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Lean Construction Practices and its Effects: A Case Study at St Olav's Integrated Hospital, Norway

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Abstract

Question: Which practices made up the totality of the LC approach, and could any of these be considered innovative approaches not already documented in literature? Were there any noticeable effects from using LC in case project?

Purpose: This paper investigates lean construction practices at St. Olav's integrated hospital implemented in phase 2 of the project and sees the effects of the same with respect to several attributes when comparing to the traditional phase 1. It aims to identify LC practices, its effects and compare with the forecasted outputs.

Research Method: Both qualitative and quantitative methods employed. The qualitative data stem from document studies, observations, and interviews while quantitative data was collected from project records and a survey, later quantitatively analyzed using statistical functions.

Findings: Three good practices are found; a set of 'lean engineering" and partnering approaches, logistics and purchasing methods, and adaptations of a lean construction process. The overall results of the empirical study substantiate positive results in several attributes and dimensions; keeping the building time in phase 2 on par with phase 1 despite increase in complexity, 3.4% cost reduction per m^2, improved build quality with 55.1% reduction in warranty costs per m^2, better HSE performance with a 56.5% reduction in H value, better cooperation, more content, etc.

Limitations: The study considers only one integrated hospital construction project in Norway. There were some logistical challenges due to the old hospital was being operational while the new buildings were being erected. As always, it is difficult to prove attribution of the positive results as being effects of the LC practices implemented.

Implications: Regardless of the positive outputs, the empirical result invites further study

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as few factors are weakly correlated. Many of the attributes that are designed and included found to be important for LC practices, but not all. Perhaps factors not included in this study would be needed for better and consolidated outputs.

Value for authors: This paper thoroughly investigates and provides LC practices, effects, and systematized structure of LC attributes. It also delivers structured review on practices and effects of LC. That would be an input for the body of knowledge in LC.

Keywords: Lean construction, Lean production, Attributes, Practices, Effects, Lean

Paper type: Full paper

Introduction

Lean thinking in general has a long history of generating radical improvements in fields like manufacturing, health care and construction (Poppendieck et al., 2003). As the lean principles are being adapted and tested in other sectors, the concept evolves and changes. Nevertheless, comparing the lean manufacturing and the lean construction literature the manufacturing field is more developed than the latter (Jørgensen et al., 2008). Currently, the construction industry is at a stage where some efforts have been made to define the theory of lean construction (LC). However, we see that the actual implementation of LC practices is still lagging the theoretical development. The topic of LC has been covered in text books and academic journals, where it is usually presented in an orderly manner. Even though theory offers examples of concrete tools that can be applied, converting LC theory into construction industry practice can be difficult. Changing the way a company or, as is often the case in the construction industry, a number of interacting companies perform their work requires a concerted effort driven by a strong motivation and/or actor. There are especially two prerequisites, according to Poppendieck et al. (2003), which typically allow new ideas to take hold in organizations:

- People who are considering adopting the change must understand why and how it works
- The idea must be proven to work operationally

These points to the two topics covered in this paper; lean construction practices that we have observed in a case project and the effects that can be achieved by implementing these practices. The paper is somehow "opportunity-driven" in that the researchers were asked to conduct trailing research of a large hospital construction project divided into two phases. Phase 1 employed a traditional project management approach, but after disappointing performance, phase 2 was designated for active use of LC principles, such as last planner and concurrent engineering principles. Last planner system is a system for creating predictable and reliable workflow in the construction, it adds more reliability and compared with other means of coordination seems to be influence rework most positively (Khanzode, 2010). Although concurrent engineering can be understood in several ways, we think of involvement of stakeholders such as architects, engineering consultants, and contractors.

Compared with documented LC practices from literature and case projects, we observed that this project was able to develop further practices that we find to be novel. In assessing the effects of using LC, we have also gathered empirical data that shed additional light on the benefits that can be achieved through the use of LC and some challenges in realizing such benefits.

Thus, this paper is structured around these two angles. First, we outline the research methods used, and then we introduce the case project, Phase 2 of the St. Olav's Hospital construction project, and describe what makes this an LC project. A brief review of the LC literature, focusing on the aspects of LC practices and documented benefits and effects, is followed by a presentation of findings of good practices from our hospital case. We then discuss the effects of LC observed in the case project, before drawing overall conclusions. Our main findings are that this case project seems to have introduced some approaches that go beyond documented methods, especially in the areas of engineering, logistics, and the construction process. Empirical data about costs, duration, quality, and HSE aspects confirm that the project achieved good results.

Research Methods

The primary aim of the research was to achieve a rich and holistic understanding of how the organizations involved in the project designed and implemented LC practices. In particular, we focused on finding an answer to the following questions:

1. Which practices made up the totality of the LC approach, and could any of these be considered innovative approaches not already documented in literature?
2. Which effects were seen from the use of LC in the case project?

The primary research method applied in this work is that of case study research. This is partly based on our belief that more research is warranted that follows real-life projects in detail to understand how their LC efforts fare and which difficulties still exist, despite the knowledge contained in existing literature. Furthermore, we were asked by the project owner of the case project to conduct trailing research for the purpose of documenting the LC practices employed and evaluating the effort. Thus, an opportunity arose where we had access to an exciting case project from its inception. As a result, a case study approach was the logical methodological choice. Under the case study research design, more specifically, the following methods were employed:

- Observation, of meetings, work practices, and support systems.
- Interviews, with key personnel in the different organizations involved in the case project.
- Survey, to collect semi-quantitative data from project participants.
- Quantitative data analysis using comparison of averages, regression analysis, and correlation analysis.

The case project was empirically observed following a qualitative case study approach (Yin, 1994). However, in addition to qualitative studies of the project's practices, we also collected quantitative data, thus using mixed methods (Morgan, 1998).

The team of researchers collected data by employing different data collection methods:

- Studies of project documents, e.g., tender documents, project plans, process handbooks, meeting minutes, etc. The extent of this documentation was extensive, but we have not made an attempt at quantifying the volume.
- Observation of practices used during the project, through participation in meetings, site visits to the construction site, etc. In the range of thirty hours of observation was carried out. The role of the researchers was to act as neutral observers during meetings and site visits.
- Interviews with project personnel from various actors, disciplines, and organizational levels. Approximately twenty-five face-to-face interviews were carried out, and the interviews were semi-structured based on an interview guide.
- Quantitative data about the project results; cost, time, quality, and HSE data normalized by calculating per square meter factors for cost and time data, comparing quality data adjusting for project volume, and comparing HSE data by adjusting for the number of work hours.
- Survey conducted by administering a paper-based questionnaire to individuals involved in the project. Almost 100 questionnaires were filled in and returned. A 7-point Likert scale was used asking respondents to grade the extent to which they agree with the presented statement (1= not at all, 7=completely). The questionnaires collected background data about the respondents and the statements covered 18 attributes (see Figure 1) of effects that had been defined as improvement objectives and that one could expect would have been improved throughout the project's phase 2. An example of such a statement is "In this project compared with earlier projects where lean construction was not used, I have found that the previous operation to a larger extent has been completed before the next is scheduled to start."

Choosing a study sample was an important step since it is rarely practical, efficient, or ethical to study whole populations (Marshall, 1996) and two different strategies can be applied: a quantitative sampling strategy and/or a qualitative sampling strategy. The choice between quantitative and qualitative research methods should be determined by the research question and the aim of the study (Marshall, 1996). The aim of the quantitative approach is often to answer the more mechanistic 'what?' questions. Qualitative studies aim to provide illumination and understanding of complex psychosocial issues and are most useful for answering humanistic 'why?' and 'how?' questions (Marshall, 1996). The research methods associated with both quantitative and qualitative research have their own strengths and weaknesses (Bryman, 2008) and therefore many writers argue that the two can and should be combined within an overall research project, referred to as mixed methods research or triangulation, to draw on the strengths of both. Triangulation - or greater validity - refers to this view that quantitative and qualitative research might be combined (Bryman, 2008). The essential rationale behind triangulation is that, if you use a number of different methods or sources of information to tackle a question, the resulting answer is more likely to be accurate, you often get a richer and fuller story (Richardson, 1996) and often one of the two research methods is used to help explain or confirm findings generated by the other (Bryman, 2008).

