Increasing productivity through utilization of new construction techniques and Lean Construction philosophies in civil engineering projects

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ABSTRACT
The implementation of Self Compacting Concrete (SCC) together with two types of reinforcement and form techniques makes it possible to increase the degree of industrialization at construction sites markedly. To be able to realize this, Lean Construction principles prove to be important utensils during the planning and design phase. Also, the working environment is improved vastly when using SCC and different prefabricated reinforcement solutions. At the construction of the first full scale project “The Industrialized Concrete Bridge”, which was built during 2006 in Sweden, the new techniques were applied. It was concluded that the working environment was improved by three fold, production time at site could be reduced with up to 20 % and that the number of workers could be reduced by virtually 25 %.

Key words: Industrialization, Lean Construction, Productivity, SCC, Prefabrication, Reinforcement

1. INTRODUCTION

1.1 General

Building bridges with in-situ cast concrete today suffers, to some extent from inefficiency and less developed production methods. The construction work is time consuming, expensive and often includes poor working environment. According to Byfors and Jäderholm [1], the productivity increase in the Swedish construction industry in general has been approximately 3% during the period 1995-2005, which should be compared with an almost 90% productivity increase for the manufacturing industries during the same time period. Since the productivity increase is that low, a comprehensive view is needed for technical development and different production planning methods together with new material and construction solutions. This is seldom realized resulting in that today’s production methods are not as productive as they most certainly can be. However, many larger companies in Sweden develop alternative methods.
primary used for houses. The system of NCC Komplett was an interesting example where elements were totally pre-manufactured indoors and assembled in a protecting tent.

Industrialization is often mentioned as the measure to be taken to increase the productivity, and its definition is frequently debated in literature. Nevertheless, it is agreed that to achieve a more industrialized process, focus cannot only be on the production apparatus, i.e. the whole process needs to be managed from a project idea to completed structure. Other important issues that must be addressed at an industrialization level are logistics, collaboration between partners, standardized concepts, prefabrication of highly processed components, information technology and Lean Construction philosophies, [2] and [3].

1.2 Objective of the research project

The objective of the Ph.D research project “Industrial Concrete Bridge Construction” at Luleå University of Technology is to try to adapt Lean Construction to concrete construction and combine them with modern construction methods to develop a more industrialized process.

Lean Construction originates from Lean Production philosophies and theories that have offered lots of benefits to the manufacturing industry e.g. [4] and [5]. An interesting example of Lean Production use is the Toyota motor company, and one question is now if and how this way of thinking can be introduced into the construction industry.

By adopting and translating the principles and fundamentals of Lean Production into Lean Construction there is a possibility that the construction industry can make a leap in productivity, minimize costs for erection of buildings and bridges, and increase the health and safety of workers. The former can thus be defined as the long term objective of the research and the latter as the short term objectives.

2. THINKING LEAN

The platform for Lean Production is simple: to deliver what the customer wants when the customer needs it in the required quantity. A key issue is the focus on the well known waste or “muda”, i.e. any human activity that absorbs resources without creating any value [6]. Muda includes: 1) overproduction, 2) waiting, 3) unnecessary transports, 4) erroneous processes, 5) unnecessary inventory, 6) unnecessary movement, 7) goods with errors and 8) to not meet customer needs.

2.1 Origin

Toyota Motor Company was formed in 1937, and in the beginning of the 1950’s they had produced 2685 cars during thirteen years of production which should be compared with Fords Rouge plant that was manufacturing 7000 cars per day [5]! Something had to be done so Toyota sent over Eiji Toyoda on a study trip to Detroit for three months. Together with Taiichi Ohno they concluded that Toyota could not convert Fords production methods into the Japanese culture. Instead they lay the foundation for the Toyota Production System (TPS).

Toyota in the early 1950’s had a small budget for its manufacturing as Japan was a poor country after the Second World War. This constrained Toyota in investing in different machines such as the stamping press that Ford for instance had hundreds of. Toyotas budget allowed them to use just a few stamping presses for a complete car model when Ford often could dedicate one press
line for a specific part for months or even years without having to change the equipment. Using only a few press lines was impossible for Ford due to long lead times when changing dies. For Toyota the issue was to develop a way to minimize lead time for the equipment changes from hours or even days to minutes.

2.2 Key concepts

In Lean Production there are five key concepts; 1) to specify customer value, 2) to identify the value stream, 3) to make the value flow without any interruptions, 4) to make the customer pull the value out of the manufacturing and 5) to strive for perfection. Womack and Jones [6] suggest that customer value is the critical starting point for Lean Production. Value can only be specified by the end customer and it is only meaningful when expressed in a certain product, goods and/or service which meet customer demands to a specific price at a certain time. Value is created by the manufacturer but can be difficult for the manufacturer to specify.

After specifying customer value the value stream should be identified. The value stream is the action needed to convey a specific product, goods or service through three critical management steps which exist in all businesses; problem solving from concept to detailed design and production planning, information handling from order acceptance to detailed planning of delivery and-, transformation of raw material to produced product or goods to customer.

