

# INDUSTRIAL BRIDGE CONSTRUCTION WITH CAST IN PLACE CONCRETE –

*New production methods and Lean Construction philosophies*



Peter Simonsson

Luleå University of Technology  
Department of Civil, Mining and Environmental Engineering  
Division of Structural Engineering





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*It is not enough to do your best;  
you must know what to do,  
and then do your best.*

W. Edwards Deming



## Preface

This licentiate thesis has been performed at the Division of Structural Engineering at Luleå University of Technology (LTU). It is a project carried out in cooperation with Betongindustri, Swedish Road Administration (SRA) Business unit Production and maintenance, Cementa and VINNOVA's research consortium "Road/Bridge/Tunnel". The work presented has been financed by Betongindustri, SRA, Cementa, LTU and VINNOVA.

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## Abstract

The construction industry is associated with high costs, low productivity, a lack of quality and low profit margins. Too often the actual cost for a project exceeds the expected cost. Industrialization of the construction industry is said to be the key to success and its definition is often debated, but what is the meaning of industrialization? How should industrialization be realized in the construction industry? Who is responsible for the change within the industry and which benefits can be achieved by industrialization? These are some of the questions brought up during the course of the research project. The project has been financed by VINNOVA's research consortium "Road/Bridge/Tunnel" and by Swedish Road Administration Business unit Production and Maintenance, Cementa and Betongindustri. SRA has also contributed with resources from the FUD Program (Research, Development, Demonstration).

The project has so far comprised different forms of full scale studies, laboratory studies and theoretical work. In the beginning of the project, interviews were carried out with management of construction sites to lay a foundation for the time and cost apportionment of typical bridges, also to examine which common bottlenecks present in production and to examine how large part of the cast in place concrete the self compacting concrete (SCC) constitutes. The interview gave also an insight in how site management views the possibilities for change in construction today.

To further find out the time and cost apportionment, ten bridge projects were examined. The results from this study were studied with regards to new production methods. Unit times for SCC were thus compared with unit times for traditionally vibrated concrete, unit times for rebar carpets were compared with unit times for traditionally clenched reinforcement, and also the effects of left formwork were studied. In these theoretical studies it was clear that great potential for changing today's construction business.

To try to verify the theoretical results, mainly two full scale studies have been carried out. The first was a replacement of an existing bridge on the European road No 4 outside Kalix in the northern parts of Sweden. The project was followed and managed by the research team in close collaboration with the client, contractor, designer and material suppliers. The study was comprehensive and started already in the design phase where the bridge was redesigned for new technical solutions aimed for production enhancement. Here prefabricated reinforcement cages to the foundation and SCC to the whole project were used. Also rebar carpets were used for the superstructure. The reinforcement in a typical bridge superstructure of today most often consists of approximately 80 % longitudinal reinforcement and 20 % shear force reinforcement. The project aimed at examining if it was technically feasible to use rebar carpets and if there were any economical benefits in using it. The aim was also to examine if it was economical to prefabricate reinforcement cages and transport them to the site for placement in comparison to traditionally fix reinforcement piece by piece. An

additional objective was to examine the effect on the working environment imposed by the change in working methods.

The other full scale project was concentrated on the use of SCC, but also the rebar carpets were examined to some extent. Here, the design phase was not followed by the researchers and no redesign for maximizing the use of carpets was performed. The aim for the project was above all to examine the economic conditions associated with the use of SCC, and to study the working environment in connection to the casting of SCC compared to traditionally vibrated concrete.

The accomplished studies were successful. Especially at the bridge in Kalix, a detailed planning could be realized and Lean Construction philosophies were utilized, this proved to be an important factor for the success. Considerable savings in work efforts at site were realized (approximately 80 % of the reinforcement fixing time and approximately 67 % of the casting time). The total project time was decreased with approximately 20 %. Also a lower total cost for the project was achieved.

For the project in Nynäshamn the same effects were not realized since the ideas of new working methods and new planning systems came in too late. However, some positive experiences were gained considering the use of SCC and rebar carpets.

The much important working environment was followed up in the project with a special analytical method, ErgoSAM. Large differences in the workload were measured in a comparison between traditional reinforcement fixing and the handling of prefabricated reinforcement as well as when comparing traditionally vibrated concrete with SCC.

The largest economic benefit from introducing SCC to a contractor in civil engineering projects is probably on the superstructure of a bridge, since the largest number of workers is needed during casting of traditional vibrated concrete and it is therefore associated with large casting costs. Hence, the number of workers needed for casting can be markedly reduced if SCC is introduced and proper planning has been carried out. However, controversially it is often easier to introduce SCC for foundations, columns or plate structures since these structural parts are less dominant in the construction and the “risk” related to using SCC is small. However, for these smaller less people demanding castings it is more difficult to achieve economical benefits in using SCC. The overall risk using SCC is that the product it is not robust enough, which might result in the concrete does not enclose the reinforcement satisfactory and rework is needed.

Probably the largest benefit with using SCC is, as mentioned earlier, the improvement in working environment. Therefore, the economy of the Swedish construction industry and society can benefit significantly from using the right kind of working method during construction.

Finally, it was concluded in the project that, to be able to utilize the “new” and improved production methods in a broader approach, it is of importance to apply Lean Construction philosophies at the planning and construction. Preferably a Lean Design Team should be established.

Key words: industrialization, self compacting concrete, prefabrication, reinforcement, rebar carpets, working environment, Lean Construction, productivity, robustness.

## Sammanfattning

Byggbranschen förknippas ofta med höga kostnader, låg produktivitet, brist på kvalitet och dålig lönsamhet. Allt för ofta blir den verkliga kostnaden för ett projekt högre än förväntat. En industrialisering av branschen nämns ofta som räddningen och dess definition debatteras ofta, men vad innebär en industrialisering? Hur ska en industrialisering av byggbranschen genomföras? Vem bär ansvaret för förändring inom branschen? Vilka fördelar kan förväntas vid en industrialisering? Det är några av de frågor som ställts under projektets gång. Projektet syftar till att undersöka möjligheterna för en industrialiserad byggprocess vid framförallt brobyggnation. Projektet har finansierats av det nationella forskningskonsortiet Väg, Bro, Tunnel (VINNOVA) samt Vägverket Produktion, Cementa och Betongindustri. Vägverket har bidragit med resurser från sitt FUD-program (Forskning, Utveckling, Demonstration).

Projektet har hittills omfattat olika former av fullskalestudier, laboratoriestudier och teoretiskt arbete. I inledningen av projektet utfördes intervjuer med platschefer och arbetsledare för att skapa en grund att stå på när det gäller hur tid- och kostnadsfördelningen på vanliga broprojekt ser ut, samt för att få information om vanligt förekommande flaskhalsar och hur stor del självkompakterande betong (SKB) som används och dess för- och nackdelar. Intervjun gav även en allmän inblick i hur platsledningen ser på möjligheterna att förändra dagens byggande.

För att ytterliggare ta reda på hur tid- och kostnadsfördelningen såg ut i några fall gjordes en uppföljning av kalkyler för tio broar. Där kunde ses att kostnadsfördelningen var ca 1/3 vardera för form, armering och betong. Resultaten från uppföljningsstudien utvärderades sedan med avseende på ”nya” produktions metoder. Enhetstider för SKB jämfördes med traditionell betong, enhetstider för rullarmering från leverantör (från husbyggnad) jämfördes med traditionell armeringsteknik samt effekter av kvarsittande formar utvärderades. Här stod det klart att det teoretiskt finns stora möjligheter att förändra dagens brobyggnation.

För att försöka verifiera de teoretiska resultaten har huvudsakligen två fullskalestudier genomförts. Den första var utbyte av en befintlig bro på väg E4 utanför Kalix. Där följdes och leddes projektet av forskare i ett tätt samarbete mellan beställare, entreprenör, konstruktör och materialleverantör. Studien var omfattande och startade i projekteringsfasen där bron omkonstruerades för nya tekniska lösningar för produktion. Här användes förtillverkade armeringskorgar till bronns fundament, SKB till hela bron och rullarmering till 80 % av total armeringsmängd i farbanan. Projektet syftade till att undersöka om det var tekniskt genomförbart och om det finns ekonomi i att använda rullarmering i farbanan givet de regler vilka man måste förhålla sig till. Syftet var även att se om det finns ekonomi i att förtillverka armeringsenheter och sedan transportera dem till arbetsplatsen för montage jämfört med traditionellt styckes montage av armering. En ytterliggare målsättning för projektet var att undersöka de effekter på arbetsmiljön förändringen av arbetsmetoder skulle innebära.

Det andra fullskaleförsöket var till största delen inriktat på användning av SKB, men även rullarmering provades i viss mån. Här följdes inte projekteringsfasen av bron och ingen omkonstruering genomfördes för att maximera möjligheten för användning av rullarmering. Syftet med projektet var framförallt att undersöka de ekonomiska förutsättningarna för SKB och att undersöka arbetsmiljön i samband med gjutning SKB i jämförelse med traditionell vibrerad betong.

De genomförda fullskalestudierna var lyckade. Speciellt vid brobyggnation vid Kalix kunde en utförlig planering ske där bla Lean Construction filosofier tillämpades vilket visade sig vara en viktig framgångsfaktor. Stora förtjänster i inbesparade arbetsinsatser på bygget erhöles (ca 80 % av monterings tid för armering kunde intjänas och ca 67 % av arbetstid för gjutning). Slutresultatet blev minskad total projekttid med ca 20 % och en minskad total kostnad för brobygget.

För projektet i Nynäshamn erhöles inte samma effekter eftersom idéerna med nya arbetsmetoder och upprättande av planeringssystem kom in för sent. Dock kunde vissa positiva erfarenheter dras beträffande självkompakterande betong och rullarmering.

Den viktiga arbetsmiljön följdes upp i projektet med en speciell analysmetod, ErgoSAM. Stora skillnader i arbetsbelastning uppmättes med jämförelser av traditionell armeringsmontering med handhavandet av prefabricerad armering respektive gjutning av normal vibrerad betong med självkompakterande betong.

Beträffande den självkompakterande betongen är det mycket viktigt att tydliga egenskapskriterier definieras för de olika konstruktionsdelarna. Kriterier bör upprättas för formfyllnad (rörlighet), pumpmöjligheter (undvika blockering) och för resistens mot separation. Dessa skall mötas med en robust SKB dvs. en betong som motstår normala variationer i ingående beståndsdelar samt effekter av transport och gjutning. Vid de aktuella fullskalgjutningarna studerades robustheten och befanns vara god när större gjutningar genomfördes av tex. farbanaplattorna. Uppföljningar i laboratoriet skedde även där speciellt inverkan av fuktvariationer i fingeruset studerades.

Stor kraft har lagts i projektet på teoretiskt arbete där det har studerats hur Lean Construction filosofier (från Lean Production inom bla. Bilindustrin) kan tillämpas på brobyggnation. Därvid skulle några av de initialt ställda forskningsfrågorna kunna besvaras: Vad innebär en industrialisering och hur ska den genomföras i ett broprojekt? Finns det några direkta hinder och vad är de viktigaste förtjänsterna? Hur kan nya produktionsmetoder implementeras och hur kan speciellt självkompakterande betong bidra till en ökad effektivitet? Vem bär ansvaret för en förändring inom branschen? Till alla frågor har inte ett utförligt och slutgiltigt svar kunnat erhållas, men ett steg i rätt riktning har tagits vid samtliga frågeställningar.

Ett tydligt svar som utkristalliserat sig är, att för att åstadkomma en förändring i branschen kan inte enbart produktionsprocessen studeras. Det går inte heller att förlita sig på att en aktör i ett projekt ska förändra utfallet av projektet utan för att skapa en förändring måste samarbetet mellan inblandade aktörer förbättras och bli mer långsiktigt. Det är ett måste för att kunna öka produktiviteten, lönsamheten och korta byggtiderna. En ökad långsiktig lönsamhet är inte heller under dessa omständigheter förknippad med enbart entreprenören utan även här ska alla inblandade aktörer kunna känna av effekterna av ett bättre samarbete dvs. kunden, konstruktören, underentreprenören, materialleverantören m.fl.

Hur ska det gå till att öka lönsamheten på kort och på lång sikt, så att inblandade aktörer kan se att det lönar sig att öka samarbetet och samtidigt arbeta smartare? För bro- och anläggningsbyggande som den här studien ägnar sig åt har det framkommit att det är i de tidiga skedena de stora avgörande besluten tas och där ribban läggs för hur projektet kommer att ta form och så småningom avslutas. Detta för oss in på ansvarsbiten. När det gäller brobyggnation i Sverige är det beställaren dvs.

Vägverket Regions olika delområden som ansvarar för projekteringen av olika sträckningar och val av dessa. Redan i detta stadium sker viktiga beslut för det rationella byggandets möjligheter eller begränsningar. Det gäller att t.ex. undvika sträckningsalternativ som ger komplexa brokonstruktioner med ineffektivt byggande som följd. Sådana och liknande projekteringsalternativ gynnar inte ett industriellt arbetssätt.

För att komma rätt med alla tidiga beslut är det därför viktigt att skapa en arbetsgrupp där alla parter i ett projekt samarbetar så tidigt som möjligt. I projekteringsgruppen som i den här studien döpts till the Lean Design Team är tanken att samarbetet mellan alla inblandade parter i ett tidigt skede ska säkerställa en byggbarhet med rationella metoder. LDT ska genom projektering säkerställa genomförbarheten med nya och förbättrade arbetsmetoder och se till att alla inblandade parter är införstådda med deras arbetsansvar och att var och en lever upp till sitt ansvar. LDT tillämpar Lean Construction-filosofier dvs. det är genom denna grupp som dessa teorier för ett industriellt byggande kan förverkligas. Här passar som slutord mycket väl det inledande citatet till hela licentiatavhandlingen av W Edwards Deming där han menar: ”Det gäller inte bara att göra sitt bästa utan man måste veta vad man ska göra och sedan göra sitt bästa”.