In the empirical studies presented in this paper, mixed methods (quantitative and qualitative methods) have been applied for the very same reasons. The aim of the study was to both answer the “which LC practices were used” question through a qualitative study, and then to answer the “which effects” question through a quantitative study.

In terms of interview sampling, of the three broad approaches to selecting a sample for a qualitative study (Marshall, 1996), judgmental sampling was employed. We actively selected the most productive sample to answer the research question, using interviewees in different roles across the involved participating companies. For the quantitative survey, no actual sampling was done in that the questionnaire was distributed to all people involved in the project, approximately 200 people. Receiving around 100 completed questionnaires gave an acceptable response rate of 50%.

The qualitative data from document studies, observations, and interviews was analyzed using tabular statement analysis and pattern identification. The responses from the survey were quantitatively analyzed using simple statistical functions. In this study, we have used linear regression and a correlation matrix to discern relationships between different attributes, trend analysis and exponential smoothing to obtain the forecasted result, and see the general characteristics of lean construction intervention in the case hospital.

An inherent weakness in the study is a failure to relate effects achieved to individual practices. Ideally, we would have liked to be able to attribute certain effects, e.g., lower costs, to certain LC practices or at least indicate which practices seem to affect certain areas of effects more. This has proven quite difficult. Initially, only a small number of LC practices were foreseen to be implemented, mainly for the sake of reducing costs. Thus, no "measurement instrument" was developed. As the project evolved, more and more practices were developed and added, and it gradually became clear that these not only influenced costs, but also time, quality, and HSE issues. At this stage, we realized that the relationships between practices and effects had become complex and identifying causal relationships would be very difficult. Not in the least would attribution be a major obstacle; to what extent is the result of fewer conflicts a result of partnering, contract models, better site coordination among disciplines, etc.? Realizing it would be impossible to achieve the ideal of identifying causal relationships, we had to settle for second-best, i.e., assessing the collective effects stemming from the totality of LC practices implemented. This is less fine-grained, and there are still attribution issues, i.e., are the effects solely the results of the LC practices or other issues (overall cost development in the market, increased attention to costs due to poor phase 1 results, etc.)? Attribution of effects is inherently difficult, and we can really only conclude that phase 2 saw strongly improved results compared with phase 1 at the same time as a number of LC practices were implemented, thus inferring that these practices contributed positively.

The St. Olav’s Hospital Construction Project, Phase 2

St. Olav’s Hospital in Trondheim, Norway, is a regional center of expertise, serving a population of 630,000 in Central Norway. The new St. Olav’s Hospital can be described as an “integrated hospital”. The buildings will house patients, relatives, health personnel, service personnel, and, being a University hospital, students, teachers and researchers. Of the existing St. Olav's Hospital, more than 80% is demolished, while the hospital is in full operation throughout the project. In addition to a number of new buildings, the project consists of rehabilitation of existing buildings as well as construction of infrastructure. After a total construction period of about 10 years, the new St. Olav's Hospital will be ready in the summer of 2013, offering indoor space nearly three times what was found in the building structures of the old hospital.

Phase 1 of the project was based on a more traditional project approach, and saw several problems in terms of delays, cost overruns, etc. When starting to plan Phase 2, a decision was made to actively put LC practices to use. Existing practices were studied in literature and international projects as a basis for designing the St. Olav's LC approach, which also included various practices not seen elsewhere.

Phase 2 started in 2005, with most of the construction work done by 2010 except for the demolition of the old main building and construction of a last center to be completed by 2013. The estimated cost for Phase 2 is approximately 1 billion euros. Being designed around "centers", there are several new buildings being erected, and a large number of actors (architect, engineering consultants, contractors, sub-contractors, etc.) are involved in the project.

The picture below shows the construction site in 2006, when phase 1 had been completed and with phase 2 in progress.[4]

Lean Construction Literature

The literature review addresses some issues of transformation from lean production to lean construction, lean construction features, finding the state of the art of lean construction practices, and its effects on different construction projects. In recent years the construction industry has adopted concepts and methods (target costing and set based

[4] In Google Maps, the coordinates are: https://maps.google.no/maps/ms?msid=201017818483181721931.00049ae92d3eb879e5aeb&msa=0&ll=63.420704,10.388796&spn=0.008996,0.033023

design) drawn from the Toyota Production System mainly used in the design phase (Ballard, 2008). Ballard also makes a reference to a statement from a Chief Architect (Sutter Health): "The hospital is a machine of which the design facilitates or impedes its fitness for use". Such implications means that the intended use of a hospital must be designed before the facilities itself can be designed. Whether due to lean construction's complex nature (Koskela et al., 2002a) or increased competition and poor productivity development (Salem et al., 2005), lean construction has become a valuable approach for increased competitive advantage and a vanguard for industries towards more lean-inspired construction. There are several reasons that companies are induced to adapt and implement lean construction approaches. For example, the techniques used within Toyota Production System are generally closely related to visualization and visibility, and since construction has mobile workstations, such visualizations can help identify work flow. Transparency can further provide feedback on performed activities, facilitate coordination by revealing interdependencies, support decision making and enable improvements (Bausch, 2004). Koskela (2000) concluded that most of the production practice and research, mentioning construction, manufacturing or other industries, has been dominated by a focus on addressing production simplicity from a more transformation perspective, while process and value aspects are under-communicated. However, for better results and before going to the transformation, it is important to ask questions like "are we doing things right"? (Moe, 2011) and what type of methods, concepts and tools exist under the lean the construction umbrella and related performance improvement efforts.

An important implication for applying the lean philosophy to construction is basically understanding waste and value (Jørgensen et al., 2008). In lean, production techniques are linked through a common framework. Transfer into construction is also attempted through the notion flow, process variability, transparency and continuous improvement (Salem et al., 2006). In lean manufacturing, the impact of flow variability is vital, which also has been seen as important in construction practices, where a late completion can affect the time performance of a project. Process variability; quality in construction is more or less dependent on finding defects, which are difficult to discover before installation. What could work are fail-safe actions which can be implemented on a job site to ensure first-time compliance (Shingo 1986; Milberg et al. 2003; Salem et al., 2006).

Nonetheless, we are aware that several authors have reported weaknesses and even also a misleading or an overly optimistic approach to what lean approaches and tools could do (e.g. Green, 1999, 2011; Jørgensen, 2008). The criticism related to construction literature is, however, applied to the lean concept without contextualization regarding empirical exploration of market structures that underpin the construction environment (e.g. Green, 1999, 2011) where he found that lean construction and lean production could be related to notions like a set of techniques, a discourse, a sociotechnical approach, or even a cultural commodity. Yet, some of the criticisms are not relevant to the construction sector where the focus is primarily on projects and not high-volume production. Nevertheless, there is a need for understanding the role of designers and the effect of early design decisions on construction activities (Jørgensen et al., 2008).

Confronting, but also learning from known weaknesses of lean manufacturing will help to shape the construction field. Evidently it is important to take into consideration that transferring the lean production practices directly into lean construction could be risky. It will always be a danger in adapting practices without understanding the underlying principles; still we should refrain from exploring new industrial solutions to achieve continuous performance improvements on cost, quality and time. For instance, lean construction may give a possibility to reduce cost or time of operation by 25%-50% (Ballard and Howell, 1994).