When the customer value is defined and the value stream is identified and optimized, the next step in Lean Production is flow. The product, goods and/or service should flow through the value adding activities. This often demands that all earlier production experience is set aside at the company and the company’s management. It is important to manufacture in small batches because large quantities often mean long lead times at different operations for the product to pass during manufacturing. All unnecessary stops, waiting times or stock is to be excluded from the production sequence.

When flow has been dealt with the next step is pull. Mass production has a way of pushing products through the different parts of manufacturing from production to delivery. This means that production is set to produce upon prognosis and not on what the customer actually requests. Lean uses a different course of action, namely pull which means that no products are produced unless there is an end customer ordering the product. More thoroughly this means that even the internal customers does not get provided with products until they ask for it.

Pursue perfection in all parts of the manufacturing is the last step in line. By using pull instead of push the company will automatically discover new procedures for minimizing work efforts, space and costs, mistakes will decrease and the fact that the company will always be able to offer what the customer desires when he wants it will be open for new solutions. One of the largest obstacles to overcome with perfection is that manufacturing includes inappropriate working methods. Another difficulty is problems with the design. It is thus important to form a vision for perfection and to choose a few different parts to put focus on [6].

2.3 Toyota Production System (TPS)

Within the Toyota Production System (TPS) there are three concepts that are connected; muda, muri and mura. Muda is as explained above any human activity that absorbs resources without creating any value. Muri is to overload people and/or equipment and mura is unevenness that
depends on lack of production planning or brake down of machinery, late deliveries, defects on parts etcetera.

Moreover, according to Liker [4], there are 14 principles of production in the TPS. These are subdivided into four different categories: Philosophy, Process, People and Partners, and Problem Solving, Figure 1. These are also called Toyotas four P’s of production.

![Figure 1 – Toyotas four P:s (middle) and 14 principles (right) of production, Liker (2004).](image)

### 2.4 TPS tools

The term *Kaizen* in Figure 1 stands for continuous improvements and it teaches individuals skills and methods for working effectively in small groups, solving problems, documenting and improving processes, collecting data and self-managing them. *Kaizen* also allows decision making to be done by the workers in the different groups. Continuous improvements also mean improvement of products processes or services over time, with the goal of reducing waste to improve workplace functionality, customer services or product performance [4].

*Kaizen* is a term that involves different methods for continuous improvements. One of these methods is the five whys, which means that when a defect part or unit comes up in production the immediate reaction within the personnel is to try to understand why this has happened and how it can be prevented in the future by finding the source of the problem. This preventing work is done by asking why five times. Another important term in this subject is value stream mapping, which helps focusing the Kaizen work, and prioritizing the customer value during the continuous improvement.
3 LEAN CONSTRUCTION IN CIVIL ENGINEERING

For the construction industry, it is of significant interest to convert the ideas of Lean Production into Lean Construction for the improvement of productivity, economy and working environment. This has been dealt with by many authors at conferences, for example organized by the International Group of Lean Construction, IGLC [7].

Toyota’s first principle (and first P) in Figure 1 is “Base management decisions on long term philosophy, even at the expense of short term financial goals”. It is evident that in the construction business most clients, contractors, designers, sub contractors do not apply this principle. They usually realize their short term financial goals in first hand because they do not see any long term relationship after the specific project. Instead, in traditional civil engineering projects in Sweden, most often clients do not contemplate anything but the bidding sum. Considering the fact that the client for such projects usually represents the community the prospects for changing their behavior are little. However, there are a few things the client can consider apart from the biding sum, e.g. the working environment to promote health and safety for the construction workers and a reduction of the overall project time.

Another dilemma of the construction business is that contractors usually consider every project as an individual project. The local manager gets a project budget which he/she has to keep and manage the project with. There is seldom any room for errors or for that matter new thinking in the form of new material and/or production solutions that possibly could contribute to a profit in the next project. Because changes are nearly never profitable at first attempt this situation hinders the development of the construction industry. Also, contractors usually purchase their designers on quantities of steel reinforcement for instance and the designer that offers the slimmest solution together with a low bidding sum most often wins the purchase instead of purchasing designers on solutions for practical on-site build-ability.

There are a few exceptions, for instance, most often material suppliers see a continuance beyond a single project and they therefore do not maximize the profit for one single project.

Toyota’s 13 other principles and their three P’s of production, Figure 1, can be transformed into the construction business. The first P, “Problem solving”, is an activity that the construction industry and contractors is very good at. However, the contractors and construction industry in general doesn’t perform it the way Toyota intended. Most often the contractors solve upcoming problems but do not concern about learning from or finding the root cause of the problems. The learning process of continuous improvement philosophy (Kaizen) is not adopted in a broad manner within the construction industry. By implementing routines for problem solving in the contractor’s day to day work, the Kaizen work can be improved rapidly and easily. What is needed is an understanding of the relative profits that can be achieved for a construction company if problems only occur once.

