DECREASING COMPLEXITY OF THE ON-SITE CONSTRUCTION PROCESS USING PREFABRICATION: A CASE STUDY

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ABSTRACT

Implementing prefabrication is by many seen as means to improve construction in terms of managing uncertainties and productivity. However, regarding Swedish civil engineering works this has not been adequately documented to date. This case study uses Value Stream Mapping (VSM) to document the construction of a semi-prefabricated superstructure. The intention of the project is to investigate if the bridge construction process becomes less complex to manage and control when using prefabrication instead of traditional on-site construction.

By relocating parts of traditional on-site construction to a factory, the time spent on site performing traditional work tasks such as constructing formwork, mounting and fixing of rebar and casting concrete, could be decreased. Nevertheless, mapping the process revealed shortcomings such as problems placing the prefabricated beams onto the on-site constructed plate structures and also that clear communication between actors tend to increase in importance when choosing prefabrication as construction method.

Results from the VSM show that the semi-prefabricated superstructure, future state, became less complex compared to current state construction and also 75% quicker to construct on-site. By redesigning the bridge to eliminate some of the infant "diseases", prefabrication will become more common in the future of small bridge construction in Sweden.

KEY WORDS

Prefabrication, Value Stream mapping (VSM), Complexity, Bridge Construction.

INTRODUCTION

Several productivity studies (e.g., Horman and Kenley 2005, Mossman 2009 and Simonsson 2011) identify large amount of waste generated in traditional on-site construction. Bridges in Sweden are most often traditionally on-site constructed. On-site construction is often associated with high complexity and unpredictable conditions (Sardén and Stehn 2006). The idea of prefabrication is to decrease needed working hours and amount of activities performed on-site, meaning the process becomes easier to plan and control. However, research demonstrating these effects for bridge construction, especially in Sweden, are absent. Comparing the prefabricated construction process with traditional on-site construction, both positive and negative sides of the two different construction methods are revealed. The prefabricated concept is quicker and easier to construct but some concerns like less flexibility and importance of correct dimensions are recognized. Prefabrication in

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bridge construction is seen as a method to reduce traffic disturbance, costs and to improve on-site work safety (Freeby 2005).

Concepts from the 1990s often consist of pre-stressed concrete elements for superstructure but have now extended to also include substructures (e.g. NCHRP 2003, Federal Highway Administration 2006, Russell et al. 2005). Prefabrication can be used as a method to deal with highly complex situations like a construction project (Björnfot and Sardén 2006). Waste can effectively be reduced by using prefabrication (Tam et al. 2006). For lean principles and prefabrication to be a major part of construction projects they have to be properly evaluated (Pasquire and Connolly 2002).

Prefabrication in Swedish bridge construction is often associated with unattractive appearance and poor quality. Thus, to improve the status of prefabrication it is important to demonstrate the benefits of the method and why it should be a natural component of the establishment. Projects within civil engineering argue to be unique and bridges are of one-of-a-kind nature, therefore standardized products find it hard to gain market share. An important factor for standardized products to become more common is that design requirements do not differ from project to project and that the product owners own the complete process (Jensen et al. 2008). Consequently, the following research question can be formulated: How is the on-site construction process affected in terms of complexity and construction time by using prefabricated bridges?

COMPLEXITY IN CONSTRUCTION

Bertelsen (2003a) argues that construction must be seen as a complex and non-linear phenomenon and therefore, projects cannot be planned traditionally. Three perspectives are analysed by Bertelsen (2003b); first that the world outside the project is non-linear, second that projects often involve several actors with different goals and last that project teams are temporary often hired from different subcontractors by the main contractor. Kenley (2005) believes that on-site construction is beyond understanding and therefore impossible to plan and manage. Koskela and Howell (2002) on the other hand implies that construction projects can be seen mainly as a linear process and that successful management is based on e.g. Transformation, Flow and Value generation theories. Uncertainties like weather, deliveries and other surrounding problems do not make construction impossible to plan and manage. The project team should reduce the degree of uncertainty by planning the process as well as possible.