The construction industry has mainly three features which distinguish it from manufacturing. These are: On-site production, one-of-a-kind projects, and complexities (Salem et al., 2006). On-site production implies that activities like installation and erection for the most part increase the value of the product. In one-of–a kind- production, customers play a key-role throughout the project cycle, where the customers define their product. Regarding complexities, the completion of activities is highly complicated. Combining these three together, reducing uncertainty under the project phase will become very important. In a construction project there will always be considerations to overcome; like weather changes, interaction between several actors, owner changes etc., and where the supply chain is more flexible than in manufacturing (Salem et al., 2006).

Recently, (Ghassemi et al., 2011) studied the transition to integrated project delivery (IPD) and explained the potential barriers as well as lessons learned from different cases. Lichtig (2006) indicated that construction owners are dissatisfied in different ways. For instance, projects take too long, cost too much, and fail to meet the expected quality standards. Thomsen et al. (2009) argued that construction projects frequently suffer from in dimensions, e.g., adversarial relationships, low rates of productivity, high rates of inefficiency and rework, frequent disputes, and lack of innovation, injury or fatalities among workers. And that is why IPD, in all its varieties, incorporated to tackle these problems. The Lean Project Delivery System (LPDS) incorporates many elements from the advanced practices in lean construction today, but focuses on using them in a complete delivery system. According to Ballard (2000a), the LPDS development was initiated for it to become a philosophy, a set of interdependent functions, rules for decision making, procedures for the execution of functions, implementation aids and tools, and including software where appropriate. The LPDS is, however, still under development, gaining experience from experimentation with industry applications in companies around the world, recently focusing on the definition and design phase of projects with concepts like target costing, set based design, relational contracts and computer integration (Ballard, 2008). Some of the established elements and techniques employed in the LPDS (adapted from Ballard and Zabelle, 2000; Ballard, 2000a; Koskela et al., 2002b, Ballard et al., 2002) are: Last Planner, set-based strategy, simultaneous product and process design, design for X, collaborative design tools, load leveling, JIT, continuous flow process, one-touch material handling, first run studies, multi-skilling, distributed planning, etc. A more extensive view of what lean construction has developed into can therefore be summarized under three themes, inspired from common elements in lean thinking (Jørgensen et al., 2008, Green et al., 2005): Production planning, control and management, Production system design and Project design and implementation and application.

Some projects in hospitals have achieved remarkable results in some specific attributes of lean construction. For example, Richard (2007) studied how hospitals use lean construction to save time and money by exemplifying some results achieved by avoiding conflicts, satisfying clients' needs, and keeping the schedule and budget. Gordon (2000) showed how lean construction boosts productivity of several projects and improve their completion time. Some empirical studies show different findings that are linked with lean construction (Thomas et al., 2003, Alarcon et al., 2006), and qualitative studies that deal with its implementation and related processes (e.g., Johansen et al., 2004; Jørgensen, 2006). Regardless of its achievements, there are also several problems that are inherent in construction projects, like low productivity, lack of quality, poor safety and inferior, dirty and dangerous working site (Construction Industry steering committee, 1999). Fearne et al. (2006) illustrated the potential danger of applying lean thinking in a project environment. Some of their findings were logical and resulted in cost savings but others were not and resulted in reduced levels of responsiveness and flexibility due to uncertainties. Another significant study (Alarcon et al. 2006) showed the impact of lean construction implementation by analyzing several measures obtained during implementation and they also listed out the implementation barriers. However, at this stage, it might be difficult to have a clear stand on the effects of lean construction adaption and implementation as several case studies showed both positive and negative impacts.

Due to diverse findings from research on lean construction, depending on geographical location, project types, applications of different lean tools, etc., it is challenging to agree on the outcomes are gained by implementing lean construction. However, we have structured (see table 1) some of the practices and effects of lean construction in various projects.

Table 1 some reviews on practices and effects of lean construction

Author(s)	Studied at/by	Practices	Effects
Garrett et al., (2011)	Anonymous	A lean tool, value stream mapping (VSM), and various other lean concepts were used, electronic versions of the submittals	Part of the coordination effort was eliminated. Activities in the process were reduced from (8 to 5), decrease lead time (40%) and process time (25%). E-copies affected review time of the submittal.
Miletsky, R.J., (2010)	Association General Contractor of America (AGC) forum	Involvement of workers.-*Three dimensional software, Models,-Direct contact between management, Immediate address worker issues*	Can show the work progress, interested in their work, positive effect on workers and workers morale and employees can list their concerns and problems.
Tuholski et al., (2010)	Lawrence Livermore National Laboratory	Design structure matrix(DSM) application	Overcome the negative stereotype of rework to understand the positive impacts of iteration rework
Yoders, J., (2009)	Turner Construction CoTennessee Medical Center.	Building information modelling (BIM) + Lean Construction	- Reduction in cost from estimated at $286 million by $3 Million, - Shortening the delivery time.
Ballard, B., (2008)	-Shawano Clinic - ARC for Sutter Roseville Medical Center and the Fairfield Medical Office Building for Sutter Fairfield	The Lean Project Delivery System	- Target cost was set 3.6% below benchmark; actual cost was 14.6% below target, and 17.6% below the benchmark. Project was completed 3.5 months ahead of schedule, generating 70 additional day's revenue for the owner ($1 million.) - Target cost ($18.9 million) was set 14.1% below the benchmark ($22.0 million). The actual cost ($17.9 million) for the original scope under-ran. The target by 5.3% and under-ran the benchmark by 18.6%
Alarcon, et al., (2006)	Over 100 projects in Chile	Last Planner System and other Lean Construction techniques in over one hundred construction projects for five years.	- 7% to 48% performance improvement were reported by 8 companies - Improve reliability of planning and PPC. - IT tools can support a more complete and standard implementation of LPS
Richard, H., (2007)	-Boldt Co. -St. Elizabeth Hospital	-Adapting Toyota motors principles -Applying software to front end design to spot conflicts Use scheduling LP, select	- Boldt co. met the client's needs for $2 per foot less than budget, - Avoiding conflicts at St. Elizabeth reward $50,000 in change orders

		subcontractors based on experiences, JIT	
Salem, et al., (2005)	Garage project GC, SubA, SubB	Implementation and Assessment of Lean Construction Techniques/tools: *Last Planner, Visualization, Daily Huddle Meetings, First Run Studies, The 5s Process, Fail Safe for Quality and Safety*	Last planner, increased visualization, daily huddle meetings, and first run studies achieved more effective outcomes than expected.-5s process and fail safe for quality did not meet the expectations.
Conte, ASI et al., (2001)	Construtora Hernandez and the Gerona building	LC production mgt. model deployed; *surplus workers/hour for unscheduled activities, Systematic reduction team size*	Reduction of the expected construction time and cost by 20% to 30% and 5% to 12% respectively.
Wright, G., (2000)	Boldt Co. and Wisconsin contractor Hewlett-Packard	- Expanding lean application to several projects to boost productivity -Fast- track and high-tech	- More suppliers involved and becoming supply management too - The project was delivered for \$3 Million although the budget was \$4.5 Million
Xu and Tsao, (2012)	Univ. of Cincinnati	DSM application	Design drivers, process mapping and DSM
Viana, D.D., (2011)	Two anonymous cases	Application of LAP and LPS	Misunderstandings of some LP ideas, two-way communication plays a key role

Results

Good Lean Construction Practices

This first part of the results section deal with the findings from the qualitative data obtained through observations, interviews, and documents studies. Having studied the hospital case closely over a long period and having analyzed our observations in the context of literature and case reports about lean construction, we see several practices emerging that we consider novel. They range from detailed technical approaches to more extensive organizational changes that we have not seen reported elsewhere and that are considered by the involved parties to have positive effects.