The second P of Figure 1 dealing with People and partners, implying that companies should develop leaders who live the philosophy of the company and that mutual respect is applied between suppliers and “main company” as well as management and workers.

The third P is dedicated to the Process flow. When production starts flowing in the right direction problems are going to surface and have to be dealt with. This is where the different concepts of the TPS are most visible and benefits the most. For instance the pull system produces only when the demand is there, it levels out the workload, and see to that the workers
have an even production rate. When quality problems arise production stops and they can be taken care of. Also, it is of importance to make sure that all involved workers understand the problem and why it surfaced to make sure it doesn’t happen again. Moreover, to further improve flow it is important to standardize work tasks, so that it is easy for workers to understand other work tasks and switch work tasks within the work group which eases and makes the continuous improvement work becomes more reliable.

3.1 Lean bridge design

To be able to increase productivity and make a specific production site more lean, the project must be designed and planned properly. To achieve a proper design and planning it is fundamental to establish a design team meeting the criteria. To be able to think lean in a project it is essential to start at the end, at the finished product, to see what is expected as an outcome. Then it is important to “walk backwards” in the process all the way to the start to locate bottlenecks and detect possible variance of construction, which are of importance and can cause problems to the production flow if not handled properly. It is also important to listen to the workers and their experience and to, in as many cases as possible, implement their suggestions for improvements.

A central point in forming the team is to include all areas of interest for the project from the beginning. Therefore, knowledge from production, design, management, future maintenance, suppliers and 3D and 4D modeling (3D plus time) should actively be implemented in the design phase together with a close relation to the customer, i.e. the client [8]. Furthermore, it is known that the earlier industrialization ideas can be introduced in the design and execution phase of a project, the greater the influence will be, see Figure 2 illustrating a traditional Swedish National Road Administration – Production department (SNRA-Production) project schedule (which of course can be valid for other contractor’s project schedules).

To get the actors working together from the beginning make them understand each others difficulties and can act upon them to solve problems before they appear. This is in line with one important principle in Lean Construction that downstream actors are involved upstream in decisions and vice versa. Creating this lean design team also ensures that products and processes are designed in collaboration between partners, which in turn means that the contractor and sub-contractor can form and design solutions in the most favorable way in terms of construction.

Traditional SNRA Project schedule
1. Preliminary study
2. Feasibility study
3. Design plan
4. Purchasing
5. Building documents
6. Execution

Figure 2. Project schedule of a traditional Swedish National Road Administration (SNRA) project and its industrialization possibilities. The earlier the efforts for industrialization the greater impact they have.
Several tools and methods are also available for planning, for instance applying Concurrent Engineering (CE) where resources are used effectively in cooperation between design, construction and production in cross functional working teams that are a part of the optimization of the planning process [2].

For the industrialization of construction with in-situ cast concrete focus should preferably be on the following six components [9]:

- Improved concrete qualities and optimal construction, e.g. self compacting concrete.
- Minimized reinforcement activities on site.
- Permanent and /or optimized formwork minimizing site logistics.
- Optimized concrete transport on site from the truck to form, e.g. pumping techniques.
- Weather independent construction processes, e.g. climate protective tent.
- IT and Lean construction tools, where multi-disciplinary decisions are made at design, production planning, and construction, e.g. reducing muda.

3.2 Responsibilities

To be able to introduce a Lean Design Team as described above it is essential that all actors take their responsibility. Therefore, a new way of thinking is probably necessary when starting the bidding process. It is thus important to develop long-term relationships between all partners. According to Toyotas 11th principle “respect your extended network of partners and suppliers by challenging them and helping them to improve” one should treat its partners and suppliers as an extension of the own business. This is one of the central cores of Toyotas reputation among their suppliers; they work together towards mutual goals. Toyota would never change supplier only because another one is a few percent cheaper. Changing partners because of price is however common in the construction industry, and here, the industry needs to implement another approach.

4 PROCESS FLOW IN CONSTRUCTION

A traditional view of looking at any kind of production is to see input become output, which is called a transformation process. In this case it is relatively easy to record productivity simply by looking at the relationship between output and input during a given time. On the other hand, the process of input becoming output (in the construction process) usually involves different sub processes which makes it more complicated to record the productivity of different workstations in relation to total productivity, see Figure 3 [10].

Value stream is one of five key concepts mentioned in Section 2.2 for Lean Production and also Lean Construction. The definition of the term value stream is all the activities that are performed when refining a product, both those who add value and those that do not add value [4]. In the traditional manufacturing industry, companies make value stream mapping continuously but on a traditional construction site it is not that common at all. The reason for this is probably the constant change in production and the relatively little repetitive work that is performed at a construction site. Nevertheless, it is important for the construction industry to survey the value stream of the building sites. This is done to be able to map the different muda (Section 2.2) appearing during the various stages of production.