Reducing the complexity at a construction site can be divided into two different strategies emerged from Lean Construction. By either developing on-site construction processes as proposed by Koskela et al. (2003), or to develop prefabrication and standardized processes as proposed by Ballard and Arbulu (2004). Höök and Stehn (2005) called the later a prefabrication strategy. The idea is to simplify and minimize work at site and by doing that involving every phase in the delivery process. Not only are the amount of activities of importance, but also the variation and interdependency between them (Baccarini, 1996). Prefabrication as part of an industrialized construction process is a way to control unpredictable events (Björnfot and Stehn 2005). Standardization and pre-assembly is not always the answer. Conflict between standardization and flexibility has not yet been resolved (Gibb 2001).

MAPPING CONSTRUCTION PROCESS

Value Stream Mapping (VSM) is an effective method to identify the activities taking place at a construction site and to map the flow of manufacturing (Alvarez et al. 2009, Mehta 2009). Not focusing on machines, transportation and personal utilization but instead studying the continuous flow, the chance of sub-optimizing the process is reduced (Ballard et al. 2003, Arbulu and Tommelein 2002). VSM is only focusing on specific parts of the company that add value to a specific product unlike traditional supply chains that map the complete activities (Hines and Rich 1997). By focusing on these specific activities, mapping a bridge construction site is easier.

VSM is intended and most commonly used in high volume production where it is easy to map the work flow backward, from finished goods back to raw material (Khaswala and Irani 2001). Wilson (2009) however disagrees implying that VSM can be utilized to any business process. There are two ground steps when performing a VSM, first mapping the current state to create a clear view of the existing construction and to highlight today's waste. Then future state is created where root causes to waste are eliminated (Rother and Shook 2004, Yu et al. 2009). After mapping future state an ideal state is created involving larger changes affecting e.g. buildability (Simonsson 2011).

USING VSM TO IDENTIFY COMPLEXITY

Traditionally, VSM is revealing waste by mapping all activities throughout the whole process and dividing them into different waste categories (Simonsson 2011). This research maps only the main product development activities performed at the construction site to visualize the site complexity. In this case complexity is seen as the amount and difficulty of on-site activities, needed working hours at site and lead time. Höök and Stehn (2005) state that prefabrication decreases complexity to some extent however new obstacles might be introduced. The main purpose of this VSM is not to identify waste in production but to compare commonly used on-site construction (current state) with the rare semi-prefabricated concept (future state). VSM is also used to identify shortcomings that arise when a new construction method is introduced.

Future state is presented by a standardized semi-prefabricated bridge concept. Prefabricated bridges are a rare feature in Sweden making it interesting to map and compare productivity with on-site construction. Mapping the future state of construction is in this case performed by observations at site, interviews with site managers and by studying timesheets. To be able to compare the two construction methods accurately, calculated values from a suggested alternative on-site constructed bridge in the tender is used as current state. Values and activities are discussed with and verified by the site managers.

OMITTED ACTIVITIES

This VSM is omitting some non-value-adding activities associated with traditional on-site construction (Simonsson 2011). By neglecting e.g. transportation and wait, the research becomes more general, not focusing too much on this specific case. Off-site manufacturing performed by the supplier is not included in the VSM; the reason for this is to see how the construction process at site is changing and not how the manufacturing process at supplier is performed. Though, most often having a short construction time at site is of interest.

A lot of small activities are performed during the construction of a bridge, e.g. repairing holes, covering the superstructure after casting concrete, and to make the VSM manageable only activities that have duration of more than 10 hours are taken into count. VSM in this research is focused on the superstructure of the bridge. This because, the superstructure is most different between current and future state and it is also the most complicated part of a bridge construction. Activities not included in the VSM are briefly discussed however, the focus is to compare the main activities of the construction process performed at site to see if prefabrication makes the process less complex and time consuming.

