Lessons Learned from Managing the Design Process of a Large and Complex Construction Project Seen in a Lean Construction Perspective

Bo Terje Kalsaas, Anders Rullestad and Hanne S. Thorud

Abstract The construction project being studied is a government investment related to a relocation of a biomedical institute delivering research-based knowledge and contingency support in the fields of animal health, fish health and food safety. The project covers a total of 63,000 m^2 distributed over 10 buildings. The buildings have a very high degree of complexity due to a large proportion of special areas, great ambitions to the minimize environmental impact in addition to strict compliance to Infection Prevention and Control in order to achieve a world class product in its field. The project is procured as a design-bid-build project divided into 40 different execution contracts. The design alone has required 1 million hours and more than 100,000,000 Euro. The purpose of this article is to study the applied methodology for managing the detailed design to identify lessons learned from the project. The theory underlying the study is inspired by lean design management and design theory linked to design as phenomena, including reciprocal interdependencies, iteration, decomposition, design as a "wicked problem", learning, gradual maturation, etc. The article is based on an abductive research design and has been implemented as a case study where both qualitative and quantitative methods have been used. First, the study describes how the design process was managed. Furthermore, challenges that are revealed through interviews and a survey are presented. Uncovered are a widespread volume of negative iterations and waste, where reasons for the challenges are linked, among others, to the use of traditional management methodology, a long user process and late owner and user decisions. Finally, the key lessons learned from the case are further explored in how they could be solved by alternative management methodology.

Keywords AEC-industry · Complexity · Design · Lesson learned

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1 Introduction

The concept of design in this paper includes both architectural and engineering design. While the design processes in construction make up a relatively small share of construction costs (about 10%), they are integral to the building's life cycle, including customer value, maintenance and operational costs (Evans et al. 1998; Gilbertson 2006). Koskela et al. (2013) regard the design-production as a chain of processes where "value is created as a potential in design, is embodied in production and is realised in the intended use by the client."

The management of the design process itself however, is more complicated than the management of the production phase due to characteristics such as iterations, gradual maturation, learning, reciprocal interdependencies and the often-fragmented design process involving several different consulting companies, the client and construction companies as well as their subcontractors (Kalsaas and Moum 2016). According to the Lean tradition, the management of design processes is often designated as Lean Design Management (LDM), e.g. Koskela et al. (1997) and Uusitalo et al. (2017).

In order to achieve efficient design management, we need knowledge of design as phenomena, structured work methodology and feasibility. This paper builds on a master thesis (Rullestad and Thorud 2019) and studies one of Norway's largest AEC projects, which has a high degree of complexity. The aim is to study the structure of the applied methodology in relation to design as phenomena regarding uncovering improvements and lessons learned. Thus, the problem can be stated as follows; *Which lessons can be identified from the process of designing a large and complex construction project seen in a lean construction perspective?*

2 Methodology

This research deals with a single project and therefore the most obvious research approach to choose is case study methodology as well as most appropriate. We were inspired by Sayer (1992) concerning critical realism (theoretically informed) case studies, then supplemented this with Yin (2014) using the case study method. The study is primarily a contextual analysis in relation to explaining obstacles in the design work (lessons learned). In terms of structure, it is in the incentives associated with the applied contract strategy (design-bid-build). We consider incentives as a structure that together with mechanisms can lead to certain outcomes, given certain conditions (Sayer 1992). Qualitative data collection was conducted using semi-structured interviews, of which two were with representatives from the client's project administration and eleven with the design team management. Quantitative data collection was conducted using a survey.

This paper has been organized in the following manner. Firstly, the researchers acquired relevant literature which worked as a foundation for further work, which is backed up by Creswell (2009) and Yin (2014). Then, an interview guide was established with specific topics of what the researchers wanted to obtain information about. Thereafter, semi-structured interviews with key actors and leaders were organized whereas the interviews were recorded. From there, the empirical data was combined and contrasted with acquired literature. Furthermore, the survey was conducted to ensure that the findings from the interviews were representative of a larger population.

3 Theory

The TFV theory (Koskela 2000) is a production theory related to lean production and lean construction. In this theory, production is seen as a flow of transformations that create value in the form of a product. Transformations are the traditional focus of production, while flow and value are the new perspectives. Koskela (2000) links value to the quality movement, where value is implied as customer value. If we go deeper, for example to the flow-section (Koskela 2000), its emphases include:

- remove waste
- reduce the lead time in the supply chain
- counteract variation
- simplify the supply chain (number of steps, parts, components and relations)
- increase flexibility
- increase transparency (visual management)
- continuous improvement.