Nyckelord: industrialisering, självkompakterande betong, prefabricering, armering, rullarmering arbetsmiljö, Lean Construction, produktivitet, robusthet.



## **Glossary, abbreviations and expressions**

Customer	The next person in e.g. a production line.
IGLC	International Group for Lean Construction
LDT	Lean Design Team
Muda	See waste
SCC	Self-Compacting Concrete
SRA	Swedish Road Administration
TQM	Total Quality Management
TPS	Toyota Production System
Waste	An activity that do not provide any value to the product and should be avoided



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# 1 INTRODUCTION

## 1.1 Background

The construction industry has through tradition been conservative regarding change. Though, in recent time construction companies have become more interested in the development of new and alternative production theories and methods. The relatively new interest might result from factors such as; the decreased number of available qualified workers on the market and that labour expensive work tasks are no longer economically viable. Furthermore, the competition among companies has risen due to new actors on the market through the EU, and/or the profit margins for projects have decreased. Additional factors, for instance shorter construction times and calculated higher risks for projects can possibly also have had an impact on the relatively new interest in alternative solutions.

The construction industry has been low in productivity in comparison to e.g. the manufacturing industry, e.g. Byfors and Jäderholm (2007), and has had problems with quality and low profit margins. According to reports by Bygghälsögruppen (2002), and by Byggnadsdelegationen (2000) the Swedish construction industry has the potential to develop technology, economy, working environment etc. Furthermore, Josephson and Saukkoriipi (2005) indicate that the identified waste (see chapter 3.2.1) when constructing buildings is approximately 35 % of the total production costs. This number might vary from company to company and from construction site to construction site etc., but the fact remains that there is a great deal of waste in production today.

This licentiate thesis is the result of efforts from companies showing interest in developing new solutions for on-site construction and to increase productivity as well as minimising waste at construction sites. The formation of the project includes contractor, material suppliers and client which show that the interest is cross- functional, i.e. the branch takes this matter seriously.

Industrialization of in-situ cast concrete bridges can, if managed properly, be a solution to the most often sought shorter construction times and higher profit margins. It can also be a solution to e.g. traffic disturbance of the third party i.e. the end customer in this case, and it can also contribute to less environmental effects during construction through less material usage. Civil engineering projects move with industrialization from solely site construction to a somewhat more manufacturing process where parts of the structure are prefabricated in factories or at a specific location at the construction site when possible.

## 1.2 Objective

The comprehensive objective/intention of this research is to develop an understanding for and possible answers to the obstacles and possibilities of introducing industrialization concepts in civil

engineering and especially in-situ cast concrete bridges. The intention is to understand a projects process steps from initiation to completion and also were the important steps for making the production phase productive lies i.e. to understand how industrialization concepts can change the construction industry today.

### 1.3 Research questions

The process steps from project idea to completion of a civil engineering project involve several complex steps. To be able to turn the execution phase into an industrialized production phase with higher productivity, less work hours, faster construction times, less material waste etc. it is not enough to just look at the production phase solely, but merely focus should be on several different areas that needs proper management. Focus should not only be on typical phases as in the Swedish National Road Administration (SRA) project schedule (Figure 1) but on steps within these phases. However, the early phases of the SRA-project schedule are crucial for the performance of the production.

Phase	Preliminary study	Feasibility study	Design plan	Purchasing	Building documents	Execution	Operation/ maintenance
Remark	Needs, demands etc	Alternative routes	Designing the layout	Entrepreneur involved	Detailed design		
Outcome		Collaborate bridge types  Aesthetics within limits  Create conditions for industrialztion	Geometrical prerequisites, Banking → cambering etc  Create conditions for industrialztion Aesthetics etc	Supply conditions Matrl conditions	Documents	Building process	Continued collaboration between contractor and client?
Possible influence industrialz		Important step for industrialization! Most influence	Important step for industrialization! Less influence	Important step for industrialization! Less influence	Might be too late!	Too late	

Figure 1. Typical stages of a civil engineering project according to Swedish Road Administration (SRA).

Given the objective above, the following research questions can be formulated:

- How can the entire (construction) process for constructing bridges be industrialized?
- Which benefits can be generated by industrialization?
- Are there any hindrances to an industrialization of the process?
- How can “new” production methods be implemented in the design process, and how can this be encouraged?
- How does self compacting concrete SCC contribute to industrialization in construction?

### 1.4 Outline

This licentiate thesis is based on five appended papers, which all are summarized in Chapter 5.

Chapter 1 gives a short introduction to the subject an objective of the research project and formulated research questions.

Chapter 2 describes the method chosen for this research.

Chapter 3 includes a theoretical framework. This includes a description of Lean Production and Lean Construction, and the focus within Lean.

Chapter 4 introduces concepts for industrialization of in-situ cast concrete bridges. The difference between technical and process platform are discussed together with the merging between them. Here also the working environment is discussed and results from the studies are presented.

Chapter 6 comprises and the concluding remarks and future work.

Chapter 7 is solely devoted to references.

## **1.5 Limitations**

The research in this thesis includes only civil engineering structures and more specifically bridge construction. However, the influences described can also be implicated to other civil engineering structures such as tunnels, harbour projects etc., the main objective is nevertheless bridge construction.

When this research project started there was no clear intentions on where the focus should be, in fact, it was more the opposite and there was no real limitations dictated more than it should include in-situ cast concrete bridges. This implied full freedom and a broad spectrum of ideas to start with. As the project preceded the range of interesting and most of all important questions needing answers increased. Since the researcher is interested in developing the construction industry as a whole, it was difficult to actually minimize the field of questions piling up. Also, the full scale projects executed show that the involved process steps are linked, and it is thus difficult to exclude parts of the chain and still get the same results. It is, on the other hand, not easy to try to comprise the whole process of the construction industry in one thesis, even though that was the ambition and intention at first, consequently there have been limitations.

According to Figure 1, an SRA-project starts with the preliminary studies and continues with the feasibility phase. These two stages have not, within the resources and time available of this work, been covered at all. Yet it has surfaced during this research project that the feasibility phase also is relatively important for the production stage due to decision making in this process step.

During this project, it has neither been sufficient research within the field of purchasing, regarding purchasing forms and cooperation possibilities. For information concerning purchasing the doctoral thesis by Toolanen (to be published in 2008 at LTU) lies close at hand to be recommended. Moreover, the operation and maintenance phase has not been covered.



## 2 METHOD

### 2.1 Research strategy

There are at least two common methods recognized for collecting data, quantitative and qualitative. Quantitative methods seek answers to such questions as how and why, whereas the qualitative methods answers such questions as how many and how much.

According to Yin (1994) research strategies can be in the form of case studies, experiments, surveys, history, computer based analyses of archival records. Some of the most commonly used research strategies within construction is according to Woksepp (2007); *interviews, experiments, case studies, ethnographic research* and *action research*. Yin (1994) also states that case studies were earlier only used for the exploratory phase of an investigation and that surveys and history were appropriate for the descriptive phase. This is on the other hand not accurate since a case study can be both descriptive and explanatory (Yin 1994).

In this research project data has been collected through four of the most commonly used research methods mentioned above namely; interviews, experiments, case studies and action research. The experiments have been conducted in laboratory environment regarding the SCC, interviews has been carried out with workers involved in the different projects followed during this research project, case studies and action research have been the form for the full scale projects studied. It is also important to bear in mind that the method selected for collecting data affects the analysis of the data, Fellows and Liu (2003). Furthermore, how the researcher views the world affects the complete research process, Merriam (1988).

Based on the aim of this research project and the formulated research questions this research project is primarily based on quantitative methods.

### 2.2 Data collection through interviews and theoretical follow ups

One of the most significant sources of information gathered in a case study is through interviews, Yin (1994). Interviews are important when the researcher is unable to observe behaviour, feelings, or how people interpret activities or occurrences around them, Merriam (1988). An interview may have several shapes, Yin (1994) argues three different shapes; an interview with an open-ended nature, a focused interview and a formal survey.

In an open-ended interview the researcher can ask the respondent for facts as well as his or hers opinions and insights in the question. The more assistance the respondent provides the more a role of informant he or she becomes. A focused interview proceeds during a specific time period. Here

the respondent and researcher still may be open-ended but the interview is more likely to follow a certain set of questions. The final type of interview proposed by Yin (1994) is the formal survey, this entails more structured questions.

This research projects first step to get an overview of how bridge construction is outlined today, started with a series of open-ended interviews with management at a main contractor company in Sweden. These interviews were continued with following up results from ten already erected bridges, also in Sweden. The results from the interviews and the results from the follow ups were compared and analysed.

The results from the follow ups were after that altered through the introduction of industrialized working methods. New unit times for production, e.g. new and different methods for fixing the reinforcement, were theoretically inserted in the previously gathered results and analysed again. This was done to be able to perceive any possible economic benefits or productivity benefits with new and different working methods from a theoretical point of view.

### **2.3 Case studies**

The results from the interviews together with the theoretical results above needed verification in practise. To be able to verify the results, the method of case study was examined as a possible approach.

The method of case study has different definitions; it varies to some extent from author to author. The definition by Meredith (1998) states: “a case study examines a phenomenon in its natural setting, employing multiple methods for data collection to gather information from one or a few entities.” Benbasat et al. (1987) defines the case study as “an examination of a specific phenomenon such as a program, an event, a person, a process, an institution, or a social group”. Yin (1994) provides a technical definition of a case study; “A case study is an empirical inquiry that; investigates a contemporary phenomenon within its real-life context, especially the boundaries between phenomenon and context are not clearly evident”. According to The Free Dictionary on the Internet the definition of case study is: “A detailed intensive study of a unit, such as a corporation or a corporate division that stresses factors contributing to its success or failure”.

The method of case study corresponds well with the intention for the research in this project, as Merriam (1988) states; there are a few factors which are decisive if the method of a case study should be used, “the nature of the research questions, the amount of control, and the desired end product”. There is also a fourth decisive factor which is if the investigation can be considered as a bounded group. Merriam (1988) also states that he believes that “research focused on discovery, insight, and understanding from the perspectives of those being studied proposes the greatest promise of making significant contributions to the knowledge base”.

Benbasat et al. (1987) also states three motives why case study research is a viable information systems research strategy. 1) the researcher can study the phenomenon in its natural surroundings, 2) the case method allows the researcher to answer the why and how questions which in turn explain the nature and complexity of the process studied, 3) a case study is a proper method in an area where a small number of previous studies has been carried out. Yin (1994) also argues that case studies have a distinct advantage when a “how” or “why” question is being asked about “a contemporary set of event over which the investigator has little or no control”.

Bearing in mind the discussion above, the method of case study seems appropriate for the research in this project. There have been two major case studies within the research project, a short description of each case is provided below.

**Case study 1**, the purpose of the first case study was to investigate possible hindrances and benefits with industrialized concepts in civil engineering projects. The objective was also to see if prefabrication of parts to a specific structure was possible. Furthermore, another determination of the full scale case study was to see what kind of effects these industrialized concepts have on the economy of the construction, on the total production time, on the amount of man hours put in, and the work related environment at the specific construction site. The methods used to obtain data and answers during this research project were action research, field studies, experiments, direct observations, and informal interviews. Based on the aim of this research and the formulated research questions, this case study is primarily based on qualitative methods.

This study was carried out on a bridge construction on the European road E4 outside Kalix in the northern parts of Sweden. The project was provided by the Swedish National Road Administration, north region, and was dedicated to research and development only. The bridge was a Slab Bridge and consists of a span of 10 metres with a width of 15 metres, Figure 2.

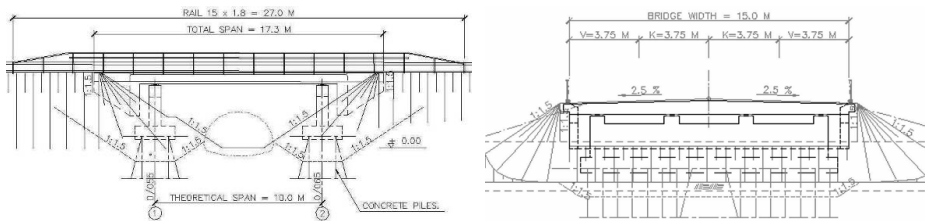


Figure 2. Full scale bridge in elevation and section (no scale).

**Case study 2**, here the purpose was to see if the achieved results from the first case study were repeatable in another project, and to somewhat verify the results. Also, one objective was to specifically study the casting of concrete and the material properties during casting.

This study was not as comprehensive as the first, as the researcher came into the project in a much later stage than was the case in the first study. Here, data was gathered through direct observations, experiments, and informal interviews and video filming. This full scale project consisted of two similar bridges right next to each other; they are located on Nynäsvägen south of Stockholm in Sweden. The bridges were slightly larger than the first full scale project, with spans of 18 meters and widths of 9 meters.

## 2.4 Research activities at site

During the first case study, a research team of three to five persons were actively engaged in the gathering of data and site monitoring. The site observations consisted of waste monitoring, measuring/recording of “new” unit times for production regarding both activities with “new” reinforcement solutions and during casting of concrete, also the consistency of the concrete were recorded at both sites.