STUDIED BRIDGE CONCEPTS

The bridge specifically studied in this research is constructed over the river Skenaån, outside Skänninge in Sweden, figure 1a. For current state, all bridge activities like constructing formwork, fixing and mounting rebar and casting concrete are performed on site, figure 1b. To construct on-site bridges over water complicated framework are needed to support the formwork for the superstructure before the bridge is complete.

a)  b) 

Figure 1: a) Complete bridge at construction site. b) Traditional on-site construction

Focus is on mapping the future state, investigating how this, within Swedish civil engineering, rare construction method is affecting the on-site construction process. Consequently, only this concept is described in detail. NCC Montagebro (future state) is a semi-prefabricated bridge concept that is developed for fast and easy construction making it suitable for passing water, railway or busy roads where traffic disruption must be minimized. The substructure consists of on-site constructed foundations, plate structures and wings while the superstructure consists of prefabricated edge beams, beams and slabs, figure 2.

a)  b)  c) 

Figure 2: a) Substructure. b) Prefabricated beams. c) Prefabricated slabs

By relocating parts of traditional on-site construction to a factory, the purpose is to reduce time spent on-site performing traditional work tasks such as constructing formwork, mounting and fixing of rebar and casting concrete. Prefabricated parts are mounted together to form permanent formwork for the superstructure. Edge beams and beams are also included in the structure, reducing the needed amount of on-site mounted reinforcement. After prefabricated parts are mounted, needed reinforcement and complemented formwork is mounted into the superstructure. Following these activities the formwork is filled with concrete to create a continuous superstructure. NCC Montagebro is not a new concept; it was developed in 1992 and between 1993 and 2000 some 11 bridges was constructed, most of them where built over railway. From 2000 until the studied object was constructed in 2011, no bridges of this type were constructed.

RESULT

CURRENT STATE

Activities from the alternative on-site constructed bridge were together with practitioners discussed and put in correct construction order. The number of activities performed during the construction of the superstructure is 12 and total lead time for the superstructure is 980 working hours, figure 3. Since the bridge is relatively small, only one parallel activity is performed meaning that lead time becomes long. If more activities had been performed parallel, the lead time could be shortened, but instead the process becomes more difficult to plan and control. Some activities are relatively complicated and therefore main activities; formwork, reinforcement and casting concrete, are performed by different teams. According to the site manager; formwork material is delivered in one batch before the construction begins and reinforcement is delivered before each structure starts to be constructed. Studying alternative calculations reveals that total amount of work for current state are about 1660 hours for the whole bridge including all activities.

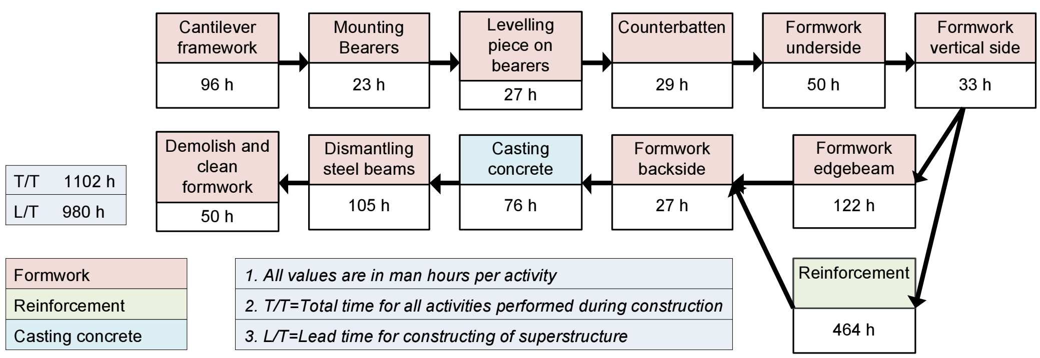


Figure 3: VSM for current state of construction

FUTURE STATE

Only six activities are performed during construction of future state and only one parallel, figure 4. Total lead time for future state is 249 working hours. The first three activities consist of simply and standardized tasks performed by the supplier, figure 2. This prefabrication supplier is working with Just-In-Time (JIT), meaning that beams and slabs arrived at construction site JIT to be mounted onto the plate structures making the handling minimal. A specialized assembly team from the supplier performed the mounting. This make the process efficient (Gibb 2001). According to the summary calculation, the total amount of hours for the semi-prefabricated concept is about 720 including all activities.