The TFV theory has furthermore been a fundamental inspiration for the Last Planner System (Ballard 2000), a well-known method for production control in Lean Construction, which is based on five principles. These are highlighted by Ballard et al. (2010) as:

1. Plan with greater detail the closer you get to the specific execution
2. Plan with those who will do the work
3. Identify and remove obstacles for scheduled tasks in teams
4. Make reliable commitments for work to be carried out as agreed
5. Learn from cases where problems with the implementation occurs.

It is common in architecture and engineering to start with the client's specifications and then develop both conceptual and practical solutions throughout several distinct stages. This method of design analysis does not guarantee that a solution will be found. On the contrary, in design one must often return to the problem by trying to solve it in a different way, i.e. a new iteration. Koskela and Kagioglou (2006) refer to the concept of iteration arising as a new idea in the 1980's based on the observation that when working, designers jump between goals and means instead of following a linear path. Regarding the method aspect of project realization, a significant shift came with the arrival of agile methods in software development (Schwaber and Beedle 2002).

Ballard and Koskela (2013) link the works on rhetoric and design by Kaufer and Butler (1996) to the concept of “wicked problems” (Churchman 1967). Moreover, because of complex interdependencies, the effort to solve one aspect of a wicked problem may either reveal or create other problems. The phrase was originally used in social planning and is contrasted with “tame problems”, which are more linear in nature, where the concept of cause and effect is well known. We may relate wicked problems to the Cynefin framework for complexity (Snowden 2000) to which the researchers relate wicked problems to the denoted “complex” and “chaotic” domains, where cause and effect is unknown.

4 Bridging Theory and the Case Study

Reciprocal dependencies are fundamental to understanding what kind of phenomenon design is. These often play out in one or, often, multiple iterations. Iterations can be linked to the Kolb’s experiential learning cycle (1984), where each loop represents a test, observation and reflections before identifying needs or desires to make a new iteration. The coordination mechanism for reciprocal dependencies is mutual adjustment, but if we have reciprocal dependencies then there are always sequential dependencies present, which then begs the coordination method. Design in complex projects can be considered a wicked problem, and as such there is no logical end for when the design is finished as it always can be improved by additional iterations.

When we analyse the case in relation to lessons learned, we have chosen theory related to design as phenomenon and the TFV theory, which means trying to answer how the applied design management method pertains to:

- Transformation
- Flow, related to complexity with reference to the Cynefin framework, gradual maturity, constructability, learning and continuous improvement, interdependencies and coordination
- Value, linked to customer/user value.

5 The Case

The AEC project being studied is a conglomeration of a faculty of veterinary medicine and an independent biomedical research institute delivering research-based knowledge and contingency support in the fields of animal health, fish health and food safety. The construction project comprises 63,100 m^2, which is distributed between ten buildings. The buildings have a very high degree of complexity due to a large proportion of special areas, great ambitions to minimize environmental impact and strict compliance to Infection Prevention and Control in order to achieve world class classification in its field. The project costs are 7.1 billion plus 1 billion in user equipment. A government administrated company is the client of the project, and it is organized as Design-Bid-Build with a total of 40 execution contracts. In relation to the design process, there was a group of four consultant companies that won the contract together. Within the design team, there are coordinators, architects, landscape architects and discipline representatives from construction, electrical, Heating, Ventilation, and Air Conditioning, fire, acoustics and building physics, as well as 11 different special disciplines such as Infection Control, laboratory design and external environment. The project started in 2010, where the detailed design was carried out from 2013 until the start of 2019. About 200 architects and engineers have worked with design in total, whereas 120 worked simultaneously at the most. The planning group has been co-located since the start of the detailed design and moved to the construction site in August 2018. The construction period went in parallel with the design process, starting in 2013 and completion scheduled for 2020.