Mapping the value stream will support the company not only to eliminate waste but also to identify causes for wasteful activities. The value stream mapping visualizes the whole
manufacturing process in a comprehensive and understandable form and demonstrates the connections between information and material flow.

![Diagram](image)

**Figure 3. The transformation process of input becoming output according to Koskela [10].**

Figure 4 visualizes the process with traditional handling of reinforcement, i.e. when reinforcement is placed piece by piece. The colored squares are non value adding steps or “activities” for the reinforcement, i.e. muda when the reinforcement is lying in a pile and not being used waiting for mounting. The waiting time can be anything from a few days to a week or several months depending on the project size and management. The waste for this “activity” is in the form of space occupancy and tied up funds etc. Different actors are affected in the various colored squares. For instance early in the stream it is the contractor, and later on it can be the purchaser or the society.

![Diagram](image)

**Figure 4. Value stream of traditional handling of single piece reinforcement on a construction site.**

The pursuit here is to minimize the number of colored squares, i.e. the waiting time, and to minimize the time spent for the reinforcement in each of these squares. As can be seen in Figures 5 and 6 using prefabricated reinforcement, the number of colored squares has been reduced as compared to the traditional handling Figure 4. This implies that the mounting of prefabricated reinforcement, as known, goes faster than the traditional mounting.

![Diagram](image)

**Figure 5. Value stream when handling the prefabricated reinforcement sections for the foundation of the first full scale bridge project.**
Some waiting time is however necessary or somewhat unavoidable with current construction methods. For instance the waiting time between finished reinforcement assembly and casting the concrete is unavoidable but it can most definitely be reduced. Also, the waiting time after casting of the concrete and before usage of the bridge is to some extent unavoidable with current construction methods.

5 THEORETICAL PILOT STUDIES

Initially, one focus of the research was to examine which parts of a bridge that can be prefabricated conveniently and which parts that must be manufactured traditionally on site. Another focus was to evaluate where most man hours at the production site are spent and how the distribution of production costs is. Therefore, the project was initiated by interviewing experienced representatives of SNRA-Production. The positions of the persons interviewed varied from site-managers and contract engineers to supervisors. The interviews considered some already constructed in-situ cast concrete bridges, in order to identify areas where major advancements in production can be achieved. The interviews included the main contractors own assignments and thus did not include work tasks assigned to sub-contractors such as asphalting, railing etc.

According to the interview results, when constructing the superstructure, the formwork is the most time consuming activity for the main contractor, and the largest costs are connected to the reinforcement and concrete, see Table 1. For the foundation, the most time and cost consuming activity is the reinforcement work. The results indicate that the reinforcement work could possibly be suitable for prefabrication.

<table>
<thead>
<tr>
<th></th>
<th>Foundation</th>
<th>Superstructure</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>time</td>
<td>cost</td>
<td>time</td>
</tr>
<tr>
<td>Formwork</td>
<td>25%</td>
<td>20%</td>
<td>50%</td>
</tr>
<tr>
<td>Reinforcement</td>
<td>45%</td>
<td>40%</td>
<td>35%</td>
</tr>
<tr>
<td>Concrete</td>
<td>30%</td>
<td>40%</td>
<td>15%</td>
</tr>
</tbody>
</table>

A follow up of already constructed bridges (a number of ten medium size highway bridges) made by the researchers at LTU based upon information from the bidding phases showed that reinforcement, formwork and in-situ casting of concrete typically make up for approximately 50% of the total construction costs with relative ratios of approximately 1/3 each [11], Figure 7 a.
The other 50% of the costs is related to general establishment at the building site, foundation, pile driving, asphalting, railing etc and mostly performed by sub-contractors.

![Figure 7](image.png)

**Figure 7.** a) Distribution of total construction costs for concrete highway bridges. b) Distribution of costs for formwork, reinforcement and concrete, both figures according to follow up from ten medium sized bridges.

From a purely theoretical viewpoint, the implementation of industrialized construction methods (self compacting concrete, prefabricated reinforcement and left formwork) can reduce the manpower substantially for these bridges. For instance, if prefabricated reinforcement is used in the foundations and superstructure, the on-site construction time can be reduced with up to 80%, Figure 8. A corresponding time reduction would also be achieved theoretically if permanent formwork solutions are adopted. It should be emphasized that full benefit of course calls for detailed design and planning of logistics before construction can commence.

Main advantages of applying self compacting concrete, SCC, are that casting rates are increased and that the number of workers needed for concreting can be reduced. Today, only one person at site is needed for casting the concrete, but in the future, SCC opens for a form filling solely performed by the concrete pump operator.

![Figure 8](image.png)

**Figure 8.** Theoretical reduction of on-site man hours during construction for an industrial process compared with traditional methods.

### 6 FULL SCALE PROJECTS

The general opinion among researchers and practitioners worldwide is that the construction industry to some extent suffers from having a lack of skilled personnel and having problems...
recruiting new people to the workforce. Therefore, the need to change production methods to less personnel and time consuming at the production site has increased. Thus, the research project has focused on how to implement “new” production methods to increase productivity and minimize waste and to decrease the number of workers needed at the production site. Another important parameter in the research is to try to improve the safety at construction sites.