The active research has to some extent been accomplished with regards to the action research model, e.g. active participation by the researcher during the different working moments at two construction sites e.g. timing different methods. Also, direct observations were used within the waste studies;

during constructing with traditional working methods the researcher “followed” workers taking notes on their activities at appointed times. Individual interviews were carried out in close correlation to work carried out while the workers had the performed work task fresh in mind.

## **2.5 Laboratory studies**

On presumption for the method of experimental research is that the researcher can manipulate the variables of interest. The researcher has control over the experiments and the research is distinguished by the cause and effect relationships, were the researcher deliberately manipulates one variable (cause) to examine what happens to the other(s) the effect, Merriam (1988). The negative aspect of experiments is that it might not be possible to control all the interesting variables and hence, a factor of error can occur.

In this research project laboratory studies were carried out on self compacting concrete to examine the robustness of the product. Different parameters were varied in the laboratory intentionally to cause effects on the concrete and to scrutinize the performance and robustness of the concrete. Furthermore, in the laboratory studies it is of interest to see the repeatability of the experimental results. The results from the laboratory studies should be compared with the results from the full scale castings of concrete.

## 3 THEORETICAL FRAMEWORK

### 3.1 Industrialization

Industrial methods have been studied within manufacturing industry for a long time. During the “evolution” of the manufacturing industry (which very much still is an ongoing process), production has evolved from solely craftsmen based production to a production with standardised work tasks and robotized manufacturing.

The term industrialized building is frequently debated in Swedish literature; see e.g. Löfgren and Gylltoft (2001), Simonsson and Emborg (2005), Apleberger et al. (2007) to name but a few. Industrialization is often mentioned as the solution for the construction industry, but what does industrialization and industrialized construction actually represent? The definition of industrialization and industrialized construction varies to some extent from author to author. Lessing et al. (2005) defines *industrialized construction* as “adjusting the present building process in order to be more efficient” and their definition of *industrial construction* is “a radical change in the process to be significantly different than the building process of today”. Other researchers e.g. Olofsson (2005) mean that there *are no differences between the terms* and it is more relevant to discuss distinction of production in a factory compared to construction on site, relating it to the degree of industrialisation. A work group within CIB (Work group W24) has the same understanding, that there should be no difference upon this and expresses industrial building as “the term given to building technology where modern systematised methods of design production planning and control as well as mechanised and automated manufacture are applied”. The definitions above are important to bear in mind as many actors of the building trade associate the industrialization solely with production of pre-manufactured components that are assembled at the building site. It is noted that, if so, large infrastructural projects (bridges, tunnels etc) could only in very limited manner be built industrialized, as prefabrication is a rare method for these applications.

The manufacturing business has other definitions on industrialization, for example according to Warszawski (1990) the definition is “an industrialization process is an investment in equipment, facilities, and technology with the intent of increasing output, decreasing manual labour and improving quality”. The Encyclopaedia Britannica (2008) defines it as “industrialization is the process of converting to a socioeconomic order in which industry is dominant”.

According to the author, industrialization may be defined as: “a modernisation process of the construction industry for a smarter and sustainable production”, in which technological development together with design for build-able solutions is realized using Lean Construction Philosophies plays a central role.

## 3.2 Lean Production

*Lean Production is Lean because it provides a way to better and better meet customer requirements while using less of everything; less material, less design hours, less manufacturing hours, less energy, less space.* Womack and Jones (2003).

Lean production is a philosophy that started with Taiichi Ohno and Eiji Toyoda at Toyota in Japan after the Second World War. Ohno and Toyoda studied the Ford manufacturing plant in Detroit for three months and soon concluded that mass production did not fit the Japanese culture. Instead they laid the foundation for the Toyota Production System (TPS).

Ford had for a long time been dedicated to standardize the product as much as possible limiting the variety for the customer and optimizing mass production. Ohno and Toyoda were convinced that they instead of mass producing a standardized car could produce a car with specific requirements from a specific customer and deliver it instantly without maintaining almost any inventory. (Liker 2004, Womack et al. 1990).

A large difference between mass production and Lean Production is the communication. The employees of a company in mass production do not speak to each other on the factory floor, they have no reason doing so either because they are simply there for doing the work tasks. If they encounter problems they just call a technician and let him/her solve the problem. In Lean, on the contrary, the employees are constantly encouraged to seek new and improved solutions and implement them, which make communication an important part for production to function properly. It is therefore important that for example machinery used in production is not noisy so that communication is allowed, Womack and Jones (2003).

This thesis is to a large extent based on the Lean Philosophy. The Lean Philosophy is a philosophy that, in the authors understanding uses the best influences from other philosophies and manufacturing tools, e.g. JIT, TQM and Kaizen etc., see Section 3.5, and takes advantage of these to make the Lean Philosophy the excellent tool it is in production today.

### 3.2.1 The focus on “muda” i.e. waste

*“All we do is to look at the time from the moment the customer gives us an order until we get paid and minimizing the time by removing activities that doesn’t add value”.* Taiichi Ohno

During their study visit to the manufacturing plant in Detroit, Ohno and Toyoda saw waste everywhere where their American colleagues saw efficiency. The fact that the machines were working constantly spitting out parts and the fact that workers were continuously keeping the line going at all costs were considered efficiency by the Ford management but waste according to Ohno. Keeping the line moving at all costs also meant producing cars with defects, since there was no time available to make corrections instantly. This in turn resulted in cars piling up with defects at the end of the line with the waste of rework as a result and a large amount of cars in stock.

The platform that Ohno and Toyoda formed for Lean Production is simple: to deliver what the customer wants when the customer needs it in the required quantity. A key issue is then the focus on the well known waste or “muda”, i.e. any human activity that absorbs resources without creating any value as defined by Womack and Jones (2003). Suzaki (1987) has another definition of waste; “anything other than the minimum amount of equipment, materials, parts, space, and workers time, which are absolutely essential to add value to the product”. Suzaki (1987) also states that as early as in the 1920’s Henry Ford defined waste in his book *Today and Tomorrow* as “If it doesn’t add value its waste”. In this licentiate thesis however, the definition by Womack and Jones (2003) seems to

suit. According to The Lean Toolbox (1999), there are 7+1 different muda: 1) overproduction, 2) waiting, 3) unnecessary transports, 4) erroneous processes, 5) unnecessary inventory, 6) unnecessary movement, 7) goods with errors and +1) to not meet customer needs. (The seven original muda has been extended with an eight, which explains the plus notation.)

### 3.2.2 Lean principles

There are five fundamental principles in Lean; 1) specify customer *Value*, 2) identifying the *Value stream*, 3) make value *Flow* without interruptions, 4) let the customers *Pull* the value from the producer and 5) pursue *Perfection* in all parts of the production chain.

It is here fundamental to understand the customer and what the customer wants before any production starts. This does not only apply to the end customer but as W Edwards Deming (an American statistician who worked with quality issues in Japan) introduced “*The next process is the customer*” which suggest that there are both internal and external customers. The internal customer consists of the next person on the production line and they are to be supplied with exactly what they need exactly when they need it i.e. in the same way as an external customer.

#### Value

*“A reason why firms find it hard to get value right is that while value creation often flows through many firms, each one tends to define value in a different way to suit its own needs”* Womack and Jones 2003.

Value can only be specified by the customer. Value is only significant if e.g. a product meets customer demands at a specific time to a specific price, Womack and Jones (2003). The manufacturer creates the value but, as outlined in the quotation above, it can be difficult for the manufacturer to specify it. Since it is difficult for the manufacturer to specify value, in e.g. an industry the definition of value can vary from company to company. The value definition in a company is often misinterpreted and fitted into their existing: organisation, technology, assets and vision of economy.

#### Value stream

After the customer value is specified it is important to identify the value stream. The value stream is the action needed to convey a specific product, goods or service through three critical management steps which exists in all businesses. The three steps are; 1) *problem solving* from concept to detailed design and production planning, 2) *information handling* from order acceptance to detailed planning of delivery and, 3) *transformation* of raw material to produced product or good to customer, Womack and Jones (2003).

Three different kinds of activities are often discovered in the value stream in a company. The first one is called value adding activities, activities that actually add value to the product. The second kind is activities that do not add any value to the product but can not be excluded from the manufacturing due to e.g. chosen production method; these kinds of activities are called Type 1 muda. The third kind of activities is called unnecessary activities they do not add any value at all to the product and can be excluded from the production at once without any affect on the production. They are called Type 2 muda.

#### Flow

*“Things work better when you focus on the product and its needs, rather than the organisation or the equipment”*, Womack and Jones (2003).

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.

### **Pull**

*"The only sure thing about forecasts is that they are wrong", Womack and Jones (2003).*

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 working closely with forecasts. This means that production is set to produce upon prognosis, which as mentioned in the quotation above can be uncertain, 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. Pull systems are generally better than push systems when it comes to projects where variability is a considerable factor.

### **Perfection**

*"To hell with your competitors; compete against perfection by identifying all activities that are muda and eliminating them". Womack and Jones (2003).*

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 always be able to offer what the customer desires when he wants it will 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 where focus is on.

### **3.3 Toyotas four P's of production**

According to Liker (2004), there are 14 principles of production in the TPS (Toyota Production System). These are subdivided into four categories or P's namely Philosophy, Process, People and Partners and Problem Solving. These are also called Toyotas four P's of production, Figure 3. In Section 3.4.3 they are developed more in detail with the concern for Lean Construction.

Often the principals and terms are called the Lean tools and some are very familiar in the industry, e.g. kaizen which stands for continuous improvements.

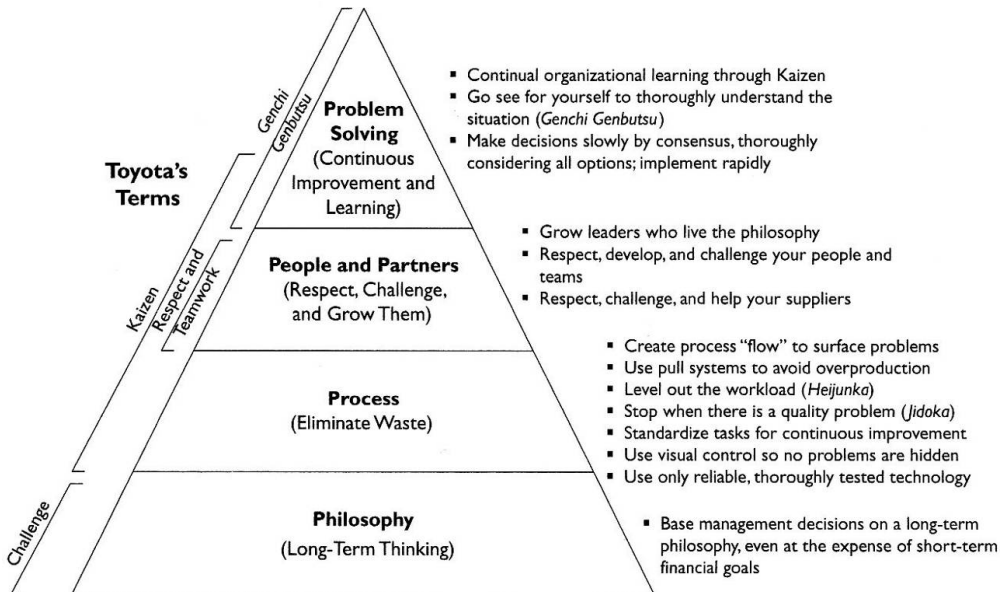


Figure 3. Toyotas four P's of production and 14 principles of the Toyota Production System, Liker (2004).

### 3.4 Lean construction

Today's construction is based on both mass production techniques and craftsmen based techniques. A large part of work on a building site is done with old fashioned methods, involving lots of workers often working in strenuous positions. Hence, the construction industry is in need for a change and therefore, the Lean Production method is of significant interest. By converting the ideas of Lean Production into Lean Construction improvements in productivity, economy and working environment can be foreseen. This question has been dealt with by many authors at conferences for example organized by the International Group of Lean Construction, IGLC (<http://www.iglc.net/>).

A key criterion for Lean Construction is that downstream actors are involved upstream in decisions and vice versa. This means that stakeholders must involve contractors, material suppliers etc. as early as possible in a project maintaining a good contact throughout the entire project. This contact ensures that products and processes are designed in collaboration between partners.

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 personnel and their experience and to, in as many cases as possible, implement their suggestions for improvements.

#### 3.4.1 Construction peculiarities

Koskela (2000), among others, argues that there are many construction peculiarities which indicate differences between the manufacturing industry and the construction industry. According to the authors own experience from construction, the following issues may hinder traditional production and an industrialization of the building process:

- Problems not solved at the right location
- Information missing in documents
- Difficulties in seeing the end product, to visualise what is being built
- Object not designed for production
- Not possible to anticipate conflicts of interest
- Errors or rework that need rectification
- Disadvantageous relations between parts e.g. client, contractor, subcontractors, designers
- Difficulties in decision making procedures
- Communication difficulties amongst parts and within own organization
- Attitude or mentality of the construction workers
- Many different contractors and subcontractors involved resulting in difficulties in controlling the project

Also, there is the well known problem with uniqueness of the project (only one object to be built once), that is constructed often during a long period of time, with a small extent of standardized parts and an organization composed just for that project. Often the authority is divided between several parties e.g. the owner, contractor, government, designers, subcontractor etc. Koskela (2000).

### **3.4.2 Early decision making (in civil engineering) - an important factor**

Decisions made early in a projects process has a large impact on the ability to build a construction. Regarding a bridge project such decisions as type of bridge, shape of the bridge, material choice, and details, will all affect the ability to build the bridge. These decisions also have an affect on the overall project economy, from project start to the maintenance of the finished product.