This chapter will describe a selection of these practices that we consider to be most interesting and have the largest potential for replication, directly or with adaptations, in other projects. We term these "good practices" since no evidence exist that these are global best practices, but we hope they can inspire others and add to the body of knowledge about how to systematize lean construction attributes and see the effects of lean construction implementation. Some of the attributes considered in the study are basically from these practices. To help structure these practices, we have grouped them under three headings:

- "Lean engineering" and partnering

- Logistics and purchasing
- Lean construction process

"Lean Engineering" and Partnering

While lean construction has its foremost focus on planning and execution of activities at the construction site, the St. Olav's hospital project has tried to apply lean principles also during the early phase and engineering stage of the project. More specifically, "lean engineering" drawing on the last planner principles has been implemented through the following principles/approaches:

- Co-location of engineers from different technical disciplines, to minimize the threshold for raising potential problems and ensuring that solutions work across disciplines, combined with making workshops (in the beginning involving project owner, contractors, and engineering consultants, later only the different disciplines of engineering consultants) a key element of the organization of work.
- Fixed engineering teams for certain types of rooms. A large hospital like St. Olavs inevitably encompasses a number of different types of rooms that exist in large numbers throughout the building complex, e.g., patient rooms, examination rooms, technical rooms, etc. By assigning fixed engineering teams to each of these different types of rooms, the lessons learned are constantly brought forward throughout the project, making each area/wing better and more efficient than the previous one.
- Solve problems/issues at the lowest level of the project organization, i.e., like construction issues are handled locally on site, engineers involved in the design and engineering of a certain area of the hospital have discussed conflicts that have arisen and tried to settle them directly, without losing time by escalating issues upward through the hierarchy. Another element of this has been to stop engineering at a certain level of detail and leave it to the discretion of the individual craftsperson to decide how to solve very specific issues on site, which has contributed to reducing the number of engineering hours spent.
- Co-engineering with contractors using concurrent engineering approaches, i.e., involving the contractors that eventually will perform the construction work in design and engineering decisions and thus allowing their knowledge about "constructability" be blended with the engineering consultants technical and system knowledge (the most direct application of the last planner principles). This seems to produce better solutions and less need for follow-up and change orders later on. However, this is dependent on the contractors making the right people available for this process, meaning people who will actually work in the project, not those that happen to be between projects at the time.
- Applying a "just in time" approach to the production of drawings and engineering documentation, to avoid obsolete documentation from design decisions based on an incomplete decision basis and to allow utilizing experiences from construction already completed in other areas of the hospital when engineering subsequent areas. "Just in time" is not meant literally in that drawings are available very shortly before construction in an area commences, but scheduling the drawing process so that the documentation for each area of the building were produced some weeks (typically 8, as explained in the next bullet point) before work started, as opposed to former practice where drawings for similar rooms throughout the hospital would typically be completed in batches months, even

years, before commencing construction of them. This either meant failing to learn from issues experienced during construction of the first rooms of that type or having to redo drawings already made.
- Drawing control up to 8 weeks before planned start of construction activities on site, to avoid disruptions due to missing drawings or drawings with errors and ensuring that ground-level people have the opportunity to verify drawings and truly understand what they will later build. The control has been a combination of multi-disciplinary verification, control by each discipline, as well as 3D collision testing of the main stretches of piping/cabling/etc.

To further maximize the benefits of this collaborative approach to the engineering phase, key elements of the partnering philosophy have also been used. These include having various stakeholders involved from very early on in the project and a "partnering phase" ahead of design and engineering to agree on overall principles regarding technical designs and work mode.

Logistics and Purchasing

A key premise for successful lean construction is that materials and tools are available when an operation is scheduled to start. With the case project at St. Olavs hospital, having been split into two phases and the first phase having seen many logistical problems, this is possibly the area where the most novel practices where developed for the second phase. Key practices here have been:

- Keeping the actual construction site as clean and uncluttered as possible. This has been achieved through a number of solutions, one being to ban all storage of materials on site, beyond what is actually being used at the moment. Instead, an off-site storage area has been made available where the different contractors and their wholesale suppliers can keep intermediate stock of purchased materials arriving from the manufacturers. To minimize the amounts of materials required to store here, agreements have also been made with suppliers to split deliveries into smaller batches and to assign and deliver batches to specific areas of the buildings. This practice can be claimed to both promote lean, i.e., by ensuring a lean construction site, as well as increasing the complexity by introducing one more set of material handling operations. We think both claims are true; in this hospital case of building a new hospital while maintaining full operations of the old, there simply is not enough space on site to allow any storage. Thus, some other solution had to be found (while turning this inherent disadvantage into an advantage of a cleaner construction site). The ideal solution would be to eliminate all needs for storage altogether, by having suppliers deliver directly and continuously to the construction site whenever materials and components were required. For many types of materials, this was indeed the chosen solution (combined with the e-Purchasing system mentioned below). However, some components were long lead time items where relying on just in time deliveries would simply be too risky, for other deliveries, the suppliers simply would not accept such an approach, but insisted on batch production and delivery, e.g., batches of similar specially made doors, lighting fixtures, etc. As such, the volume of off-site intermediate storage was kept low.
- To aid an uncluttered site through off-site storage, some means of transporting materials to the actual site had to be put into place. What seems a stroke of genius in this respect was to exploit this need for transport to maximize the value-

added time of this highest paid people, i.e., the craftspeople. A number of "logistic couriers" was employed (the number determined through a formula of couriers proportionate to the number of craftspeople active in any given phase of the project) and trained to undertake a number of important logistical tasks. The couriers were unskilled laborers hired, through a staffing agency, by and paid for by the contractors, at a cost of about 1/3 of skilled craftspeople. Their tasks encompassed bringing materials to the craftspeople and distributing these among relevant rooms/areas, unpacking materials, performing quality control, removing packaging and other garbage, bringing large tools around the construction site to where they are needed, disassembling, moving, and reassembling scaffolding, simple "cleaning tasks" like vacuuming before craftspeople are installing floor coverings, sorting and storing drawings after completed work in an area, refilling of VMI stock, etc. The costs of the logistics couriers are much lower per hour than for craftspeople and they increase the productivity of the craftspeople dramatically, altogether having a huge productivity effect.

- For certain contractors, the productivity of the craftspeople has been further improved by a new type of scaffolding for long stretches of cabling work. A 90 cm high platform stretches the full length of corridors (assembled by the logistics couriers) allowing the electricians to simply walk up and down the corridor while installing cabling. This is much faster than the traditional approach of stepladders and much safer.
- Purchasing has also been simplified by using e-Purchasing systems that control and transfer orders to suppliers directly and thus allow delivery of materials within hours or the next day, depending on volumes and where the materials are stored. The e-Purchasing systems used were normally web-based systems already operated by the contractors or wholesalers within the different disciplines, and both increased the speed of orders and helped check that the correct materials were ordered. In cases where required materials, despite careful planning, seemed likely to not be on site when an operation was planned to start, this purchasing system allowed very speedy replenishment. Still, it should be mentioned that the project saw some delivery problems that had a negative effect on progress, with delays for some long lead time items.

Lean Construction Process

A major problem in the first phase of this project was that construction required substantially more work hours per square meter than what was planned, as a result of poor productivity of the craftspeople. Looking into this problem, it was found that too much time was wasted on transport work, waiting, tidying up, etc. To improve this situation, massive changes were required to allow better utilization of the expensive craftspeople's time. Some of the practices, systems and procedures implemented to achieve this involved creating more of a lean construction processes, and can be summarized as follows:

- Breaking down the work and planning it with a focus on letting the different disciplines work as much alone in an area as possible and handling the interfaces between disciplines. This was achieved through defining a number of "construction phases" (e.g., interior walls, electrical, ventilation, painting, etc.) and sequencing these. To some extent, this might sound less "lean", but we find some justification why this approach makes sense. First of all, much of the floor area in a hospital consists of small rooms with very little space for several people to work concurrently. And since the duration of the work by each discipline varies and is difficult to estimate in advance, a planned balanced flow is difficult. Thus, a compromise has been to define an optimal sequence of when the different disciplines perform their operations, and creating a quasi-pull system out of this, where the completion of one disicipline's work is the trigger signal for the next discipline to commence its work. The result is less actual concurrent collaboration in each room among the disciplines, but in fact better coordination of the overall construction process.