6 Empirical Findings

6.1 Detailed Design Before Bid

The design process was mainly managed according to traditional principles of management. There were organized weekly design meetings and the earned value method was used to measure progress, and a design plan was prepared in Gantt. Figure 1

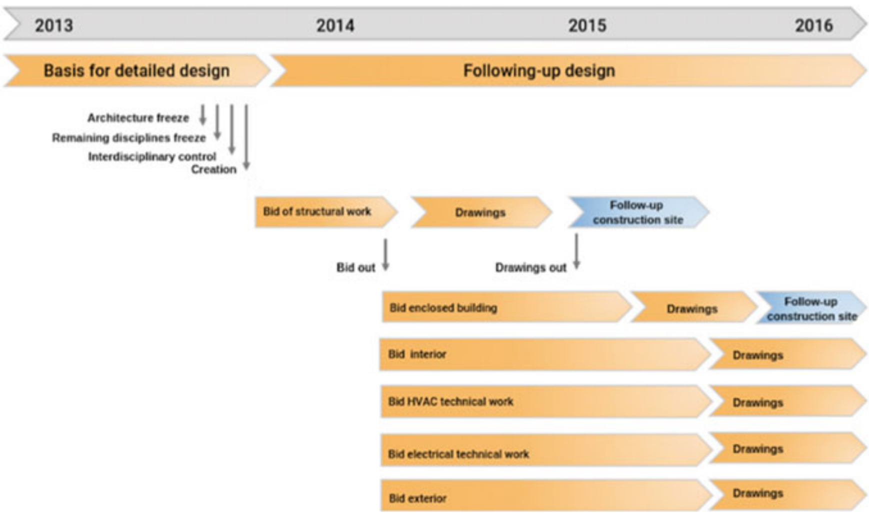

Fig. 1 Illustration of the strategic schedule for the design phase

shows how the design management in the case has presented the overall schedule for the design phase. In the context of progress, it was planned in detail longer than 6 months ahead. Because of an owner/client decision, the project had to reduce the area in several rounds at relatively early stages. It was reduced from 120,000 to 63,000 m^2. Although the project was cut in area, they did not compromise features. For design alone, it has required 1 million hours with a value of more than 100,000,000 Euro.

From start-up, to detailed design and until completion, it was planned according to area design. Each of the ten buildings in the project represented its own sub-schedule, led by its own area team and with its own administrator in addition to representatives from all the disciplines.

BIM has been actively used in the project, continuously for drawings, calculations and quantity extraction, and to achieve better task understanding, coordination and interface planning, reporting, communication, quality assurance and control. There has been an overall BIM coordinator for the project, in addition to a BIM coordinator for each of the disciplines.

The design team had little knowledge and experience with Lean beforehand. However, Lean processes were initiated in the detailed design phase, approximately half a year before the bidding, when a Lean influenced actor with Virtual Design and Construction (VDC) certification joined the design team. One of the measures introduced was Integrated Concurrent Engineering (ICE) meetings. These were held 1–2 times a week and lasted a maximum of 45 min. In addition, elements from Last Planner was applied on the last of the 10 buildings to be built, on the initiative of the same person.

6.2 Follow-up Design

In total, the project was divided into 40 different execution contracts. After the offers were picked up, the client chose to change the structure, and redesigned the hierarchy as a contracting organization. Most disciplines had between 1 and 5 contracts each, while HVAC had 16. The design team moved out to the construction site in August 2018 and redistributed the organization around six “fronts”. Each front represented one or more buildings, and within each front there was a leader in addition to representatives from both the design group, the client, the building management and the contractors. One of the purposes of the reorganization was to facilitate problem solving in design in interaction with those on the construction site. In summary, the design was first organized as site design for buildings, then it went over to contracts, and then it went back to being projected for buildings in the form of “fronts”.

7 Empirical Analysis

7.1 Transformation

The project mainly used traditional methods for management which are based on the waterfall model. Kalsaas (2020) claims that traditional methods are suitable for construction projects with a relatively high degree of predictability, but to a lesser extent for projects that are complex and unpredictable. The case study indicates that the methodology used is based on being in the single domain of the Cynefin framework and is not equipped to handle wicked problems. The methodology did not seem to capture all the reciprocal dependencies that emerged from the data. The design process requires a more agile design management that can capture the complexity of using alternative methodology. Eg. Last Planner as a planning method could have been combined with a structure for management based on Scrum, cf. Ballard (2000), and Kalsaas (2020). This could have contributed to better handling of reciprocal dependencies, breaking down complex work tasks into smaller work packages and having a more realistic schedule by planning in more detail the closer one comes to execution.