Unfortunately, the construction industry today has a lack of education needed to make the right decisions as often an overview of all the influencing factors is lacking. Also, a methodology for choosing e.g. the right bridge type and shape does not exist, Troive (2000). This is confirmed by Wong et al. (2004) which state that, especially designers most often lack both the practical knowledge and the incentive to make the right decisions. In Swedish civil engineering most consultants are purchased upon two parameters, price and quantity of material, i.e. the designer that offers the least amount of e.g. rebar reinforcement together with a low price wins the bidding and gets the contract. It is understood that this is not an optimum incentive in regards to e.g. the build-ability of a project.

Constructability is a key word within civil engineering projects when the different constructions have low repeatability. It is closely related to the expression build-ability which stands for the possibility for a product to be able to be produced in a competitive manner, regarding the complete process, Ståhl (2006).

Considering the build-ability only, during the early design decisions from the builder (which most often in Swedish civil engineering projects is the government) and the contractor is of significant importance. These decisions affect the number of persons/workers to be involved in a project, which materials to be used, building methods, etc. Build-ability is according to Adams (1989) (Wong et al. 2004) “the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building”.

Constructability is engineered during the design process and this is often neglected within early stages of project processes when different designers are becoming involved in projects. Controversially, it is in these early stages most of the conditions for making the project build able emerges.

In Singapore the government has outlined regulations for their house construction. They have invented a build ability score, whereas builder and/or contractor is not granted building permit if not a minimum build ability score is reached. The build ability score is said to increase quality on buildings and increase ease of construction without limiting the builder's architectural design.

### 3.4.3 Toyotas Principles in Lean Construction

Toyotas first principle of Figure 3: “base management decisions on long term philosophy, even at the expense of short term financial goals”. It is obvious that in the construction business most clients, contractors, designers, subcontractors does 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, most often clients do not contemplate anything but the bidding sum, considering the fact that the client for such projects in Sweden usually represents the community the prospects for changing their behaviour are little. However there are a few things the client can consider apart from the bidding 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.

There are a few exceptions from above of course. For instance, most often material suppliers see a continuance beyond a single project and therefore not maximizing profit for one single project.

Toyota's 13 *other principles* and the other *three P's* of production, Figure 3, can be transformed into the construction business. The first P, Problem solving, is a activity that the construction industry and contractors is very good at. However, the contractors and construction industry in general doesn't perform this the way Toyota intended it. Most often the contractors solve the upcoming problems but do not concern about learning from or finding the root cause to the problem. 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 3 dealing with People and partners, implies 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. This is of course applicable to construction industry.

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 produce only when the demand is there, level out the workload, see to that the workers have an even production rate, when quality problems arise stop and take care of them make sure that every involved worker understand

what is wrong and why and make sure it doesn't happen again, is all something the construction industry can learn to utilize more extendedly. Use standardization of work tasks, so that it is easy for workers to understand and switch work tasks and the continuous improvement work becomes easier and more reliable.

#### 3.4.4 Customer value in civil engineering

Customer satisfaction is the central point in all types of production; as a result it is of great importance to understand customer needs and expectations before starting production. According to Karlsson et. al (1998) it is important to implement/transfer customer needs and wishes into specifications for a product and let these specifications greatly influence the design phase of a project. The design documents ensure that the product will function as the customer requires. Crow and Barda, (2004) found in a study that contractors, designers and suppliers often focus on making profit instead of focusing on providing the end user service, this instead repeatedly has the opposite effect and results in economic losses.

Considering customer value for a typical bridge project, there are several factors to have in mind and several parts that need to be dealt with, Sundquist (1999). Specific areas to consider is e.g. safety for the users, easiness of maintenance, appealing aesthetics, durability through life span, little impact on users and people living in the vicinity, impact on environment during and after service life, see Figure 4. The customer of a civil engineering project in Sweden is represented by the SRA. They are a part of the central government and their predominant function is to take responsibility for maintaining the national road network and its safety. The end user however, is the public, e.g. anybody frequently using the bridge.

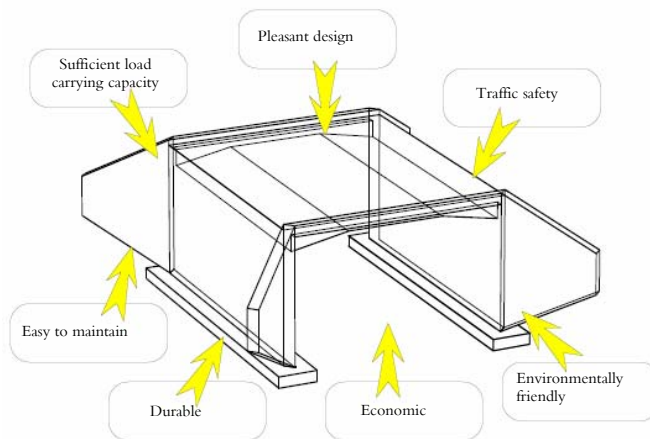


Figure 4. Different customer's demands on a typical bridge, Sundquist (1999).

#### 3.4.5 Waste in construction

*"The difficulty in eliminating waste is that most of us have not directed our efforts to finding waste and eliminating it"* Suzuki (1987).

The waste in construction is a variety of different factors. According to a study by Josephson and Saukkoriipi (2005) the direct value adding time on a typical construction project in Sweden is approximately 17 %, Figure 5. In their study they had divided the time spent on a construction site

between value adding time, Type 1 muda and Type 2 muda, (explained in Section 3.2.2, Value stream). They state that the Type 1 muda in their research is approximately 45 % and their Type 2 muda is roughly 33 %.

Koskela (2000) indicates that there has never been a systematic attempt to observe all waste in a construction process. However, there have been studies on individual subjects that can indicate the total extent of waste in construction projects. Typical areas where waste is created during a construction project are, poor/incorrect quality of the product, rework during construction, waste of excessive/left over material, waste of time when handling the material (e.g. unnecessary transport), waste of material in stock, working under suboptimal conditions, and so on. These different wastes can be compared with the 7+1 forms of waste (Section 3.2.1)

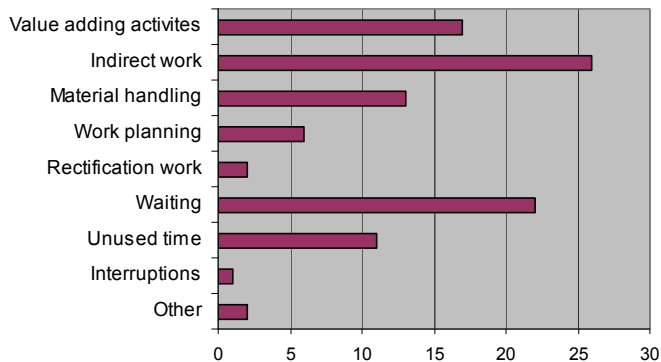


Figure 5. Time spent on different activities during construction, Josephson and Saukkoriipi (2005).

### 3.4.6 Productivity

Productivity is a measurement of performance. Forsberg (2008) concludes productivity as output in relation to input, where production resources such as workers, machinery, and material are considered as input. As output; products, services or payment for sales of products is considered. There can be different kinds of performances to measure or compare, for instance the total productivity can be measured which is the productivity of i.e. a company and then there is partial productivity which can e.g. be the productivity of a single work task. Velasco (1998) states how productivity is brought about by the technical inputs and the quality of the performance of the worker i.e. the physiological abilities of the worker, Abdelhamid and Everett (2002).

The value for the output from a process is related to the value of the cost for the input. Often the improvement of productivity is generated through a reduction of workers and an implementation of machinery in the process, but improvement can also come through economics of scale.

### 3.5 Lean methods and tools

Lean Production and Toyota Production System (TPS) have inspired many researcher and developers to develop a number of methods and tools often referred to in the literature, Liker (2004):

**TQM (Total Quality Management)** has two main objectives for the involved suppliers in a project, the first is to satisfy the customer and the second is to do this with continuous improvements, Sörqvist (2004). Also, the focus of TQM is for each supplier of the services/goods to identify and satisfy or exceed their customer’s needs in terms of cost, quality and time.

**JIT (Just In Time)** is a strategy for inventory to improve the return on investment by reducing the inventory and the costs associated with carrying inventory. JIT-includes such areas as reduction in stock, quality control, reduction in complexity, reduction in cassation and waste, delegation of decisions etcetera. *“Just in time (JIT) is the central principle in my plan. The rule is that no good should be transported to early or to late.”* Kiichiro Toyoda (1938)

**TPM (Total Productive Maintenance)** is used for optimizing the effectiveness of and to prevent breakdowns of machinery. It is based on teamwork and involves every level and function of an organization. The objective is to be profitable when utilizing machinery and equipment, which requires control over four different techniques; Preventive maintenance, corrective maintenance, maintenance prevention, and breakdown maintenance.

TPM has 8 key strategies, Figure 6: 1) Focused Improvements (Kaizen); 2) Autonomous Maintenance; 3) Planned Maintenance; 4) Technical Training; 5) Early Equipment Management; 6) Quality Maintenance; 7) Administrative and Support Functions Management; 8) Safety and Environmental Management.

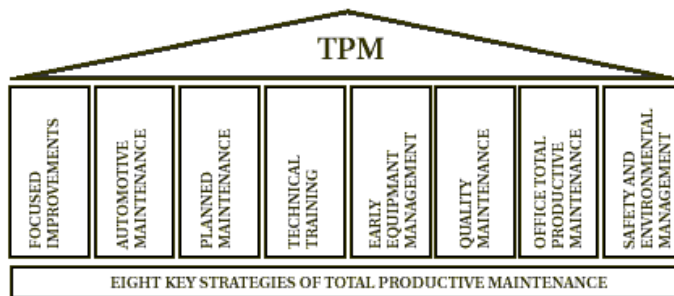


Figure 6. Eight key strategies of Total Productive Management. (from <http://www.mamtc.com/lean/>)

**Standardised work:**

*“Most improvements seem so basic that people wonder why they did not think of it before”* Suzaki (1987).

Such an improvement is the standardization of work tasks. Standardization is used to systematize how parts are being processed. It includes interactions between man and machine and studies of human motion between the operations. Standardizing work is used to systemize parts and operations so that all tasks are carried out in the best known order using the resources most effectively. Standardised work is something workers and management should develop together. The term is about making work easier with less confusion and errors as result. The operation process is documented in writing with photos and the ideal is that anyone could comply with the instructions and be able to perform the tasks within three days of training. The result of a successful standardization work helps ensure high quality on products, reducing variability, satisfied customers and profitability within the company.

**Workplace organisation, 5S**

Workplace organisation is about creating possibilities for the operations to be successful; hence, a manufacturing plant has difficulty in being prosperous if workplaces are disorganized, dirty and in a mess. Poor workplace conditions can lead to unnecessary waste as for instance extra motion to search for machinery or material. The 5S system helps organize workplaces by: Sorting of material, Store the material right, Shining clean the workplace consistently, Standardize all the work areas and finally Sustaining make the work a habit. Also, a structured and clean workplace contributes to give the customer a good impression of the company, Sörqvist (2004).

### **Kaizen**

The word kaizen denotes continuous improvements; kaizen work seeks to continually improve product development. Constant improvement is achieved through all workers participation. The fundamental idea is that continuous improvements should be a natural part of every day work. According to Imai (1986) (Sörqvist, 2004) the kaizen work should be carried out at three different levels within a company, corporate level, group level and individual level.

However, the key to successful implementation of Lean is not the function of a single method but how they are connected and implemented in the production system:

*“Many companies have respect for the individual and apply kaizen and other TPS-tools. But what is most important is that all parts cooperate in a system”.* Fujio Cho, chairman Toyota.



## **4 INDUSTRIALIZED IN-SITU CAST CONCRETE BRIDGES – CONCEPTS AND OBSERVATIONS**

### **4.1 Introduction**

Building bridges with in-situ cast concrete today suffers to some extent of inefficiency and less developed production methods. The construction works is time and labour consuming, expensive and often consists of poor working environment. A comprehensive view is therefore needed for the process and technical development using different production planning methods and new material and construction solutions. This is seldom realised; resulting in that today's production methods are not as productive as they could be.

Most objects within the construction industry are of one of a kind nature, with a long service life, and they are almost always constructed at the final destination. A bridge is thus, most often constructed at the site over an obstacle of some kind; i.e. bridges in Sweden are seldom manufactured in a factory and then placed over the obstacle. The production team of designers, clients, contractors' etcetera is of a temporary nature and almost always composed for a specific project and then dissolved afterwards. In the Project Management Institute, (PMI's) "A guide to the project management body of knowledge" the definition of a project is "A temporary effort to produce a unique product or service", Ballard (2000). According to this definition, construction work is of a project nature. Therefore, the clear step towards a sustainable development would be production teams working together for a longer period of time with learning and spontaneous and systematic collecting of experience, ideas and results from one object to another.

There are a number of different motivating factors for industrialization of civil engineering: companies need to improve their economic results to satisfy shear holders and investors, they also need to be competitive on the market; a shortage of skilled workers is expected within the construction industry, globally. Moreover, Harryson (2002) points out the ongoing globalization which introduces an increasing competition on the market.

### **4.2 Possibilities and challenges**

The possibilities for positive change within the construction industry are significant if an introduction to industrialization is managed properly. Benefits that can be expected is; improved productivity, increased profit margins for all involved stakeholders, increased quality of structures and increased safety on the production sites.