- Combating a well-known “volume paralysis” that often impedes progress control in a large projects where sections of the building are so large that it is difficult to keep track of people, progress, etc. With weeks, perhaps months, between milestones/checkpoints, much time can pass before realizing there are deviations from plan. In the case project, this was done by breaking the whole project down into a number of “control areas” with corresponding “work packages”, here as many as about 1,100 of them, that allow more detailed follow-up. This has also allowed benchmarking to be used as a motivational tool by creating “competition” among work teams.
- A structure of planning meetings to ensure that all operations can start when planned; meetings respectively six/three/one weeks in advance of commencement of work to check that everything is ready to start and take action on any outstanding items.
- Delegating the decision power about problems that occur continuously to those with the best/most knowledge to solve them. There are detailed "rules" for the decision power of each level. Most often, this means issues are dealt with by foremen on site, but often also through direct discussions among craftspeople from different disciplines. When necessary, problems are escalated up through the hierarchy, but this has helped relieve people who should maintain a high-level focus from getting involved in details and sped up the problem-solving process.
- Facilitating quality control throughout the construction process, rather than doing this at the end, when correcting problems is much more cumbersome and expensive. This has partly been done through having the craftspeople test assemblies and sub-systems as they are installed, and partly having more comprehensive completion tests of “work areas” as they have been finalized. To rectify any problems identified through the quality controls, so-called "rescue squads” were appointed to deal with the identified defects, so that the original team could focus on progress at the “front line”. This can also be construed as going against the lean idea of zero defects and not wasting time and effort correcting errors. However, until the real world truly catches up with the ideal theory, errors in such a complex building project as a hospital sadly seem inevitable and the disruptions from fixing them are minimized using dedicated people instead of pulling people from their work in other areas.
- Co-location of key personnel from the project owner with project managers and other key people from the contractors and engineering consultants, allowing a more open communication and handling of issues as they surface.

All in all, these different practices, in addition to a number of others that we have not included here, to us seem to constitute a thorough and consistent approach that embodies much of the lean construction principles and in our view bring these even further than what we have seen before. As the next section shows, this has indeed produced positive effects, providing some evidence that they work as intended.

Effects of the LC approach of the St. Olav's University Hospital Construction Project

The second part of the results section presents the findings derived from the quantitative data obtained from the project through project records and survey data. In terms of the quantitative project data, seemingly comparable numbers were collected for phase 1 and phase 2 respectively for the factors of m^2 area built, total costs, total number of worked hours, injuries leading to absenteeism, H value, and warranty costs. We use the word "seemingly" since in real life it is very difficult to achieve a study design with a true "control group" when studying project management issues. In this project, there are probably many factors that make this direct comparison less valid, but one main concern is the composition of the building area produced. Table 2 shows a rough breakdown of the building area and the corresponding size. While it may not be apparent from this list, there is a tendency toward larger and more complex buildings in phase 2, while phase 1 included a patient hotel with far less complexity than treatment centers. Furthermore, as this project progressed, the construction site grew increasingly more built-up and thus with less space for movement, storage, etc., and phase 2 also included the demolition of the old main building of the hospital. This should be kept in mind when analyzing the data.

Table 2 Building area breakdown

Phase 1	**No. of m^2**
Patient Hotel	5419
Nevro Center	34943
Lab Center	25556
Women & Child Center	31184
Total Phase 1	*97102*
Phase 2	
Movement Center	19304
1902 Building	7442
Supply Center	9622
Intensive, Heart & Lung	40093
Gastro Center	24154
Gastro, Rehab & Cancer Center	7079
Knowledge Center	17680
Total Phase 2	*125374*

Lean Construction was expected to yield positive effects along several dimensions. The dimensions that saw findings confirming positive effects were:

- Reduced building time/increased schedule adherence
- Reduced costs
- Improved build quality

- Improved health, safety and environment (HSE) and job satisfaction

Each of these is discussed below.

Adoption of lean production principles to lean construction is not an easy task and it requires well-structured approaches. In this particular study (St. Olav's Hospital construction project), we have considered 18 attributes that have been systematically classified into three major categories (see Figure 1). The first category is based on the dimensions that are linked with time and cost reductions. We grouped the causes for waiting/delay separately and actual waiting time together with time-to-build and time needed for administration work. In total, the overall objective is to free up more time for actual value-added construction work to shorten the project's life cycle. The second and the third categories respectively cover improved quality and health, safety, and environment (HSE), thus representing many of the factors considered in the study.

To put these attributes into a lean construction framework, we have linked them to Ballard's LPDS model, see Figure 2. The numbers/letters behind each attribute in Figure 1 indicate which aspect of the LPDS model they relate to.

Reduced build time/increased schedule adherence

The impact of the lean construction approach in this case study is predominantly positive when it comes to the time dimension in terms of reducing building time and staying on schedule. In spite of some difficulties, the main contractor kept the project on track according to the original schedule. This is not always the case for projects at this level of complexity. Our interviewees attribute the project's ability to stay on schedule to a) breaking down individual buildings in the project down into control areas, b) clarifications made in the LC meetings, and c) having realistic plans to start with.

At an overall level, comparing the actual figures for the number of hours required per m^2 of building is deceptively simple; the average in phase 1 was 41.47 hours per m^2 completed building area, while in phase 2, this had in fact increased to 41.73 hours per m^2. The challenge is; are these numbers directly comparable, and we have concluded that they are not. As we mentioned, the phase 1 total building area was on average of less complexity than phase 2 as well as the conditions on site. Thus, achieving almost the same number of hours per m^2 in phase 2 as in phase 2 indicates positive effects of the LC efforts made.

With equal challenges in direct comparisons, at the sub-contractor level, an electrical installation sub-contractor estimates a reduction from 3.3 hours per square meter in phase 1 of the construction projects, where lean construction principles were not applied, to 2.4 hours per square meter in phase 2. We have not been able to validate these numbers in detail, but they seem to compare directly the numbers of hours worked in both phases divided by the area constructed. The much higher time saving for this sub-contractor compared with the overall numbers for the whole project is somewhat understandable, as this sub-contractor was among the 2-3 actors implementing LC practices to the largest extent. According to the sub-contractor, this considerable reduction in time consumption is related to adequate staffing and an efficient work situation for the workers (e.g., the use of innovative approaches to logistics). The increase in time spent in meetings, compared to the traditional way of running construction projects, is claimed to be very small.