The first full scale project was a bridge provided by the Swedish National Road Administration, north region, that was dedicated to research and development only. The bridge was located in Kalix in the northern part of Sweden and was a slab bridge with a span of 10 m and a width of 15 m, Figure 9. Here, SCC and prefabricated reinforcement in different shapes were tested.

Figure 9. First full scale project with a bridge span of 10 m and a width of 15 m.

The second project was the erection of a bridge in connection to a hydro power plant in Boden, also in the northern parts of Sweden. The width of the bridge is 7.3 meters and the length is 60.2 meters. At that specific project solely the carpet reinforcement was tested.

The third full scale project within civil engineering consisted of two similar bridges as a part of a highway project at Nynäsvägen south of Stockholm. The bridges were somewhat larger than the first full scale project, with a span of 18 meters and a width of 9 meters. Primary, focus of the third case was on the SCC but the carpet reinforcement was also tested to some extent.

Moreover, a house construction site has also been followed up regarding the carpet reinforcement; this to study possible differences with the use in civil engineering projects.

6.1 Production methods

As known, SCC is not a new production method - it has been used in Sweden and the rest of Europe for the past ten years and for an even longer period of time in Japan. A central point for the successful realization of SCC is to define the performance of the product, which can, according to the Growth project Testing-SCC, be discerned into three main parameters: 1) *Filling ability* i.e. the ability to flow and to completely fill the formwork 2) *Passing ability* i.e. the ability to flow around reinforcement without blocking and 3) *Segregation proneness* i.e. the tendency of coarse aggregate to sink downwards. For these parameters, criteria can be established to be met by a proper mix design. These criteria depend on geometry of structure to be cast, reinforcement, form type and method and local tradition on how to pour the concrete [12].
The production benefits of SCC are that the need for workers during casting decreases; concrete workers can perform other activities during casting that should have been done at a later moment and the construction site becomes less congested, Figure 10.

There is also a considerable increase in health and safety of SCC when compared to traditional vibrated concrete, due to less noise level (no compacting work needed) and less heavy lifting of material and equipment.

![Figure 10: a) Casting SCC on the Nynäsvägen project. b) Casting of normal vibrated concrete.](image)

Considering the reinforcement, a very unhealthy and stressful operating position for the craftsmen is the assembly of reinforcement piece by piece, Figure 11a. It requires long working time and is therefore often a bottleneck in production [13]. Prefabricated reinforcement often consists of ready to use traditional mesh reinforcement or reinforcement welded together to cages varying in size. Thus, prefabricated reinforcement is a most interesting alternative for Lean Construction.

For the foundation, the reinforcement was placed in two different prefabricated cages, one for each foundation, Figure 11b.

![Figure 11: a) Normal working position for traditional placing of reinforcement. b) Cages of reinforcement placed directly in the form at the Kalix project.](image)

Another option available in the last decade is the carpet reinforcement system, which are loose bars welded up on thin steel bands and then rolled together [14]. The roll of reinforcement is then fixed on the specific starting place for the reinforcement and rolled out into a finished...
product. The first full scale project was designed for using three different methods for placing the reinforcement.

The reinforcement for the plate structures was of a traditional type and the longitudinal reinforcement of the bridge deck was of the carpet reinforcement type, Figure 12. The shear reinforcement of the deck was pre-manufactured in sections and lifted on place.

![Figure 12: Rebar carpets, rolled out on the superstructure at the Kalix project.](image)

### 6.2 Designing of the full scale bridges

To be able to introduce changes in production methods at the first full scale project, it was important to utilize Lean Construction philosophies. Hence, it was essential for the different actors to understand each other and work together as a Lean Design Team. As a result the actors, that normally only are involved when construction starts, were involved in the design stage and production planning of the bridge. The main designer, the prefabricated reinforcement designer/supplier and the concrete supplier worked together in cooperation with the contractor and client using the techniques of Concurrent Engineering to solve problems and to find possibilities in their different areas simultaneously. This thinking was settled at the first meeting of the Lean Design Team which led to a redesign of the bridge to find alternative solutions for improving the constructability.

To be able to utilize the full potential of the SCC, the designer and the concrete material supplier decided together with the contractor and client to increase the strength of the concrete from a traditional concrete strength class C35/45 to class C55/60. In this way some of the very dense shear reinforcement could be left out.

Concerning the superstructure, carpet reinforcement has not been used in bridges in Sweden earlier, since rules and regulations do not allow welding of the reinforcement if it is exposed to stress variations larger than 60 MPa. It was however possible to analyze where those conditions were valid and redesign the bridge allowing for partly welded, and partly clenched carpet reinforcement.