There is however challenges to overcome before the possibilities can be realized in a larger scale. These challenges are divided in technical related and process related platforms, Figure 7. The

technical challenges are related to new thinking when it comes to production methods. The process related challenges addresses the way we do business, i.e. the relation between involved actors is also related to the design and planning process, the attitude of workers, management, clients and subcontractors. The process challenges are also related to laws and regulation that needs consideration.

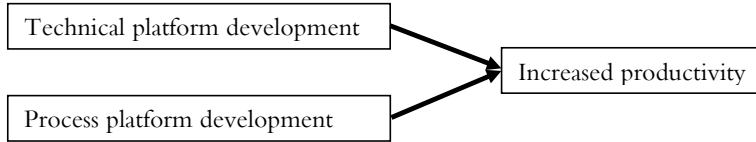


Figure 7. Platforms needed for success in the construction business.

Lessing (2006) states eight characteristic areas that comprises his Industrialized House-building Process Model (IHP Model), they are: 1) Planning and control of the process, 2) Developed technical systems, 3) Off-site manufacturing, 4) Long-term relations between participants, 5) Logistics integrated in the construction process, 6) Customer focus, 7) Use of information and communication technology (ICT) and 8) Systematic performance measurement and re-use of experience. He also suggests a radar chart where these characteristics are weighted from 0-4 to measure the levels of implementation within companies.

These characteristics are not far from an industrialized civil engineering model. However there is one important difference, focus for industrialization in a civil engineering project should be much earlier than that for a housing project. The design stage is of most importance for civil engineering i.e. this is probably the only stage when it is possible to introduce new technical systems.

### 4.3 Technical platform

There are three major material types involved when constructing a bridge; *concrete*, *formwork* and *reinforcement*. The technical platform needs solutions that are based upon these types together with a system securing an independence of weather.

For the industrialization of construction with in-situ cast concrete focus should preferably be on the following six components, Emborg (2005):

- 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.
- Information Technology i.e. IT-based planning tool.

A general thought of the technical platform is to preassemble structural and building parts that are suited for prefabrication. At in-situ cast bridges some parts are well suited for prefabrication, e.g. foundation and column reinforcement, and some reinforcement in the superstructure. The formwork can partly be subjected to prefabrication.

According to Pasquire and Connolly (2002) there are three different kinds of benefits to be acquired when prefabricating parts of structures. The advantages are; *on-site benefits*, *programme benefits* and *manufacturing benefits*. These factors mainly concern housing projects and all of them do not comply to a 100 % with civil engineering projects.

The *on-site benefits* are: reduced labour activity and consequently health and safety risks, reduced waste of material and less breakage of material, reduced site-coordinator activity, reduced storage requirement, reduced installation time, reduced need for establishment, and reduced complexity.

Their *programme benefits* are: increased up front commitment, increased quality, increased flexibility, increased installation efficiency, increased reliability of installation, increased reliability of delivery. To somewhat summarize these programme benefits, the commitment of suppliers of material to a construction site will automatically increase due to a larger engagement from the suppliers side, resulting in overall improved construction process.

The *manufacturing benefits* are: improved working conditions, increased productivity, improved processes, improved control, improved performance, improved cost, improved quality, improved safety records and improved delivery. These benefits are all related to the improvement in a factory compared with traditional onsite production.

#### **4.3.1 Weather independence**

A condition for industrial bridge construction is that the weather dependence is minimized. Cold climate clearly reduce the productivity at construction sites. For example, the “concrete winter”, i.e. the temperature when measures against cold climate must be taken to achieve a controlled hardening and strength growth, starts when the mean day temperature is below + 5 °C. In the Stockholm region, in Sweden, this corresponds to nearly 50 % of available construction days! The use of mobile weather shields is rather common and at some house building sites, the shield has covered a whole multi-storey frame to be build i.e. a transformation to an indoor factory-like building site has been made, Emborg (2005). One question is how this technique can be further adapted to bridge construction.

#### **4.3.2 In-situ cast concrete**

In the late 1990s there was a step taken towards a more industrialized casting of concrete in Sweden, when Self Compacting Concrete (SCC) was introduced. The development of SCC started in Japan during the 1980s. There were two main reasons for developing SCC, firstly to be able to ensure the increasing demand on quality of structures, and secondly there were problems finding competent personnel for castings, Okamura and Ouchi (1999).

SCC is an important link in the development of the industrialization process of civil engineering projects as it can, if managed properly, decrease the number of workers needed during casting and concrete workers can perform other activities during casting and the construction site becomes less congested with possibly reduced risk for accidents as a result, Figure 8. Also, an improvement of the working environment in general will be realized through lower noise level and less heavy lifting of material.

According to recent international findings, SCC is on the cutting edge of scientific and technological developments, Shah et al. (2007) and Cussigh (2007), and it is essential to introduce the technique in a broader manner in cast in place concrete construction. However, still, the adoption of SCC is very low and one important reason is, according the authors above, the economy. The need for high

quality constituents of materials results in a more expensive product that do not compensate for the possible economical benefits.

Shah et al. (2007) has also other technical explanations for the hindrance of introducing SCC on a broader front; questions regarding the development of formwork pressure, problems related to static and dynamic segregation resistance, rapid loss of slump flow and doubtful robustness. Also, insufficient accuracy of production equipment, quality control requirements and a lack of standards can be mentioned as reasons for the low adoption of SCC. In addition, it is difficult to establish a quality assurance system for difficult castings, Swedish Concrete Association (2002), especially when the structural section is narrow or the reinforcement is very dense as in most bridges today.

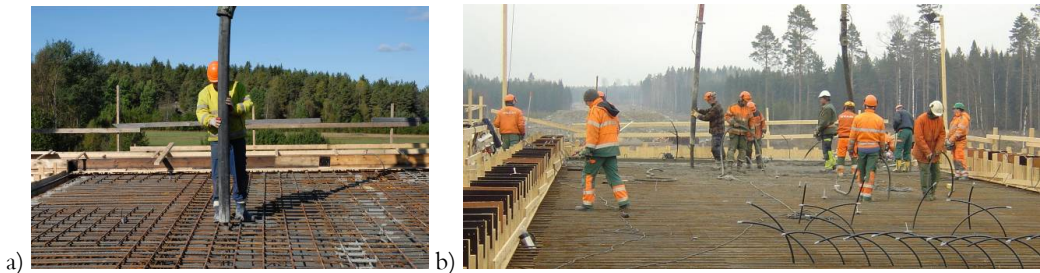


Figure 8. Typical work situation when a) Casting SCC. and b) Casting of normal concrete.

### 4.3.3 Formwork

Most often formwork is traditionally manufactured at site built up at the very location of the future concrete structure. There are of course other possibilities of formwork such as, climbing systems for e.g. high columns, slab and wall formwork for castings of repetitive nature. Another interesting formwork is left formwork. For civil engineering projects the left formwork can be made out of prefabricated concrete for e.g. the foundation or for plate structures, like the lattice girder and Filigran systems. The left formwork is an interesting alternative for the industrialization process as it both eases and speeds up production without increasing the workload and it helps diminish possible leakage of paste and eliminates possible problem with surface pores. Another type of such a left formwork that has been used in house building at several sites in Sweden, Austria and Germany, is the VS-System, made of cement-bonded particle boards, see e.g. Peterson (2008).

To utilize the formwork in an optimum manner, a joint effort among the formwork manufacturer, concrete supplier and contractor is needed. When using e.g. SCC the demands on the formwork are increasing due to a more rapid casting and the possibility of casting larger sections. Also, an increase in form pressure can be expected that the formwork needs to be designed for.

### 4.3.4 Reinforcement

The steel reinforcement is through tradition most often on-site placed piece by piece. This traditional placing of reinforcement is considered to be very unhealthy and involve stressful operating procedures for the craftsmen, Figure 9a. It often requires long working time and is therefore often a bottleneck in production, Sandberg and Hjort (1998).

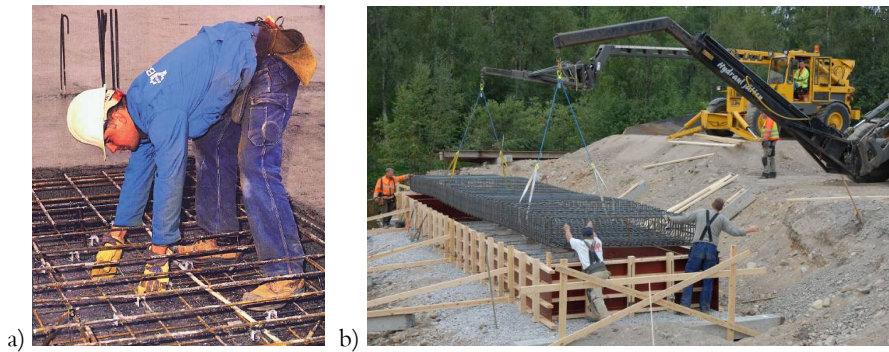


Figure 9. a) Normal working position for traditional placing of reinforcement. b) Cages of reinforcement placed directly in the form.

An alternative to traditional placing of reinforcement is prefabrication of the reinforcement. Prefabricated reinforcement often consists of ready to use traditional mesh reinforcement or reinforcement bars welded together to cages varying in size. Prefabrication decreases the number of stressful working positions for the workers, Figure 9b, and increases construction pace without intensifying the workload on the workers. Also, the manufacturing of the cages are done in a controlled environment with appropriate tools resulting in a clearly improved working environment, Figure 10.

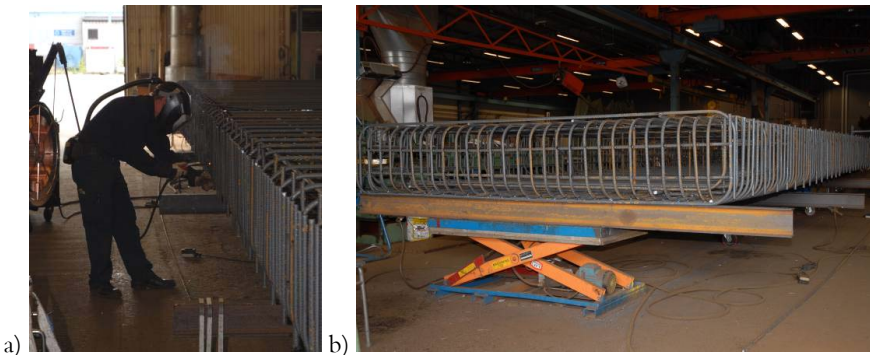


Figure 10. Manufacturing of reinforcement cages in a controlled environment in a factory.

Another option available in the last decade is the *carpet reinforcement* system. It consists of loose bars which are welded up on thin steel bands and then rolled together, Ålander (2004). The roll of reinforcement is then fixed on the specific starting place for the reinforcement and rolled out into a finished product, Figure 11.

Different kinds of prefabrication of reinforcement are essential parts of an industrialized construction industry. However, all reinforcement on a bridge is not suited for the use of prefabricated reinforcement, and hence, the piece by piece reinforcing must still be a part of the every day work.



Figure 11. Rebar carpets, rolled out on a superstructure at a studied project.

#### 4.4 Process platform

*“A manufacturing system is an objective-oriented network of processes through which entities flow.”* Hopp and Spearman (1996).

The process platform needs to control and encourage the environment in which the technical platform is supposed to be realized and to prosper on the construction site. The platform of processes relates to, as mentioned earlier, the design process, relationship between actors, rules and regulations among other things. The process platform lays the foundation of the entirety for a construction company.

##### 4.4.1 Transformation, flow, value and planning in the construction process

The classical depiction of production is that of solely transforming input to output, i.e. there is no focus on the different stages of a production. Comparing output to input is also the easiest method of measuring the productivity. However, to be able to acquire control over the production and the involved production costs, it is necessary to breakdown the overall process of production into smaller sub processes, Figure 12. Koskela (2000) introduced an alternative to the traditional focus on transformation, the TFV-model of production which stands for *transformation, flow* and *value*, Table 1. This is done to better allow the five principles of Lean Production (Section 3.2.2) to be implemented to Lean Construction.

Also, according to Ballard (2000), the production process can be divided up into three steps: step 1) a process where input becomes output, step 2) a process with flow of material and information through time and space, and step 3) a process where value to the customer is created. All three steps need to be managed simultaneously. This is all in accordance with Koskelas TFV-theory. Both Koskela and Ballard conclude that the model of translating input into output is inadequate for the construction industry due to a complex nature of projects and therefore the need for a more thorough model of explanation is at hand.

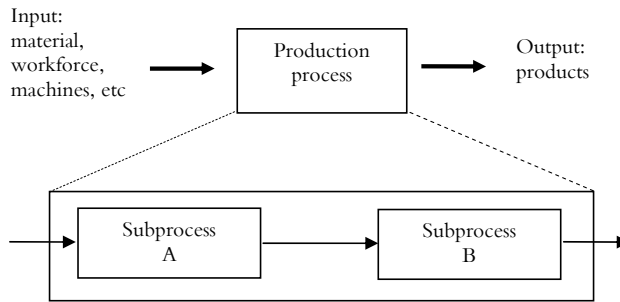


Figure 12. The transformation process of input becoming output according to Koskela (2000).

Table 1. An overview of the TFV-theory by Koskela (2000) for the implementation of the Lean Production principles to Lean Construction.