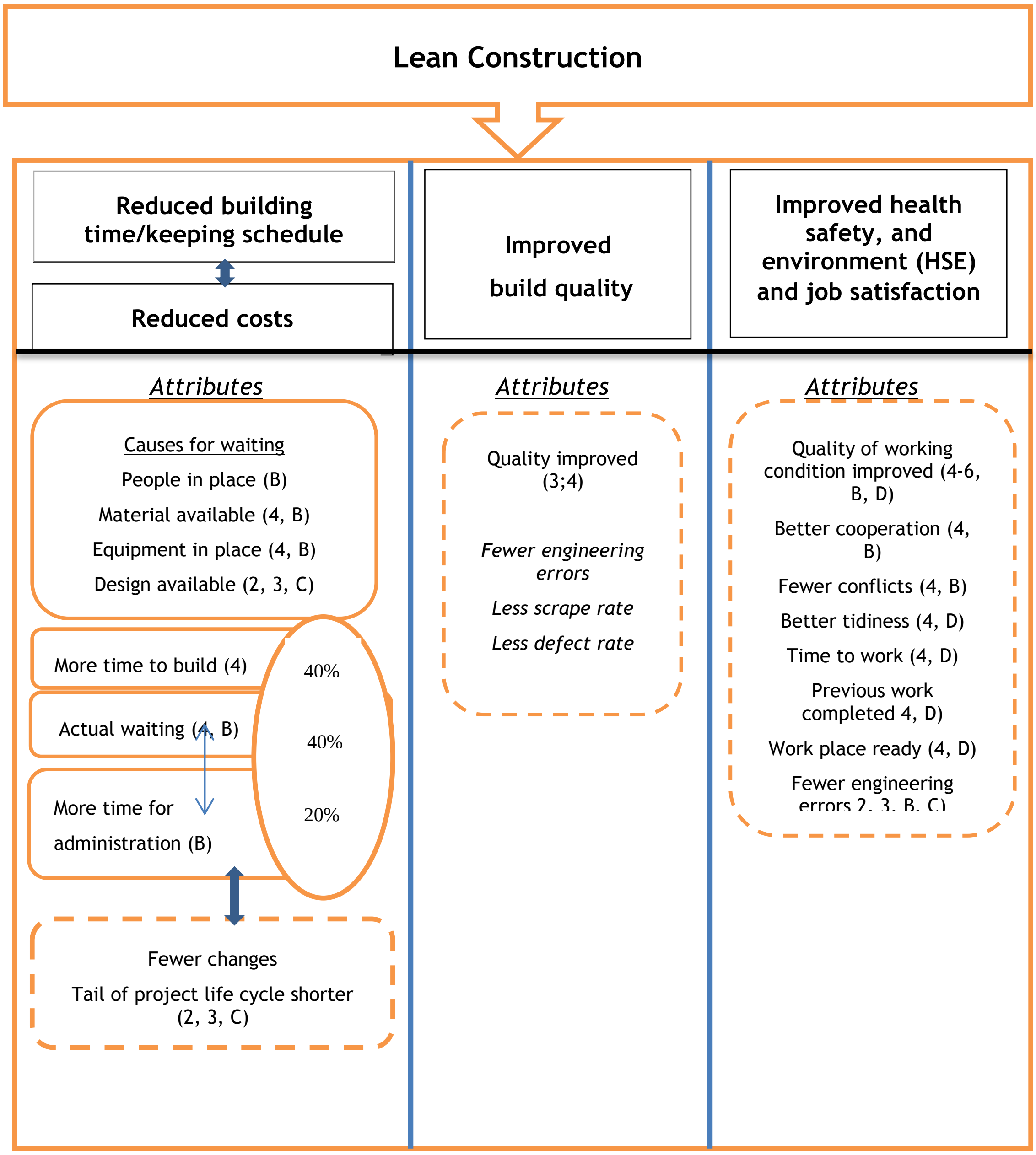


Figure 1 Systematic structure of lean construction attributes

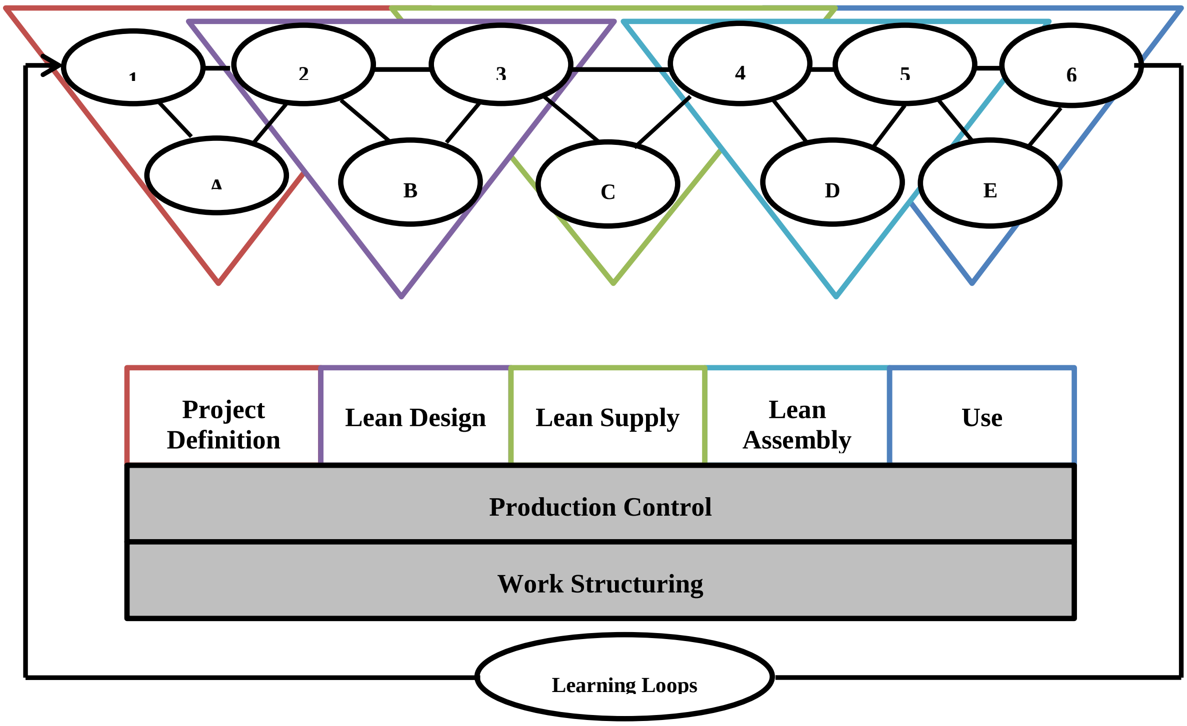


Figure 2 Lean Project Delivery System (LPDS), adapted from Ballard (2000, 2006), where the numbers/letters denote: 1. Purposes, 2. Design Concepts, 3. Product Design, 4. Fabrication and Logistics, 5. Commissioning, 6. Alteration and Decommissioning. A. Constraints, B. Process Design, C. Detailed Engineering, D. Installation, E. Operations and Maintenance

Even though the project managed to stay on schedule, there seems to be more potential in running lean construction projects. This construction project could have been completed ahead of schedule if it had not been the victim of material deliveries failing to appear, resulting in thorough planning being in vain and loose ends having to be dealt with.

Costs

Cost is connected to build time in that reduced build time usually is followed by reduced cost, unless reduced build time results in poor quality, which leads to additional costs of rectification or financial compensation. Following this line of argument one would expect reduced cost in construction phase 2 compared to construction phase 1 and comparable construction projects following a traditional approach. Table 3 contains cost data per building in phases 1 and 2.

Table 3 Costs per building

Phase 1	No. of m^2	Cost per m^2	Cost per m^2 treatment centers
Patient Hotel	5419	32690	Excluded
Nevro Center	34943	58237	58237
Lab Center	25556	55551	55551
Women & Child Center	31184	54671	54671
Total Phase 1	*97102*	*54959*	*56275*
Phase 2			
Movement Center	19304	53587	53587
1902 Building	7442	26947	Excluded
Supply Center	9622	39366	Excluded
Intensive, Heart & Lung	40093	56785	56785
Gastro Center	24154	53159	53159
Gastro, Rehab & Cancer Center	7079	46727	46727
Knowledge Center	17680	68286	Excluded
Total Phase 2	*125374*	*53540*	*54352*

Comparing the total numbers for the entire area of each phase, there is a 2.6% reduction in cost per m^2. If only including the patient treatment centers in the comparison, the reduction is 3.4%. Unfortunately, it is impossible to conclude how much of this can be attributed to LC practices.