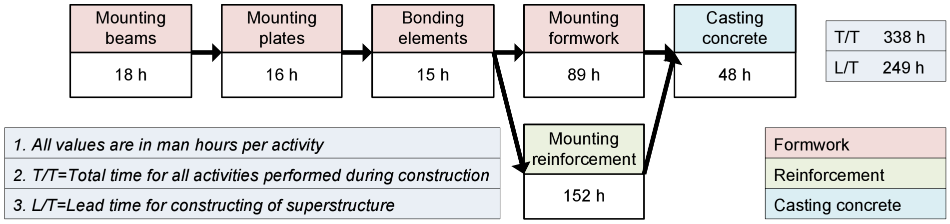


Figure 4: VSM for future state of construction

Shortcomings of future state

The performed case study reveals some shortcomings that have to be corrected for the construction method to become optimal. For instance, mounting prefabricated beams onto the on-site constructed plate structures created some difficulties because of reinforcement collisions. Workers had to fix the reinforcement before beams could be placed correctly, figure 5a. Edge beams had to be stabilized to not fall down, because of unsymmetrical dimensions, figure 5b. Some of the prefabricated slabs where too long and had to be cut before mounting onto the beams. Reinforcement sticking up from beams causes working environment risks, such as workers falling when mounting slabs, figure 5c. The rebar sticking up from the beams were bent down over the slabs after mounting, causing a time consuming task, included in mounting reinforcement. If for some reason, delivery problems for the prefabricated parts occur, construction process would stop. Because activities are depended on each other the process becomes sensitive.

a) 

b) 

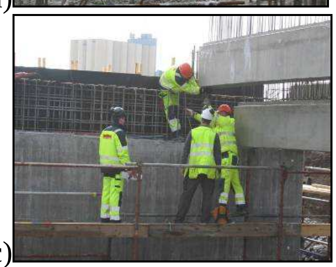
c) 

Figure 5: a) Mounting beam. b) Stabilizing edge beam. c) Reinforcement sticking up.

ANALYSIS & DISCUSSION

Comparing the two construction methods reveals a decreased complexity for future state. On-site activities are decreased by 50% and are simpler to perform, making the construction process easier to control, table 1. Lead time for the on-site construction process decreased with approximately 75% for future state.

Table 1: On-site (parallel) activities, working hours and lead time for current and future state

Process response	Current state	Future state	Complexity reduction
Performed activities (pcs)	12	6	50%
Parallel activities (pcs)	1	1	0%
Working hours (h)	1102	338	69%
Lead time (h)	980	249	75%

Because the prefabricated parts do not only form permanent formwork but also contain reinforcements and concrete, the amount of rebar to be mounted and concrete to be cast on-site are decreased. Also the complicated framework needed to construct current state is not needed in the construction of future state. Less working hours at site for all main activities; formwork, reinforcement and casting of concrete are therefore foreseen for future state. Time spent on-site, constructing the superstructure is decreasing from approximately seven weeks down to two weeks for a team of four workers. Activities performed constructing the future state are more standardized, meaning the activities become less complicated to perform. Working hours between the three main activities are in both construction methods distributed roughly as follows; formwork 55-60%, reinforcement 25-35% and casting concrete 10-15%. Harmful work postures that are associated with traditional on-site construction can be reduced by using prefabrication (Rwamamara et al. 2010).

For future state, all activities except mounting formwork, which is a parallel activity, can be seen as value-adding activities meaning the critical chain does not change if waste decreases for non-value-added activity. For current state, only two value-adding activities, reinforcement and casting of concrete, can be identified. All other activities can be seen as non-value-adding activities, e.g. formwork is seen as type 1 muda (Womack & Jones 2003). For current state, non-value adding activities represents about 45% of total lead time.