Regarding the bridge in connection to the hydro power plant at Boden there was no need for any large redesign as the rebar carpet was only decided to be used in one layer on the superstructure.
For the third project, the bridges were redesigned partially to facilitate rebar carpets in the top and bottom layer of the superstructures. The main test on these bridges was, as mentioned earlier, the SCC which replaced the traditional concrete. No additional design was performed for enabling the use SCC.

The house construction site was only studied regarding the placing of the rebar carpets and no other insight of the project was possible. Hence, no information on how the buildings were designed has been available.

6.3 Organization

Using the traditional method of constructing, most often trades are subdivided into activities dedicated for formwork, reinforcement and concrete. At an optimized industrial process using different segments prefabricated and SCC, a new approach when composing the working teams must be introduced. The working team on site needs to be cross functional in knowledge and experience. Hence, in the optimized production, a worker needs to be able to handle formwork and reinforcement as well as casting the concrete. This of course depends on the size of the project and for these rather small bridges studied here, the prerequisites for the workers are that they simply have to be multi skilled.

6.4 Research activities at sites

To be able to follow up the activities at the different sites, various measurements and observations were conducted. Regarding the concrete, air content and slump flows were measured on the majority of the concrete deliveries to the bridges of the first and third projects. Concerning the rebar carpet, measurements were performed on productivity. Also, economical studies comparing traditional reinforcement with rebar carpets.

Interviews with the workers were also carried out to see if the attitude towards the different working moments changed during the project.

6.5 Working environment

To have the right working environment is an important factor of a fully operating construction site. It is therefore important that production methods are developed continuously and adapted to today’s construction sites and workers. The Swedish construction work environment is regarded as the safest in the world on the subject of physical health, working conditions, illnesses and accidents [15]. Nevertheless, there are still work environment related health problems to be tackled.

At on of the building sites, ergonomic analysis through ErgoSAM was carried out. ErgoSAM is based on SAM (a sequence-based activity method), and a higher-level method-time-measurement (MTM) system. The SAM system is the result of work carried out in Sweden to shorten the time needed for analyses made with MTM systems [16]. The ErgoSAM method considers two pieces of information: the work zone relative to the worker’s body in which the activity is carried out or ends; and the weight of the objects handled or the force exerted in the activity [17]. The output of ErgoSAM is the product of three types of variables namely, work posture, force and repetition (frequency), according to a scientific model, the Cube model [18].
The Cube Model, Figure 14 a, is used on site observations to acquire the risk of work-related musculoskeletal disorders, WMSDs, on combinations of the variables mentioned (work posture, force and repetition). For a specific working task, and for each variable separately, demand levels may be defined as low, medium, or high, where the demand criteria are chosen so as to discriminate between good or poor work ergonomics, and assigned weight factors 1, 2, and 3 respectively. Combinations of demands are evaluated by multiplication of the three weight factors, and this product determines the acceptability of the task [18].

ErgoSAM has been used by different Swedish companies within the manufacturing industry. For instance, studies have been carried out at Volvo Cars in Gothenburg [19].

At all the full scale projects, the observations were done in a form of walking through the site, video filming of identified steel reinforcement and/or concrete casting activity work cycles and interviews with the workers. These observations were the basis for a further risk assessment; the ErgoSAM analysis, see Section 7.5.

7 RESULT AND EXPERIENCE

7.1 Kalix

In Kalix the most comprehensive studies were carried out. The bridge was designed for the “new” production methods, i.e. SCC, prefabricated reinforcement and rebar carpets. Some 13 tons out of the total of 16 tons reinforcement on the superstructure were able to be rolled out using rebar carpets. The on-site construction time for this reinforcement went from predicted 80 hrs to 15 hrs, see Table 2a. This meant that the theoretical estimation of an 80 % reduction (Chapter 5, Figure 8) of on-site construction time when using prefabricated reinforcement was fulfilled at the first full scale test.

Table 2. Using rebar carpets for the different full scale projects as compared to traditional reinforcement (left). Casting of SCC as compared with traditional vibrated concrete (right).

<table>
<thead>
<tr>
<th>Kalix</th>
<th>Traditional Craft hrs/ton</th>
<th>Industrialized Craft hrs/ton</th>
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</thead>
<tbody>
<tr>
<td>Prd time at site</td>
<td>2.5 days</td>
<td>80 hrs</td>
</tr>
<tr>
<td>Craftsmen</td>
<td>4 persons</td>
<td>13.2 ton</td>
</tr>
<tr>
<td>Total</td>
<td>80 hrs</td>
<td>6 hrs 4 min</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Boden</th>
<th>Traditional Craft hrs/ton</th>
<th>Industrialized Craft hrs/ton</th>
</tr>
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<tbody>
<tr>
<td>Prd time at site</td>
<td>4 hrs</td>
<td>8 hrs</td>
</tr>
<tr>
<td>Craftsmen</td>
<td>2 persons</td>
<td>1.48 ton</td>
</tr>
<tr>
<td>Total</td>
<td>8 hrs</td>
<td>5 hrs 24 min</td>
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</tbody>
</table>