Construction quality

Some of the people we interviewed were not satisfied with the construction quality, as a number of defects had been identified. Looking at warranty costs, the best obtainable indicator from quantitative data, the changes from phase 1 to phase were significant:

- Phase 1: Total warranty costs of 25.9 million NOK, per m^2 266.84 NOK
- Phase 2: Total warranty costs of 15.0 million NOK, per m^2 119.92 NOK

This represents a 55.1% reduction in warranty costs per m^2 built area.

The majority of our interviewees also pointed out that seen in relation to the technical complexity of hospital buildings the construction quality was very good. Figure 3 shows the distribution of survey responses to the question whether LC has led to better build quality. The distribution is heavily skewed toward agreement with the question, with the average response being 5.2 on the 1-7 scale.

The following were mentioned as factors contributing to construction quality:

- The design basis contained less errors now compared to construction phase 1.
- Demanding owner representatives.

- Interface management requiring that one discipline has completed their work before handing the area over to the next discipline (e.g. formally signing that the work of one's discipline is completed).
- Installers got the opportunity to concentrate on their trade, as a logistics partner provided a delivery service bringing the building materials to the room where the materials were to be fitted.
- A tidy workplace.
- Well-managed coordination between trades/disciplines.
- A test regime revealing defects at an early stage.
- "Rescue squads" dealing with identified defects, so that the original team could focus on progress at the "front line".
- Improving quality by identifying possible improvements before commencing work on a similar floor/building as the one that was just completed.

HSE and well-being

This is the area with the clearest positive findings:

- Phase 1: 58 injuries resulting in absenteeism, per m^2 this amounts to 0.0006, and an H value (number of work-related injuries resulting in absenteeism per million work hours) of 13.1
- Phase 2: 30 injuries resulting in absenteeism, equaling 0.0002 per m^2, and an H value of 5.7

Comparing the two phases, this represents a 59.9% reduction in injuries per m^2 and a 56.5% reduction in H value, both impressive performance development from phase 1 to phase 2.

The low number of injuries at the construction site was explained by the interviewees as a result of lean construction. As everyone knows what to do at any given time there are no surprises (e.g., no live electric circuit when it was supposes to be disabled). A tidy construction site contributes to the low injury rate as the risk of tripping over stored building materials or waste is reduced. At St. Olav's Hospital there was a strong focus on what they termed "clean, dry building" in the construction phase, and there were some discussions regarding whether or not this was part of lean construction or a separate initiative. Some argued that the principle of clean, dry building has had a larger effect than lean construction on HSE.

Numerous mechanisms were put in place to make sure continuous attention was being paid to HSE. For instance delivery service personnel were assigned the additional task of looking for and reporting non-desirable events, and with a bonus in the form of lottery tickets for reports submitted.

When asked to compare this construction project with previous projects where lean construction was not made use of, the people working in this project reported overall well-being at work being better; improved cooperation with other trades/companies; less conflicts; a more tidy and orderly construction site; sufficient time allocated for the job to be done. Some of this is in contrast to construction phase 1 where people asked to be transferred to other projects and the Norwegian Labor Inspection Authority uncovered psychosocial challenges in the project.

Some more specific data from the survey reveal additional details. Build quality was improved with an average of 5.2, people in the project were in general more content with their work situation than in other non-LC projects with an average 5.4, the cooperation climate among the different companies involved was also seen as much better with an average of 5.7. Further average values of some attributes found in this research are shown in table 4.

Table 4 Average value of some attributes

Attribute	Mean value
LC has led to fewer conflicts in the project	5,3
The work place is tidier	5,8
Previous operations are completed on time	5,0
Drawings are available when an operation is planned to start	5,0
Persons required for an operation are in place when planned	5,3
Materials required for an operation are in place when planned	5,4
Equipment required for an operation are in place when planned	5,3

All in all, the data about effects of the LC approaches point quite unequivocally to many positive results. The general trends of three factors of improvement are presented in Figure 3:

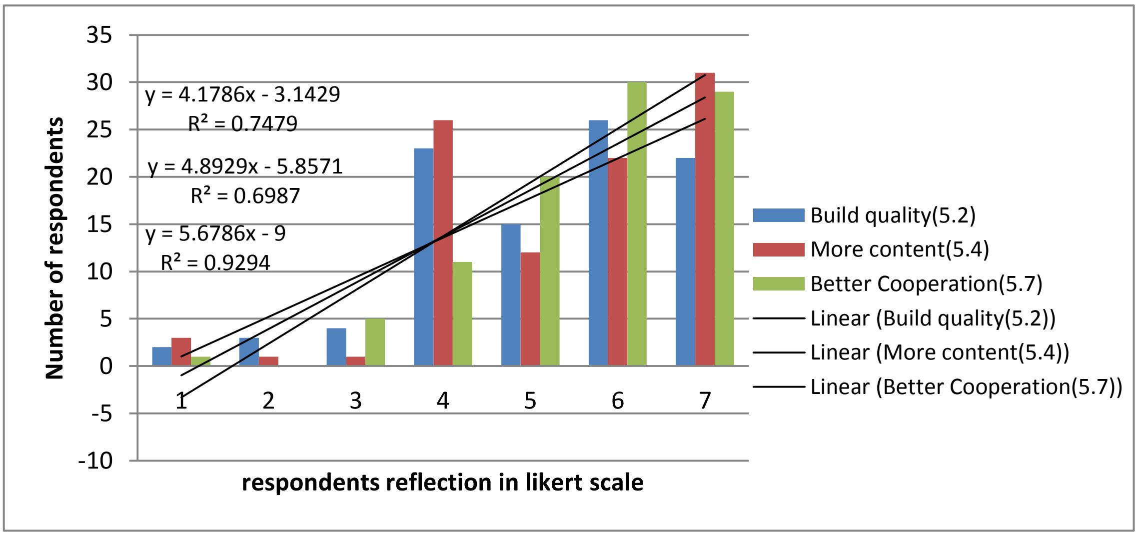


Figure 3 Respondents' reflection on LC from phase 2 project at St. Olav's hospital

The regression lines in all cases show positively increasing gradients that reveal positive improvements, although the coefficients of determination (RSQ) are somehow lower than what it should be. However, the attribute linked to cooperation improvement is relatively close to the norm (>0.95). In general, such a lower square error line or higher coefficient of determination with three attributes could be reasonable since we consider only three factors. For the sake of space, we omitted some attributes and their values.

Table 5 and table 6 are presented to show the correlation between systematically grouped attributes. In table 5, we can see a strong correlation between several paired attributes except the correlation between actual waiting and causes of waiting, which is very weak with negative value. The probable reason could be due to some factors that are not included in the survey. For instance delay due to decision making and other external factors that could be the object of future work after this research. As an insight, we would think of concurrent engineering from a fast-tracking perspective and robust decision making to improve the performances that are related to time. The 18 attributes that are classified into 5 sub-groups with corresponding respondents and weighted averages of each sub-group are presented in table 5.

