

Despite delving into the existing literature on technology-based practices and using multiple cases to increase the validity of the invented concept, this research has several limitations, which can be addressed in further research. First, our concept validation is mostly conceptual and theoretical. In terms of design science research, the practice is a design proposal and hardly a field-tested and evidence-based design as yet. We acknowledge this limitation and appreciate the need for in-depth research into the field-testing and empirical evidence of the invented DDC concept.

During the development of this paper, we did not have much information about the actual time and cost savings from the case companies. The application and measurement of the benefits of the DDC concept should be researched in the future. The scope of the partial case examples is limited due to various material and technical factors. Moreover, the customer value and architectural perspectives should be considered in terms of the reuse of the same designs in different projects as customers may prefer original designs. Also, the ownership issues regarding the product designs and control system in DDC require further research. On a different albeit related note, our case studies included cases from different countries. This approach may have introduced country- and culture-specific biases into our findings.

The construction industry's adaptation of the DDC concept requires increased effort from individual organizations and existing company networks in terms of overcoming shortsightedness and recognizing the lifecycle benefits of its implementation. Future research should further analyze the existing and emerging examples of DDC applications by utilizing objective data to evaluate the long-term impact of DDC in 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 benefits gained from the DDC concept.

10. Conclusion

In this research, a new practice for technology-based management of construction operations and supply chains was developed through design science research. The core principle of the practice is to direct the value-adding operations over the building's lifecycle through the digital design model, resulting in increased reusability, project-specific differentiation, and automation of designs and processes across projects. The DDC concept improves efficiency, not just in a limited project

or product part of construction industry operations but also in the entire construction supply chain over its lifecycle. Evidence from the industry examples that already use the operational practice elements illustrate the solution potential and feasibility of the concept. The DDC fills an existing gap in the technology-based construction operations practices and creates additional value by removing inefficiencies and establishing a continuously improving way of designing, engineering, producing, and maintaining buildings.

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