	Transformation view	Flow view	Value generation view
Conceptualization of production	As a transformation of inputs to output	As a flow of material, composed of transformation, inspection, moving and waiting	As a process where value for the customer is created through fulfilment of this requirements
Main principles	Getting production realized efficiently	Elimination of waste (non value adding activities)	Elimination of value loss (achieved value in relation to best possible value)
Methods and practices	Work breakdown structure, MRP, organizational responsibility chart	Continuous flow, pull production control, continuous improvements	Methods for requirements capture, Quality function deployment
Practical contribution	Taking care of what has to be done	Taking care that what is unnecessary is done as little as possible	Taking care that customer requirements are met in the best possible manner
Suggested name for practical application of the view	Task management	Flow management	Value management

When the production process is divided into sub processes, it can be controlled and monitored on costs. The sum of these costs is then the total cost of the production. It is thus important to make these subprocesses work as smoothly as possible resulting in as little variation as possible which in turn minimizes process costs.

Koskela (1999), introduces seven preconditions that need to be controlled to be able to perform a work task properly, Figure 13. There can be variability among the preconditions e.g. information missing in documents when construction task is supposed to commence or workers may be dislocated to other tasks to name but a few variability's common in construction (see Section 3.4.1).

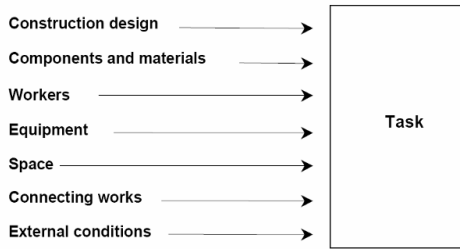


Figure 13. Preconditions for completing a construction task according to Koskela (1999).

According to Ballard (2000) and the Last Planner System of production control, traditional project management consists of controlling time and resources. Resources which consists of man hours, material, machines etcetera is planned and controlled by economy systems where productivity is measured to get as an effective use as possible of the resources.

Ballard and Howell (1998) inaugurate five principles of the Last Planner method, these principles has been further developed by Koskela (2000) and Ballard (2000);

The *First principle* concerns the definition of assignments, is the assignment precise enough so that the right type of material and equipment can be collected and is the work task organized to comply with previous tasks and other trades operating in the same area. Also, can the assignment be determined weather it was carried out or not during the appointed time.

The *Second principle* regards soundness of the assignment, i.e. is all the prerequisites for being able to execute the assignment completed. Is design complete and/or previous work performed adequately are questions to be answered. The purpose of the soundness principle is to make work tasks ready to be performed the week before execution week.

The *Third principle* is about causes for non-realization of assignments. The causes are investigated and made sure they are avoided in the future creating continuous improvements in the process.

The *Fourth principle* suggests keeping a backlog of work tasks ready to be performed if a suggested task turns out to be unable to be accomplished.

The *Fifth and final principle* proposes lookahead planning. The time horizon should be approximately 3–6 weeks, and scheduled upcoming work tasks should actively be made ready for execution during this time period.

In short, the Last Planner System advocates criteria for effective production control, partly by minimizing variation through active learning and partly by preparing upcoming work tasks making certain they are prepared and planned for. Also, keeping a buffer of work that needs to be and can be done if problems occur with the assigned work tasks. This encourages a pull system within production; a focus is created around the flow of work and creating customer value. The lookahead planning implies planning through prognosis and the duration of the lookahead planning is among other things dependent upon the nature of the project, lead times for material, personnel, machinery and the reliability of the planning.

#### 4.4.2 Design, production and maintenance process of an industrialized construction apparatus

In today's construction, there are most often short term relations between clients, contractors, and designers as mentioned earlier (see e.g. Section 3.4.3). Contractors try to optimize their business due to economic constraints as well as clients need to optimize theirs; here a conflict of interest is close at hand. In the optimized industrial process, the Lean Design Team (LDT) should have a focus on maximizing a construction's total life cycle cost (LCC). This means that e.g. a bridge should be designed not only for the optimum production solution but also for optimum maintenance over the total life span, Figure 14. A good example of this can be the continuous maintenance on the edge beams on a bridge. Corroding reinforcement in edge beams is often the main reason for comprehensive maintenance on a bridge during its lifespan and could be minimized with the use of corrosion free reinforcement. Optimum LCC can be somewhat difficult to achieve due to several factors, one of these factors is the expected maintenance cost. Although, this maintenance cost and related questions are not further developed in this thesis, it is an important question to bear in mind for the LDT, i.e. that the optimization of a project includes the complete life cycle.

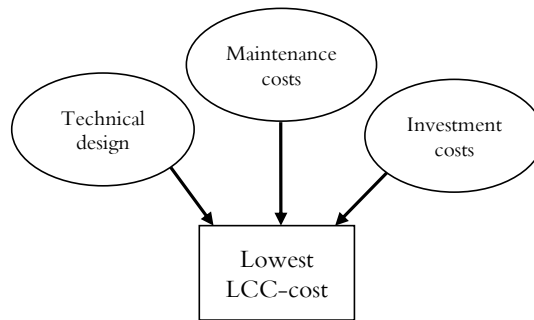


Figure 14. Factors affecting the total life cycle cost of i.e. a bridge project, after Sundquist (1999).

To be able to utilize new innovative developments within the technical platform, a design process is necessary to meet demands. The design is of importance due to many factors. Besides optimising for new production methods, it is central in planning a project optimally, including factors such as optimizing material usage and associated handling costs, also to optimize the usage of personnel, equipment and space.

To achieve a proper design and planning it is fundamental to establish a design team meeting the criteria. To successfully generate such a design team, i.e. a LDT, it is important 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 modelling (3D plus time) should actively be implemented in the design phase together with a close relation to the customer, i.e. the client.

Important is to get these various actors to work together from the beginning in a project and make them understand each others difficulties and act upon them to solve problems before they appear is. It is also important to remember that it is only the designers who have the power to eliminate or change different work tasks!

This is inline with one important principle in Lean Construction i.e. 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 favourable way in terms of construction.

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 15 illustrating a traditional Swedish Road Administration (SRA) project schedule.

Traditional SRA Project schedule:

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

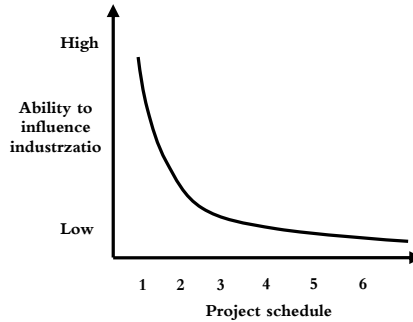


Figure 15. Project schedule of a traditional Swedish National Road Administration (SRA) project and its industrialization possibilities. The earlier the efforts for industrialization the greater impact they have.

A process model for industrialized civil engineering construction combining technical and process platforms may be visualized according to Figure 16. The early design stage is emphasised where tender documents are processed by the LDT for the establishment of construction documents. A first test of buildability (constructability) is made at construction planning or at real construction giving feedback to the design activities. For example the feedback can include updated need of resources/material. The iterative loop includes Lean tools like means for standardization, experience, improvements for more industrial construction.

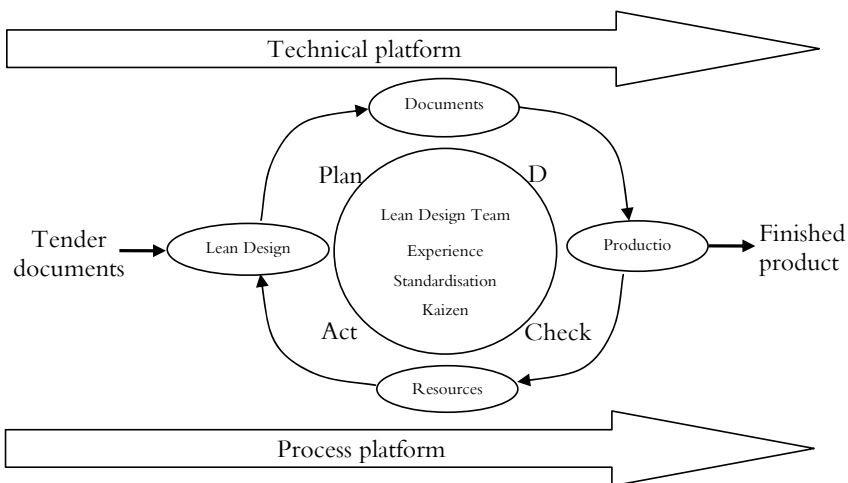


Figure 16. A production process model used at a full scale project in Kalix.

### 4.4.3 Responsibilities and relationships

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 important to develop long-term relationships between all partners. According to Toyota's 11<sup>th</sup> principle “respect your extended network of partners and suppliers by challenging them and helping them to improve” you should treat your partners and suppliers as an extension of your own business. This is one of the central cores of Toyota's 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.

### 4.4.4 Mapping value

Value stream is one of five key principles (Section 3.2.2), 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, Liker (2004). 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 3.2.1) 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.

Figure 17 visualizes the value stream with traditional handling of reinforcement, i.e. when reinforcement is placed piece by piece. The coloured 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 coloured squares. For instance early in the stream it is the contractor, and later on it can be the purchaser or the society.

The pursuit here is to minimize the number of coloured 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 Figure 18 and Figure 19 using prefabricated reinforcement, the number of coloured squares has been reduced as compared to the traditional handling Figure 17. This implies that the mounting of prefabricated reinforcement, as known, goes faster than the traditional mounting.

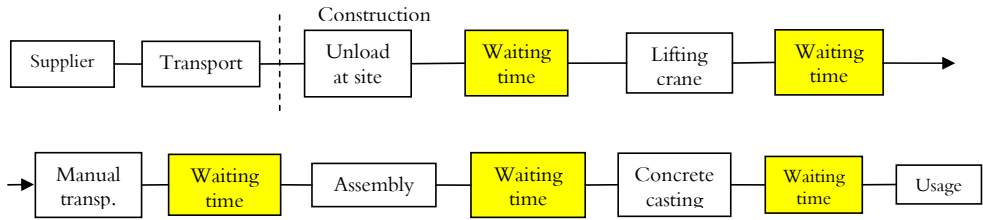


Figure 17. Value stream of traditional handling of single piece reinforcement on a construction site.

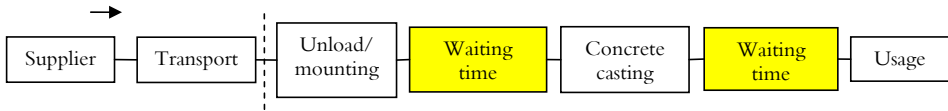


Figure 18. Value stream when handling the prefabricated reinforcement sections for the foundation at the first full scale project. (See Section 2.3).

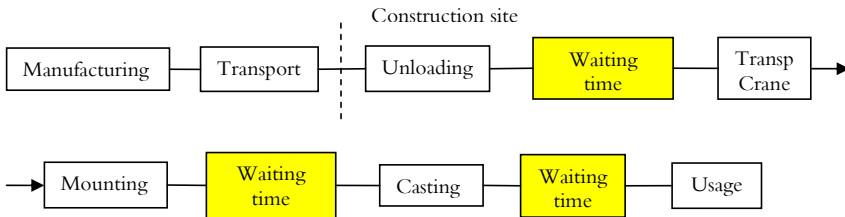


Figure 19. Value stream when handling the rebar carpet reinforcement used at the first full scale bridge project. (See Section 2.3).

Some waiting time is however necessary or somewhat unavoidable with current construction methods: for instance the waiting time between finished reinforcement assembly and casting of the concrete is probably unavoidable but 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.

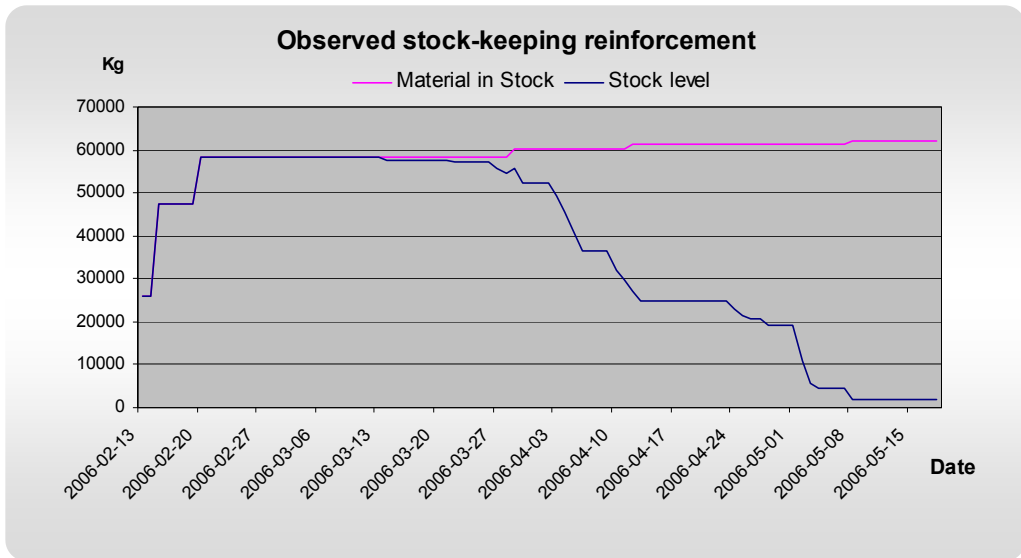


Figure 20. Storage of reinforcement on a building site in Sweden. Material in stock is the total material on the building site (built in and in stock). Stock level is the material on the building site not built in yet.