7.2 Flow

7.2.1 Complexity with Reference to the Cynefin Framework

It was pointed out by the design manager that "*this project is defined as one of the most complex construction projects in Norway ever (…), and there is very limited space for applying standardized solutions as few rooms are of same kind*". Several respondents pointed out that the project has been more complex than initially expected, and both the design team and the client underestimated the amount of work required for the design process. The project has, to a small extent, been able to transfer solutions from previous projects, as it is, especially nationally, only hospitals that can be compared.

The project has a total of 80 different ventilation systems, and several informants pointed out that the requirements for the HVAC installations have complicated the design process. Findings indicate that it was challenging to provide sufficient personnel who had experience from similar installations and also possessed the skillset to model well enough in relation to the technically complicated tasks that were presented. In cases where the progress of the design process was lagging, manpower was increased in the relevant disciplines. HVAC was heavily manned in 2015, and at one point six different HVAC companies worked on design at the same time. This meant that the progress was maintained, but it went beyond the continuity of solutions.

Several informants point out that design rules and design requirements should have been more clearly described, and that these should have been stored in a design manual. Beforehand there should have been examples of how things should be done, and prototypes should have been prepared for how the designer should work. It should have been specified and predefined which products should be used and how the different guides should be relative to each other for the different types of rooms, to ensure that everyone knows exactly how to do it on the project and that things are done equally. One informant points out that "*I think it could have been avoided frustration by those who project, if you had a blueprint*." This shows that coordination through a degree of standardization has failed.

7.2.2 Reciprocal Dependencies and Coordination

Findings indicate that handling the information flow in the project has been challenging based on the size of the project and the size of the project organization. The information flow between disciplines and interfaces has, by several informants, been described as "*challenging and chaotic*". The use of Last Planner could improve the information flow in the project and make it easier for the group to communicate needs and clarifications sequentially. Furthermore, in connection with decision making in the project, findings indicate that it might be challenging to get actors involved to make interdisciplinary decisions, and that the decision-making processes lasted longer than necessary. The data also indicates that it could be challenging to know who to deal with. This suggests that there has been inadequate coordination in relation to problem solving, which created waste in the form of resource focus.

Contrastingly, one factor that appears to have strengthened coordination and customer value is co-location of the design group. Many of the informants claimed that such a large and complex project would not have been possible without co-location. This has been an advantage for information and communication flows, as well as allowing ICE at times to be an effective way of dealing with reciprocal dependencies. Nevertheless, there is agreement that co-location to the construction site should have been done simultaneously with the client in 2016 and not in 2018.

7.2.3 Gradual Maturation

With respect to gradual maturation, findings show that the project lacked an efficient way to deal with this, and it was pointed out that it was mainly dealt with using "gut feeling" and previous experiences. Initially, a procedure was described for the design, where it was first architect freeze, then freeze for other subjects, and finally interdisciplinary control. However, due to scarce time in the project, the procedure has not been followed and the disciplines have had to work in parallel. When some disciplines lagged behind, other disciplines have continued with their own prerequisites that did not always turn out to be right, which contributed to inactivity in the design and waste of having to restart tasks. In addition, it was challenging to get disciplines to set the freeze status of objects in the BIM model. E.g. the architects claimed that they always worked further after the freeze. In conjunction with gradual maturation, LoD could have been used, cf. Grytting et al. (2017).

7.2.4 Constructability

In relation with constructability, findings show that achieving design solutions with good constructability has been a challenge. An influential factor was that it was cut down on areas without reducing the number of functions in the project, which affected areas that users did not use daily, such as shafts and technical rooms. Both the representatives from the design team and the construction management pointed out that it often happened that the design solutions were not possible to build, and they therefore had to restart. In addition, several informants stated that there have already been identified areas that will not be inaccessible, which lowers the customer value and which most likely will result in increased costs related to operation and maintenance.

Further, the crude building was completed before the technical disciplines had sent out the furnishings for tenders, which meant that many holes were taken at an early stage. As learning and maturing process increased throughout the project, and new and better solutions emerged, it was necessary to make changes. The later a change is made, the higher the cost and consequences of the change. Technical disciplines and entrepreneurs should therefore be involved earlier in the design process as this is where the influence and the value creation potential are strongest.