<table>
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<tr>
<th>Nynäsvägen</th>
<th>Traditional Craft hrs/ton</th>
<th>Industrialized Craft hrs/ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prd time at site</td>
<td>12 hrs</td>
<td>24 hrs</td>
</tr>
<tr>
<td>Craftsmen</td>
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<tr>
<td>Total</td>
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<td>6 hrs 40 min</td>
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</table>

<table>
<thead>
<tr>
<th>House</th>
<th>Traditional Craft hrs/ton</th>
<th>Industrialized Craft hrs/ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prd time at site</td>
<td>12.5 hrs</td>
<td>25 hrs</td>
</tr>
<tr>
<td>Craftsmen</td>
<td>2 persons</td>
<td>1.91 ton</td>
</tr>
<tr>
<td>Total</td>
<td>25 hrs</td>
<td>13 hrs 5 min</td>
</tr>
</tbody>
</table>

When studying the prefabricated reinforcement cages for the foundation, the time spent on the construction site went down from 2,5 days using two construction workers for each foundation...
to 1 hour in total, resulting in an on-site reduction with almost 40 man hours. Even though the prefabrication manufacturing time is added, there is still reduction in total production time. The main importance is though that the actual on-site production time can be vastly decreased and hence the total construction time for the project was reduced.

The production times given in Table 2 for the traditional placing of reinforcement and casting of concrete were estimated from both the experience of the local site manager and from the sum given in the calculation at the bidding stage.

Regarding the concrete in the Kalix project, the total man hours were reduced from predicted 70 hrs of casting to 19 hrs a reduction of approximately 70 % in on-site man hours, Table 2b. The concrete was cast at four different occasions, varying in volume and casting time.

7.2 Boden (hydro power station bridge)

At the hydro power station in Boden the research considered only the placing of rebar carpets. The bridge was not redesigned for optimizing the use of rebar carpets, and did not have the best conditions for using rebar carpets. However, as can be seen in Table 2 a, the implementation paid off in reduction of on-site construction time. Since it was only three rebar carpets used in total, the reduction was not large in hours but approximately 80 % of the predicted placing time for the reinforcement was reduced. This also meets the theoretical estimations of Chapter 5. The traditional production time given in Table 2 a was obtained from the local site manager.

7.3 Nynäsvägen

At Nynäsvägen, the most comprehensive concrete research was performed. All concrete used on this bridge was SCC. On the construction site the slump flow and air content were measured and at the concrete plant, in addition to the slump flow and air content, also the moisture of the aggregate was documented. The target value of the slump flow at the construction site was 720 mm ± 20 mm. That outline was kept most of the time, i.e. the concrete was robust and had little variation in consistency, Figure 13. Some variations were however detected regarding the air content in the concrete during the beginning of a casting, but it was rapidly adjusted. The main experience of the concrete was that it was robust, easy to use and reliable.

![Figure 13: Slump flow of tested SCC, measuring approximately 700 mm.](image)
The only prefabricated reinforcement used in this project was the rebar carpets for the top and bottom layer of the reinforcement in the superstructure. The bridge was not redesigned for optimizing the use of rebar carpets, hence the amount used was sparse. However, even though the bridge was not optimized for rebar carpets and the amount used was only approximately 1.8 tons out of a possible 22.2 tons, which gives 8% of the total amount, the results show the same as in the two previous cases. There is approximately an 80% savings of on-site placing time possible when using rebar carpets in comparison to the traditional single piece placing of reinforcement. This is the third full scale test giving the same result!

The production time for traditional handling of reinforcement and casting of concrete was obtained by the experience of the local site manager and the bidding calculation.

7.4 House project

The results when using the carpet reinforcement in the housing project is the same as when compared with the civil engineering projects, there is, again, approximately an 80% reduction in on-site production time.

It is difficult to compare the reinforcement design and construction within civil engineering with the design and construction of houses or dwellings because there are e.g. much tougher terms when considering the rules and. In fact, it is easier to introduce for instance rebar carpets into the design of houses than it is into the design of civil engineering structures.

7.5 Ergonomic analysis, ErgoSAM results

After several weeks of observing concrete workers performing their jobs on the construction site and after informal interviews with them, classic work cycles for different methods of reinforcement and concrete casting became obvious. Based on this information, video films were taken and analyses of representative short work cycles were performed to identify any risks for WMSDs (see Section 6.5) for concrete workers performing their tasks using different construction methods, namely conventional and industrialized methods.

Results of the analyses for representative work cycles are presented in Figures 14 and 15, where different loads on concrete workers are represented by Cube values. The Cube value or the load level falls within three levels; below 6 is acceptable (green colour), 6 to below 9 is conditionally acceptable (yellow) and 9 and above is unacceptable (red). For example, the work cycle mean value of 7.4 obtained in ErgoSAM analysis in Figure 14 falls into the conditionally acceptable area. The situations which still fall short of being acceptable are attributable to those tasks that have high degree of repetition and bending, such as fixing the steel structure and cutting metal rings off the rolled out carpet reinforcement.
Figure 14: a) Using the Cube model [18] for a specific working task, force, posture and frequency are given weight factors 1, 2 or 3 and then multiplied to be able to discriminate between good and poor work ergonomics. b) ErgoSAM analysis of a short work cycle of a concrete personell working with prefabricated steel reinforcement, mean value 7,4.