Figure 20 shows an example of actual storage of reinforcement on a construction site. It can be seen that all the used reinforcement for the whole project (nearly 60 tonnes) is bought and delivered to the site on three different transports during the first two weeks of the project. After the delivery, the reinforcement lies unused for a period of almost six weeks before the commencement of reinforcement fixing. Figure 21 on the other hand; show a suggested change of reinforcement handling for the studied project. Here, the reinforcement is delivered at three different occasions. The difference however, is that the deliveries are carried out when the project needs reinforcement according to the pull system, see Section 3.2.2. Other noticeable difference is that the construction site will become less congested due to less material lying around on the ground, the time in stock for the reinforcement will be halved from 89 days to 44 days and the average stock level will become only 19 % of the one showed in Figure 20. With an average reinforcement cost of 0,8 € per kg, the reduced stock value is € 25.000 to a capital cost of approximately € 500. It is important to point out that the suggested solution in Figure 21 is not optimized; it is merely a solution with the same number of transport occasions as the actual outcome in the project. These results are a part of an ongoing final thesis study at the civil engineering program at Luleå university of Technology.

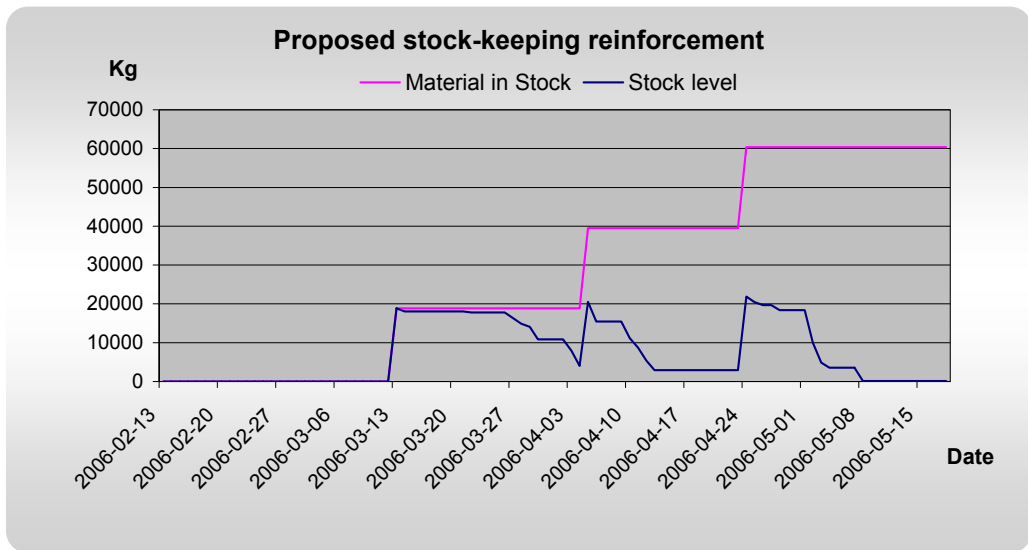


Figure 21. Suggested storage of reinforcement on the same building site as Figure 20. Notation see Figure 20.

#### 4.5 Working environment

A concern of the building sector is that not many workers today are able to work until retirement; most often early retirement is the case due to ergonomic unhealthy work. Since the construction business as mentioned earlier have difficulties in recruiting qualified personnel, there is a motive in introducing improved working methods to keep the workers working until retirement. According to a study at the Danish Technological University (Nielsen, 2006) some 26 % of a workers average day consists of concrete casting (~10 %) and reinforcement fixing (~16 %). If this is translated into time, it will be just over 2 hours per working day. This work is often done in awkward postures with heavy equipment such as the poker vibrators for the traditional concrete or with heavy material when placing the reinforcement traditionally piece by piece. Thus, 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, working climate and workers. However, most often is a chance of improving the working environment denied because of the contractor only considers the short term prize for material and man power and do not consider the total possible long term cost reduction from e.g. an enhanced working environment.

The Swedish construction work environment is regarded as the safest in the world on the subject of physical health, working conditions, illnesses and accidents, Flanagan et al., (2001). Nevertheless, there are still work environment related health problems to be tackled. By introducing SCC, various prefabricated reinforcement solutions and "new" formwork solutions the working environment can be improved. With an increasing technology input into the construction workplace, not only does the productivity become enhanced, but it also adds value to the whole construction project. In the full scale projects the working environment was studied along with the integration of Lean Construction and safety management as the emphasis is in Saurin et al. (2006).

Off-site produced prefabricated reinforcement and SCC were shipped into the construction site and lifted into the site by cranes or pumped into the formwork with out any compacting work, thus

avoiding any manual material handling. To be able to measure the difference in working methods a program called ErgoSAM was used. ErgoSAM is based on SAM (a sequence-based activity method), and a higher-level method-time-measurement (MTM) system, Laring et al. (2005). The SAM system is the result of work carried out in Sweden to shorten the time needed for analyses made with MTM systems. 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, Swedish Productivity Center, (1995). 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, Sperling et al. (1993).

The Cube Model, Figure 22, 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 Laring et al. (2005). 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).

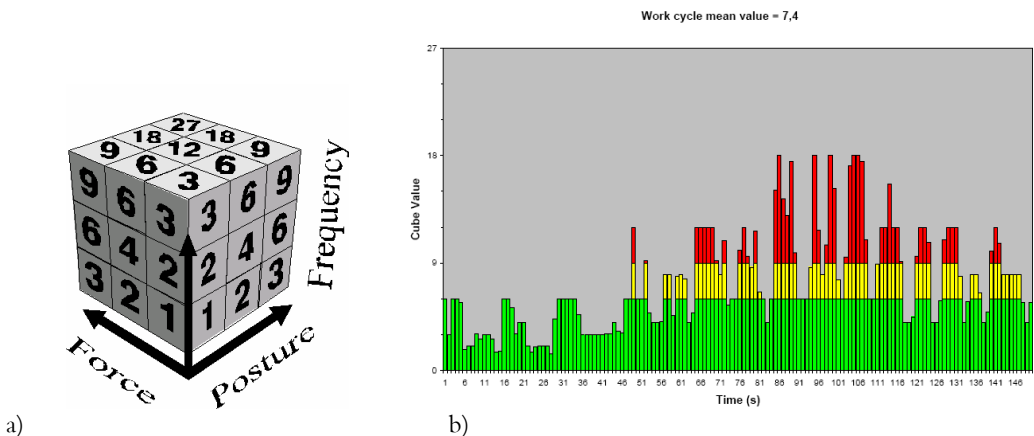


Figure 22. a) Using the Cube model Sperling et al. (1993) for a specific working task, force, posture and frequency are given weight factors 1, 2 or 3 and then multiplied to be able to discriminate between good and poor work ergonomics. b) ErgoSAM analysis of a short work cycle of a concrete personnel working with prefabricated reinforcement, mean value 7,4.

## 4.6 Results from the full scale tests

### 4.6.1 Construction

The first full scale test near 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 2. This meant that the theoretical estimation of an 80 %

reduction of on-site construction time when using prefabricated reinforcement was fulfilled already at the test.

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 casting of concrete at 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 2. The concrete was cast at four different occasions, varying in volume and casting time.

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).

<b>Kalix</b>	Traditional	Craft hrs/ton	Industrialized	Craft hrs/ton	<b>Kalix</b>	Traditional	Optimum SCC
Prd time at site	2,5 days	80 hrs	5 hrs	15 hrs	Prd time at site	10 hrs	7 hrs
Craftsmen	4 persons	13,2 ton	3 persons	13,2 ton	Craftsmen	4 persons	2 persons
<b>Total</b>	80 hrs	6 hrs 4 min	15 hrs	1hr 8 min	<b>Total</b>	40 hrs	14 hrs
<b>Nynäsvägen</b>	Traditional	Craft hrs/ton	Industrialized	Craft hrs/ton	<b>Nynäsvägen</b>	Traditional	Optimum SCC
Prd time at site	12 hrs	24 hrs	1 hr	3 hrs	Prd time superstr	20	14
Craftsmen	2 persons	3,6 ton	3 persons	3,6 ton	Craftsmen	9	7
<b>Total</b>	24 hrs	6 hrs 40 min	3 hrs	50 min	<b>Total</b>	180	97

In contradiction to the first full scale project the research within in the second full scale project at Nynäsvägen started in close proximity to commencement of the production and hence, the possibility to alter the production phase was moderate. However, the most comprehensive concrete research was performed at this project. 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, also the moisture of the aggregate was documented. The target value of the slump flow at the construction site was  $720 \text{ mm} \pm 20 \text{ mm}$ . That outline was kept most of the time, i.e. the concrete was robust and had little variation in consistency. 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.

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, and 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. 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.

Again, the production time for traditional handling of reinforcement and casting of concrete in Table 2, was obtained by the experience of the local site manager and the bidding calculation.

## 4.6.2 Working environment

The results in this study were obtained through observations done at site in a form of site-walk through, video filming of identified reinforcement fixing and concrete casting activity work cycles. Also, interviews with the workers were carried out subsequent to the work. These observations were the basis for a further risk assessment; an ergonomic analysis in the ErgoSAM program.

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 23. 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 reinforcement which has a value of 7.4, Figure 22b. 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. The very high values of traditional reinforcement work represent manual lifting and carrying of heavy reinforcement bars, and 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 24, 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 over three times higher.

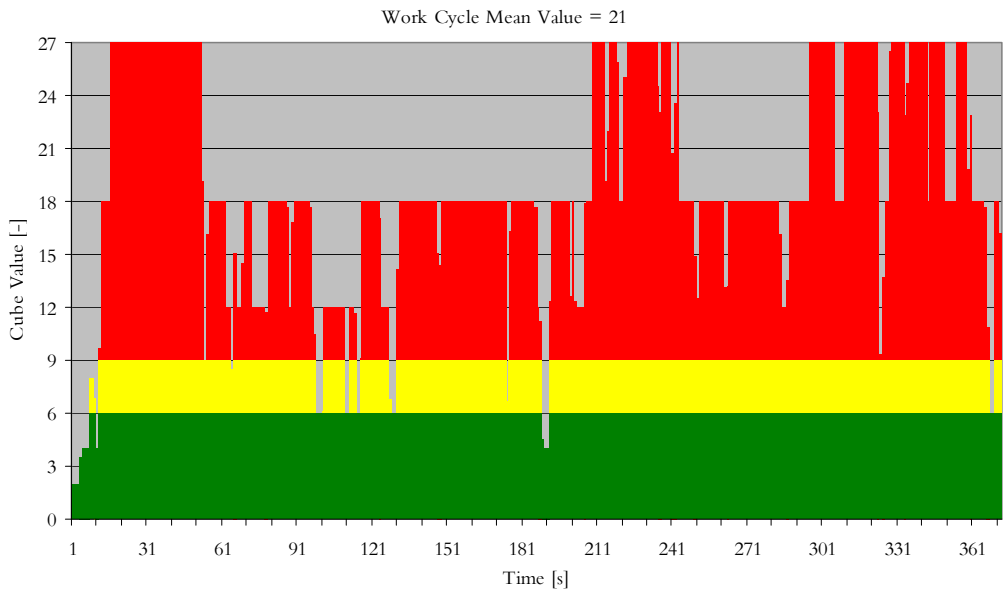


Figure 23. ErgoSAM analysis of a short work cycle of traditional reinforcement placing, mean value 21. Below 6 is acceptable, 6 to below 9 is conditionally acceptable and 9 and above is unacceptable.



Figure 24. ErgoSAM analysis of concrete worker's short work cycle during SCC casting.

#### 4.6.3 Laboratory studies

To be able to produce a robust SCC product the focus should be on keeping the fluctuations of the different constituents as low as possible and to design a robust concrete mix. Among possible fluctuations e.g. the quality of the coarse aggregate, cement or additives can be specially mentioned, whereas, the moisture content in the coarse aggregate might be the factor causing the most common and largest variations. Therefore, the recipes of the SCC used in the two full scale projects, were tested in the laboratory regarding sensitivity to fluctuation in water content corresponding to a moisture content variation of  $\pm 0,5\%$  and  $\pm 1,0\%$  without compensating done in the mix. Two test series were performed with a slight variation of mix proportions. Variations of filler content were performed by adjusting the aggregate content. The fine and coarse grained aggregate curves featured  $\pm 14\%$  deviations from the original curve at the fractions 1 mm.

Generally, it is observed that both SCC mixes are relatively insensitive to the moisture variations studied even though the filler content was increased and decreased from the reference mix. However, one of the mixes is somewhat more sensitive than the other to the changes of moisture content. Furthermore, some relation between slump flow and shear stress is present at the tests as well as between T50-time, V-funnel time and viscosity.

## 5 SUMMARY OF PAPERS

In this chapter the published articles are summarised in the order of dates for publishing. The articles are presented with title, authors, where they have been published and the state of publishing, with key words. The background is presented as well as purpose, research methods, summary and a short comment on the results and the scientific contribution.

### 5.1 Summary of paper I

#### **Title and Authors:**

Evaluation of a GPS support system for fleet management control.

Peter Simonsson and Jonas Carlswård

#### **Published:**

13<sup>th</sup> Annual conference on Lean Construction, Sydney, Australia, 2007, International Group for Lean Construction, IGLC.

#### **Research questions in focus:**

This article was composed before any research questions of the PhD project were methodically formed. However, the focus of this article was on one of the fundamental issues in Lean, namely waste. The study was aimed at minimizing waiting time for workers at the construction site waiting on the concrete trucks and for the concrete trucks waiting for the next batch to be ready at the concrete plant.

#### **Key words:**

GPS system, Waste time, Fleet Optimisation, Non-Value Adding Activities, Pilot Study, Production Planning.