7.2.5 Learning and Continuous Improvement

Findings indicate that there have been few systematic processes for learning during the project. When informants were asked if the design team had a focus on evaluating during the process, an informant replied that: "*We could probably have been a little better at writing deviations when we do things wrong, so we get a better learning from the deviations during the planning. Here it has been a challenge not to make the same mistake several times*." Another informant argued that: "*It is common in "our world", that we should invent the wheel every time. We are not that good at evaluation.*" Furthermore, many in the staff have gone in and out of the project during the 10-year project period. For example, it emerged that the automation discipline has had seven replacements in management over an eight-year period. When people left the project, they also took valuable tacit knowledge and experience. Findings indicate that there was not enough focus on knowledge transfer in the design. An informant from the architectural discipline supports this with the statement: "*Lack of continuity has been one of the greatest challenges at all levels. Tacit knowledge disappears when someone leaves. Getting that knowledge transfer right has not been good enough.*"

The use of Last Planner and Scrum could facilitate learning and reflections, cf. Ballard (2000), and Kalsaas (2020). In addition, in order to build on and exploit the lessons from the project, it is important to gather and share the experiences, for example through the use of conducting seminars reflecting lessons after project completion.

8 Value

Customer value has been sought through extensive user processes. The design team has been dependent on input from users to understand the room functions, and since the sketch project phase there have been regular meetings with the users to clarify user needs and requests. However, it was used too long to establish the room-function-program. Optimally, this should have been completed before the start of detailed design rather than one month prior to the bidding, where an agreement on what needs to be built in relation to user needs can be established so that the design team could convert it to technical solutions. When technical solutions and functional needs were discussed simultaneously, it created resource demanding iteration processes.

Throughout the project, there has always been a desire for changes from the users' side, and it was noted that heavy user processes were still ongoing when things should have been frozen. This has greatly influenced the design process, and it has been pointed out that the user process has not been managed strictly enough from the client's perspective. In order to ensure customer value, the design team has therefore made many redesigns. An example was an area of 3000 m^2 that was drawn 19 times. This generates waste when each conversion takes 2–3 weeks. Furthermore, as technology developed during the project period, users often wanted to replace older designs with newer products, and these inputs could come as late as in the final phase of detailed design. The design team managed to handle the late user changes, but it resulted in inflated accrued hours and a sub-optimal process. The customer probably gets its functionality, but likely at an unnecessarily high cost. There are measures within target value design (Zimina et al. 2012) and choosing by advantage (Arroyo et al. 2016) that could have been used to increase customer value.

9 Conclusions

At a slightly more strategic level, the biggest challenge encountered in this case study is the need for a project model that captures the complexity of designing world class infection control buildings located in an important agricultural area. The large-scale nature of the project divided into many contracts with several organizations within the same discipline add to the complexity. A project model should be able to add frames and structure to capture the integration of both product, process and organization. Having an integrated information flow structure is an important part of this. For example, the data shows that the same message is given via multiple channels to different roles with tunnel vision and different departments are often blind to the information of other sectors. The substantiated material shows that traditional planning and management do not work as intended when dealing with the complexity of significant reciprocal dependencies. For the future, we propose a transition to more agile and flexible methods in combination with Last Planner and VDC. Gradual maturation in design must necessarily be handled in a structured way to reduce the extent of negative iterations, waste and processes that easily slip into a chaotic area characterized by "fire extinguishing" and "muddling through". We refer to LOD as an example of method for dealing with gradual maturation. Gradual maturation is further related to learning, and we have not been able to observe a systematic approach to learning and continuous improvement during implementation.

An important driver of uncertainty and waste has also been the lack of standardization of technical solutions for equal problems. It is obvious that it increases the complexity unnecessarily and has the potential to generate waste. The data furthermore shows that significant changes have been made by the owner and the client. This seems to be a driver which has generated many extra rounds of design. The user processes close to the detailed design are part of this waste.

In relation to the theoretical basis of the lean design management perspective, the identified lessons learned means that the process flow could have been considerably better by removing the causes of waste both in terms of the transformation (the actual design work) and in terms of the processes around it. There have been extensive user processes that ensure customer value, but as pointed out, these processes came temporally late, near the completion of the detailed design just before the bidding process.

We have not considered whether the project has been appropriately organized, including whether design-bid-build is an appropriate form of contract for such a large, complex project with high risk on both time, cost and quality. Future research is warranted to investigate this question.

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