After completion of the bridge, a follow-up involving contractor, supplier and designer were conducted. The follow up discussed problems and shortcomings of future state and root causes to problems were pointed out, table 2.

Table 2: Causes to problems

Causes to problems	Effect
New construction method	Lack of knowledge from involved participants
Lack of start up meeting	Establish demands and communications channels
No continuous meetings	Simple problems could be solved earlier
Lack of clear communication	Communication only through design documents cause confusion
Lack of off-site knowledge	Designers could have designed the bridge for increased buildability
Bad cooperation	Involve participants in design to solve problem quicker

Combining the case study with the follow-up of the future state, three problem areas could be highlighted. First, clear communication and cooperation between involved participants is increasing in needs, because understanding the process of off-site manufacturing is important. Secondly, the prefabricated product becomes less flexible and late changes are difficult to handle at construction site. Controlling parameters have to be set earlier, before prefabrication of parts are started (Koskela et al. 2003 Björnfot and Stehn 2005).

Last problem area summarizes all present difficulties; this by saying that a standardized product likes NCC Montagebro has to have a standardized process to maximize the outcome. Much focus is on developing the standardized product instead of developing the standardized construction process to become more efficient and effective. By having a standardized process, it becomes possible to measure how changes to product and process affect the outcome (Liker 2004).

IDEAL STATE

Developing the product even more will have to involve participants from; contractor (concept owner), prefabrication supplier, designer and client because changes will affect all. Superstructure is already developed but, by using e.g. prefabricated reinforcement and rebar carpets and utilizing Self Compacting Concrete (SCC) instead of traditional concrete on-site construction time could be decreased. Utilizing rebar carpets could decrease construction time by 140 h, from 152 h down to 12 h, and by using SCC time spent on casting concrete could decrease from 48 h down to 16 h (Simonsson 2011).

Investigating other components of the bridge, e.g. foundations and plate structures, that today is on-site constructed, to see if these have potential to be prefabricated or semi-prefabricated would be a step towards ideal state. Using permanent formwork, prefabricated reinforcements and using SCC are possible solutions (Rwamamara et al. 2010). Calculated values reveal that about 55 percent of the total construction time for the entire semi-prefabricated bridge is spent performing on-site constructed components.

CONCLUSIONS & FUTURE RESEARCH

Results from the case study indicate that both on-site construction time and complexity associated with on-site construction are decreasing by implementing prefabrication. Prefabricated bridge is quicker to assemble and the amount of on-site activities is decreasing, meaning the process becomes easier to plan and control.

Because prefabrication is rare in Sweden some problems occurred during construction, e.g. connecting on-site constructed parts with prefabricated parts and importance of right dimensions from the supplier. Consequently, communication and cooperation between organizations are increasing in importance. A whole new approach to the construction process is needed before the intended result can be optimized. By redesigning the bridge to eliminate some of the infant “diseases”, prefabrication will have a chance to progress in the future for small bridge construction in Sweden.

This research is only studying the superstructure of one bridge and consequently, limited conclusions can be drawn. Since prefabricated bridges are uncommon in Sweden, it is difficult to find more objects to study. Performing a VSM for the superstructure of a bridge is not optimal because the chance of mapping the process from the end and back to the beginning is impossible, considering this only one case. By only looking at on-site activities for superstructure the VSM misses some important activities like; transportation, logistic, and off-site activities performed at the prefabrication supplier.

Mapping the whole process, from design to operation and maintenance would be of great interest. Creating a standardized process for the product would enable to measure future product changes. Studying the present on-site constructed parts would be the next step for developing the end product. Performing several case studies and using IT- visualization tools, creating 3D, 4D and Building Information Models (BIM) in order to analyze any possible solutions of prefabrication would be an appropriate method for future research. This in order to maximize buildability of the concept before the actual construction commences.

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