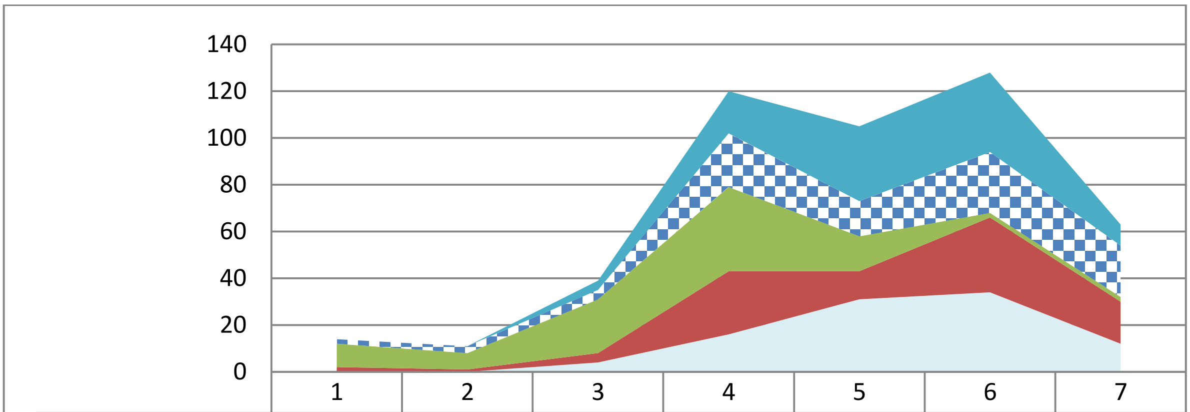
Table 5 Correlation matrix between the five classified attributes

	Causes for waiting	Time to build	Actual waiting	Improved quality	Improved HSE
Causes for waiting	1	0,771261893	-0,011888844	0,78614177	0,994940222
Time to build	0,771261893	1	0,145830792	0,965474212	0,761899778
Actual waiting	-0,011888844	0,145830792	1	0,078374757	0,05927683
Improved quality	0,78614177	0,965474212	0,078374757	1	0,760880461
Improved HSE	0,994940222	0,761899778	0,05927683	0,760880461	1

Table 6 Weighted average of different dimensions from Lean construction respondents

Scale	Causes for waiting	Time to build	Actual waiting	Improved quality	Improved HSE
1	0	2	10	2	0
2	0	1	7	3	0
3	4	4	23	4	4
4	16	27	36	23	18
5	31	12	15	15	32
6	34	32	2	26	34
7	12	18	2	22	9
Weighted average	5	4,9	3,5	5,2	4,9

The respondents' reflections on lean construction with an average score of more than 5 on a likert scale of 1-7 are shown in Figure 4. It shows that the case project performs better in HSE and quality. Each group of attributes shows reasonable achievements in performance improvement after lean construction is introduced. However, the forecast shows that the case hospital can get even better and continuously grow results with some additional effort by encompassing other relevant attributes.



	1	2	3	4	5	6	7
Improved HSE	0	0	4	18	32	34	9
Improved quality	2	3	4	23	15	26	22
Actual waiting	10	7	23	36	15	2	2
Time to build	2	1	4	27	12	32	18
Causes for waiting	0	0	4	16	31	34	12

Figure 4 Lean Construction project trends at St. Olav's Hospital

When we compare the performance of the case project before and after lean construction (Figure 5), a significant positive improvement has been attained. However, the forecasted result from the exponential smoothing reveals that there would still be a possibility for further positive achievements as some attributes show lower values compared with the present ones

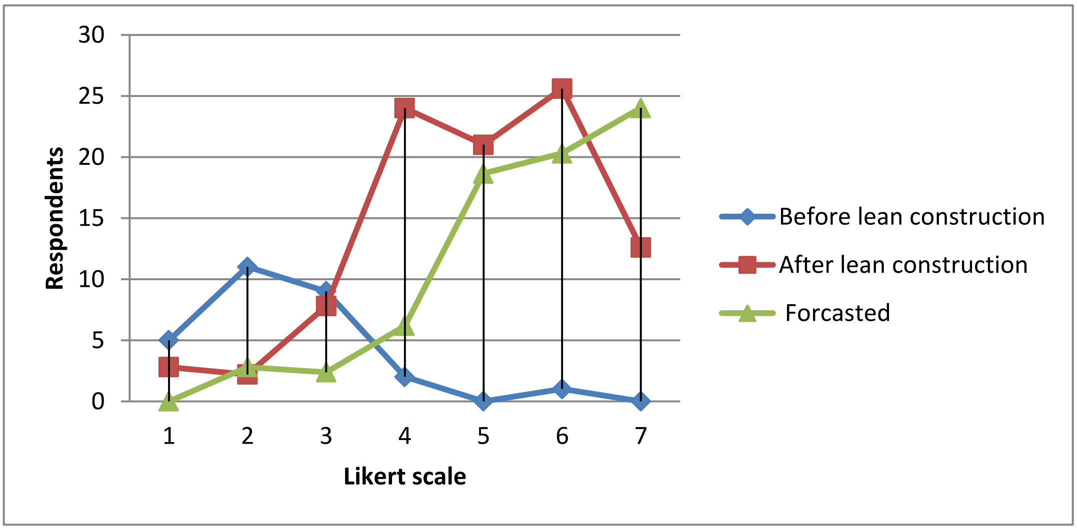


Figure 5 Performance comparisons from Lean Construction project at St. Olav's Hospital

Richard (2007) showed that some Hospitals gained a significant benefit by implementing lean construction. However, our study included some additional dimensions on health, safety and environment besides the factors that only focus on saving time and money. The aim of this research is not only to give pertinent suggestions and keep an open mind on lean construction implementation but to build a systematic and integrated framework that constitutes several attributes and dimensions that could help to measure and improve the performance of different projects. As the correlation from the study depicts on the causes of the delay and having included additional dimensions, we are optimistic to have a well-established and systematized framework that will help those projects in implementing lean construction and/or projects in the planning stage. The challenges of comparing the effects and results of lean construction on different projects are projects' peculiarities, objectives, sizes, resources and etc. We believe there should be some flexibility on using the proposed attributes and modifying the generic framework based on the characteristics and type of the project.

Conclusions

Lean principles in general and lean construction in particular are approaches developed to improve the productivity of the construction industry and its projects. In transferring lean production from the manufacturing industries, the forerunners in this field made an excellent job of adapting the main principles into practices that are tailored to the characteristics of construction projects. One main tenet of lean thinking is of course that everything can be further improved, and as a consequence, also lean construction practices continue to evolve as new actors implement LC.

This paper has described a case project where poor performance in the first phase of a large hospital project prompted the project owner to implement LC in phase 2. The project lasted several years and had a project owner organization that was willing to invest in the LC methodology employed. When following the project as researchers, we realized that some practices were developed and successfully used in this project that we had not seen documented anywhere else. One main purpose of this paper has therefore been to document these practices in order to allow other researchers and practitioners to learn from this project and develop the practices even further. We believe this to be one of two main contributions from this paper.

Although a hospital project is somewhat different in some respects than other construction projects, we see no specific reason to believe that these novel practices should not be transferrable. Perhaps the most specific singular aspect of this project has been the fact that the old hospital was fully operational while the new buildings were being erected around the old ones. This has posed certain logistical challenges that necessitated novel thinking, i.e., the use of an off-site storage area and dedicated logistics providers on the construction site. However, we rather believe this was an important impetus for new thinking and not a factor limiting the applicability of these approaches in "regular" projects.

In terms of effects realized through the use of LC, our data obtained from a number of the different actors involved in the project indicate positive results. This is in line with other studies of LC benefits and as such offers represents the other main finding in the shape of further proof of this relationship. However, we also see some variation in which benefits are achieved. From one of the findings of this research, the negative correlation between actual waiting and causes for waiting, we can see clearly that there are still additional attributes that should be studied to fill the gap by finding out the factor that causes the actual delay in addition to the attributes considered. However, the general trends of most attributes show a positive strong relationship; better achievements and overall very high scores. The forecast also confirms this result though some values show projections below the existing ones. Of course, there is also the question of attribution, i.e., to which extent we can be sure that the positive results in terms of cost, time, quality, and HSE, are in fact caused by the LC practices.

These findings, in our view, are important for two reasons. First, they provide further empirical evidence that LC, even in a complex project like this large hospital project, can lead to strong benefits across a range of performance dimensions (building time, quality, HSE, etc.). This should contribute to inducing further implementations of LC practices in the construction industry. Second, the data collected show some variance in terms of the "strength" of the benefits and also reveal some inter-correlation among variables.

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