If the worker performed tasks with the manual steel rebar work, the worker is exceedingly exposed to WMSD risk factors contributing to very high cube values and a mean value of 21, Figure 15. This number denotes almost three times higher risk exposure to WMSDs when working with the traditional rebar reinforcement than when working with the off-site manufactured steel reinforcement. The very high values represent manual lifting and carrying of heavy reinforcement bars, it also represents awkward working positions and the high repetitiveness when clenching single reinforcement bars.

In the case of using SCC, a work cycle mean value of 5.7 was obtained in the ErgoSAM analysis, Figure 16, thus making these work tasks acceptable as far as the workers work-related musculoskeletal health is concerned.

When the traditional concrete casting work cycle was examined, the ErgoSAM analysis showed a mean value of 18.2. Thus, the risk factor for WMSD is very high.

Figure 15: ErgoSAM analysis of a short work cycle of traditional reinforcement placing, mean value 21. Below 6 is acceptable, 6 to below 9 is conditionally acceptable and 9 and above is unacceptable.
Figure 16: ErgoSAM analysis of concrete worker’s short work cycle during SCC casting. Below 6 is acceptable, 6 to below 9 is conditionally acceptable and 9 and above is unacceptable.

8 CONCLUSIONS

It can be concluded that, applying Lean Construction principles is possible on bridge construction with ready mixed concrete. In fact, Lean Construction is an important prerequisite and tool for the development of a more industrial process.

The full scale projects performed were successful, although in different ways and to different extent. The first project, the bridge in Kalix, was thoroughly designed and planned for the “new” approach on production methods and therefore all involved actors were prepared, when production started. This has been proved to be a key factor to the success. For instance the introduction of SCC with higher strength could decrease the amount of the very dense shear force reinforcement in the superstructure.

At the bridges of Nynäsvägen the design for the new approach i.e. rebar carpets and SCC started late in the project and therefore, the possibilities for changes were limited. Consequently, there were only a few roles of rebar carpets used and the higher strength of the concrete was not considered in design.

To be able to utilize the “new” and improved production methods in a broader approach, for example when it comes to constructing, a larger part of a highway with a dozen bridges or so, it is of importance to standardize work tasks, material and different parts of the bridges or structures.

The reinforcement in a typical bridge superstructure of today most often consists of approximately 80 % longitudinal reinforcement and 20 % shear force reinforcement. If, as in the Kalix bridge project, all the longitudinal reinforcement, some 13 tons out of a total of 16 tons (i.e. 80 %), can be designed for placing through rebar carpets there is an immense opportunity to reduce the on-site production time and also to cut down production costs. Consequently, the on-site production time can be reduced with virtually 80 % of the traditional placing time. The total
production cost for placing reinforcement will also decrease with roughly 30 % depending on the productivity at site, planning and management.

The risk analysis on steel reinforcement and concrete casting work tasks by the ErgoSAM method, has indicated that working with the prefabricated steel reinforcement and SCC reduced a great deal of physical loading on the musculoskeletal system of the worker. The prefabrication of steel reinforcement structures allowed a much safer working environment without risk factors such as heavy lifting and working in bent, awkward and repetitive postures. The casting of SCC, without the need for mechanical vibration usually associated with concrete placing, has led to the improvement of the construction work environment. Also, when working with these industrialized methods it does give significant benefits both in terms of a healthy and safe work environment for the workers, reduced staff-related costs for the company as well as the client and the society as a whole, both in short term and long term perspectives.

Considering the prefabricated sections, i.e. steel reinforcement cages, the on-site production time was reduced with more than 2 days or approximately 3 % of total construction time. The costs were only cut marginally for the studied bridge in Kalix, but if there had been another two foundations on the bridge were cages could have been prefabricated the cost would probably have been cut by 30 % due to scale effects.

SCC has the potential to decrease the total on-site production time, i.e. less man hours will be consumed during production, as can be seen in Table 2b. This is however in great deal a responsibility of management at site. The management needs to have a good knowledge on the benefits with SCC in comparison to traditional concrete.

The cost for purchasing SCC is greater than the cost for traditional concrete, consequently in order not to increase the total costs all the benefits of SCC needs to be implemented.

The plate structures are the part of a bridge that has the largest potential of improving when considering the working environment. When constructing these plate structures there can be a considerable tough working environment. For instance it is not exceptional that the plate structures are several meters high and the workers need to climb down on the reinforcement inside the formwork to be able to vibrate the concrete properly. Using SCC, there is no need for vibrating the concrete and hence no need to climb down inside the formwork either.

REFERENCES

7. http://www.iglc.net/