#### **Background and Purpose:**

This article came as a result of a PhD study course. The topic of the course was logistics within the construction industry. At the same time as the course was taken, there were discussions concerning the delivery precision and the utilization of concrete trucks at Betongindustri. The article included experiment and was initiated by Betongindustri as a part of the increasing focus of delivery precision and utilization of the concrete trucks.

## **Methods:**

Data gathered using GPS support systems, was evaluated in Excel.

## **Summary of main contents:**

Within the ready mix concrete industry, delivery precision and fleet optimisations are highly prioritised. Introducing a Global Positioning System (GPS) system for logistic steering and planning provides a tool to make improvements on these areas. Such a system is presently under evaluation at various ready mix concrete suppliers in Sweden. One of the systems consists of GPS receivers in the trucks that send relevant information via the General Packet Radio Service (GPRS) net to a server.

Implementation has been made as pilot studies in Stockholm. A direct effect of the use of the GPS system is that the plants and the order central will be able to better control the whereabouts of the concrete trucks. As a result it will be possible to decrease the waste time at the concrete plants. Another result is that the ratio of usage of concrete trucks will increase, leading to possible cut-downs in the truck fleet. It is further believed that the lead-time at work sites can be reduced as the delivery precision is improved. By eventually letting the contractor be a part of the system the possibilities for a good production planning and execution at the work site will increase and the non-value adding activities will decrease due to reduced waiting time.

The article presents findings from a pilot study in Stockholm, Sweden. An important ambition is to find out if the system gives the expected benefits. The customer value is evaluated through interviews and time measurements.

## **Research results and scientific contribution:**

Next after cost for raw material the most significant cost for a ready mix concrete firm is the ones associated with transportation. Delivery is further an important part of the product and the associated service. An ambition is to maintain a high degree of service and make it as efficient and cost effective as possible. It is anticipated that this is achieved when introducing a GPS based system for fleet management control.

Expected positive effects are e.g. an increased degree of usage on the trucks and concrete pumps and a higher number of deliveries at the agreed time. The system is further expected to bring more valid information to the customers giving them real time notification on the positions of the trucks. Another beneficial effect is that the customer will be able to see at an early stage if a delivery is delayed. Thereby it is possible to make a change in the planning of the personnel activities. This gives ready mixed concrete suppliers a better customer focus and will lead to better productivity at the construction site due to less waiting time. The map system will further aid the drivers in planning the route to the construction site, thus resulting in less transportation time and better delivery efficiency.

Although the intent of the pilot study was more or less to verify the functionality of the soft- and hardware some conclusions can be drawn based on results from the rather limited pilot study. Firstly, it was shown that the efficiency of concrete deliveries was slightly increased, possibly due to the GPS system. The average usage time was approximately 30 minutes higher for trucks with GPS as compared to trucks without. Secondly, results showed that waiting times were in average 5 minutes shorter per delivery for trucks equipped with GPS. For a single truck this may not seem much. However, it can result in savings corresponding to one or several trucks considering a fleet of 50 trucks that are delivering up to 5 or 6 deliveries a day.

Important to mention is also the fact that the automatically generated data in the GPS based system is more reliable than the manually obtained as used today. This is important since many decisions are based upon statistics analysed from the data.

## **5.2 Summary of paper II**

### **Title and Authors:**

Industrialization in Swedish bridge engineering: a case study of Lean construction.

Peter Simonsson and Mats Emborg

### **Published:**

15th Annual conference on Lean Construction, East Lansing, Michigan USA, 2007. International Group for Lean Construction, IGLC.

### **Research questions in focus:**

The study deals with the first full scale project, in fact, addressing nearly all the research questions of Section 1.3.

### **Key words:**

Bridge design, Concrete, Productivity, Industrialization, Lean, Waste, Logistics, Full scale test, Prefabrication, Reinforcement

### **Background and Purpose:**

This full scale study was the result of an initiative between SRA North Region, SRA Business unit Production and maintenance and Luleå University of Technology. The full scale object was taken out of the traditional purchasing system and devoted to research and development only. There were several motives involved in this research. It was of interest for the SRA to test new production technologies in full scale where a comprehensive documentation will be carried out. For the material suppliers the purpose was to verify and market the potential of cast in place concrete to industrialization for the concrete supplier and the rebar carpets for the reinforcement supplier. Main purpose for the university project was to, for the first time in full scale apply Lean Construction philosophies together with new production techniques.

This was at first an initiative comprising client, contractor and a research team but was very soon extended to comprise designer and material suppliers. All involved actors were interested in supporting the project and their counter parts and to be able to maximize the result of the study.

### **Methods:**

The research included theoretical “desk” studies (planning, evaluation etc). However, main activities were in the form of full scale planning documentation, verification and mapping.

### **Summary of main contents:**

Earlier theoretical studies have indicated that, if prefabricated reinforcement, self compacting concrete (SCC) and permanent formwork are used the degree of industrialization can be increased markedly. To be able to realize this, Lean Construction principles prove to be important utensils

during the planning and design phase as well as during the construction of a full scale project. The purpose was thus to verify these hypotheses.

Throughout the design and planning of this first full scale bridge project, intensive contacts between designer, contractor, client and material suppliers were established. The design team concluded that the production time at site could be reduced with up to 20 % and the number of workers could be reduced by virtually 50 % during almost half the project. This was realized by planning with Last Planner ideas, and designing the project properly using modern construction tools and materials. The design team also concluded that if the concrete class increased some of the very dense shear force reinforcement could be left out.

The evaluated outcome of the demonstration project, i.e. potential productivity improvements, structural quality improvements, immediate feasible waste and cost reductions and the positive impact on the working environment, shows that the predicted benefits made were fulfilled.

### **Research results and scientific contribution:**

The full scale bridge studied could be constructed using less resources, less materials and less construction time both in theory and in reality, e.g. for the bridge the production time was reduced, and the costs for construction were reduced. Moreover the bridge was constructed with a better and less stressful working environment, increased safety and less physical loads.

The difference between the industrialized and traditionally performed production alternatives was typically demonstrated for the foundation and shows the importance of planning. It is clear that if construction of all structural parts of a bridge is planned and performed large reductions in production time and increase in productivity is foreseen. To achieve these improvements it is vital to build up a confidence between involved actors to strive in the same direction. It is also important to build up knowledge on the material and processes used in the entire project. For instance, the contractor had no previous experience of SCC which led to some faults during the construction phase of the project, implying that possible benefits were not realized as anticipated. The study verified that a correct combination of Lean Construction philosophies and “new” production methods for cast in place concrete was successful.

## **5.3 Summary of paper III**

### **Title and Authors:**

Consequences of industrialized construction methods on the working environment.

Peter Simonsson and Romuald Rwamamara

### **Published:**

15<sup>th</sup> Annual conference on Lean Construction, East Lansing, Michigan USA, 2007, International Group for Lean Construction, IGLC.

### **Research questions in focus:**

The research question in focus in this paper deals with which benefits can be generated by an industrialization process and especially the working environment.

**Key words:**

Working environment, Steel reinforcement, Concrete casting, Industrialization, Lean construction

**Background and Purpose:**

The background is the well known poor working environment in the building industry and certainly handling of reinforcement and formwork as well as pouring concrete belongs to the more unhealthy activities on building site. The purpose was to in a more scientific order document these well known situations on the site.

**Methods:**

Full scale inspections, documentation with video films, evaluations with methods for working environments specially adoptions to construction activities.

**Summary of main contents:**

The working environment has been poor, especially when it comes to reinforcement handling and concrete casting at construction sites. Industrialised construction methods, such as self compacting concrete (SCC) casting and prefabricated steel reinforcement, are creating a basis for an improved working environment. By using these methods, it is assumed that the cost for sick leaves due to ergonomic injuries and accidents could be reduced as health and safety risks inherent to the traditional working methods are decreased.

Observations along with video filming and informal interviews were performed. With a sequence-based activity method ErgoSAM, an ergonomic risk analysis was conducted. The analysis showed that industrialised methods markedly reduced ergonomic workload on concrete workers.

The industrialisation of the production process through the introduction of new construction methods, has from the studied case, benefited the construction workplace environment as well as the customer value in terms of improved material handling, elimination of additional adverse affect on health of handling vibrating tools, reduced on site congestion and reduced over all material costs.

**Research results and scientific contribution:**

The ergonomic risk analysis on reinforcement handling and concrete casting work tasks by the ErgoSAM method, 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 elimination of physical strain due to the common risk factors was made. These are generally part of the traditional methods of rebar reinforcement and the use of conventional concrete.

The prefabrication of steel reinforcement structures allowed a significant reduction of on-site steel fixing and associated labor costs as well as providing a much safer working environment without risk factors such as heavy lifting and working in bent, awkward and repetitive postures. The SCC cast into a frame of reinforced steel without the need for the labor intensive mechanical vibration usually associated with concrete placing, has led to the improvement of construction work environment and the promotion of health and safety of concrete workers. In a project such as a bridge construction in areas with heavy traffic, the project completion time can be extremely important. As the new steel reinforcement was prefabricated, there was higher quality control than the traditional rebar system. The off-site fabrication of steel reinforcement accomplished difficult construction tolerances, improved handling as well as it contributed to the speed of construction and minimized wastage of

material. All mentioned above contributes to the customer value, in this case to the National Road Administration in Sweden.

The use of SCC in the full scale project offered many benefits to the construction: the elimination of the compaction work resulted in reduced costs of placement, a shortening of the construction time and the number of involved workers during casting, and therefore in an improved productivity. Considering the economics of SCC, the material cost was higher than traditional concrete; however the total cost was slightly lower for SCC. The largest benefit though was the reduction in man hours used for casting the concrete, man hours that can be used for preparing upcoming work.

When working with these industrialized and innovative working 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.

## **5.4 Summary of paper IV**

### **Title and Authors:**

Industrialized construction: benefits using SCC

Peter Simonsson and Mats Emborg

### **Published:**

Journal paper in the Nordic Concrete Research, 2008. Conference paper in the Nordic Research Conference, Bålsta Stockholm June 2008.

### **Research questions in focus:**

The focus in this paper is on the concrete part of a full scale project, and how self compacting concrete SCC contributes to industrialization in construction.

### **Key words:**

SCC, benefits, economy, productivity, working environment, robustness

### **Background and Purpose:**

The industrialization level is rather low for building site (object oriented) construction. Furthermore, the share of SCC as compared to normally vibrated concrete is low. The research aiming at investigate the possible obstacles using SCC and to study effects on industrialization.

### **Methods:**

Application of SCC and prefabricated reinforcement at full scale construction where Lean Construction philosophies are utilized. Documentation of output and theoretical evaluation. Laboratory studies of concrete robustness.

### **Summary of main contents:**

The product SCC comprises many advantages compared with traditional concrete but yet it has not changed the market of cast in place concrete as expected, since the market share is as low as 5 % in

Sweden. This may be related to some robustness problems of the concrete and to a general opinion that the use of SCC is considered to be more expensive than if the normally vibrated concrete is used. However, SCC has become more robust over the last few years and manufacturers have improved their quality vastly.

To increase the use of SCC, the actors of the building trade need to be informed how to benefit from all the advantages of SCC (i.e. the working environment the health and safety of the workers, the productivity etc).

The paper deals with full-scale examples on the use and the realization of SCC obtaining several benefits during the whole project time. Specially, the economics and the working environment - are treated.

### **Research results and scientific contribution:**

From the full scale tests and theoretical observations it is observed that, the largest economic impact when introducing SCC in civil engineering projects is probably on the bridge superstructure, this since a large number of man power is needed during casting of traditional vibrated concrete and is associated with large casting costs. Hence, the number of workers needed for casting of the superstructure can be markedly reduced if SCC is introduced and proper planning has been carried out before casting.

Controversially, it is however often easier to introduce SCC for foundations, columns or plate structures since these structural parts are less dominant in the construction and the “risk” related to SCC is small. But, for these smaller structural parts with less people engaged, it is more difficult to achieve economical benefits in using the “new” concrete.

The overall risk using SCC is that the product is not robust enough, which might result in that the concrete does not enclose the reinforcement satisfactory and rework is needed. Also, after casting, it can be visual lines (inward bends) in the finished construction which is not acceptable. Therefore, most often, contractors calculates the risk when using SCC to be too high, especially for the more important superstructure and simply does not use the product even though both costs and time evidently can be saved.

The SCC delivered to the superstructures on both projects was robust and was of desired quality i.e. the “risk” was minimal and the contractors were satisfied with both the delivered product and the order of in which the casting was performed. Hence, the castings of the superstructures on both projects were carried out in shorter time and could have been carried out using fewer personnel than planned with traditional concrete.

Probably the largest benefit with using SCC is, as mentioned earlier, the improvement in working environment. Therefore, the economy of the Swedish construction industry and society can benefit significantly from using the right kind of working method during construction. For the year 2004 1342 sick leaves were reported due to ergonomic risk factors. If these sick leaves costs as much as expected above e.g. € 4600 per sick case, the total costs ends up on roughly € 6 170 000 annually! This is according to Lean Construction a great deal of muda, which in this case is muda for the society.

To be able to utilize the redundant personnel during casting of SCC, projects need to be planned and managed properly. Hence, the organisation at the worksite needs to be optimized during the whole project, clear work instructions need to be formulated for all workers involved for all work tasks to be performed. Also, a list of buffer work needs to be logged so that workers can be

temporarily occupied with other productive work tasks during casting but still within reach if needed during casting.

## **5.5 Summary of paper V**

### **Title and Authors:**

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

Peter Simonsson and Mats Emborg

### **Published:**

Journal paper in the Nordic Concrete Research, 2008. To be published during 2008.

### **Research questions in focus:**

This study deals with two full scale projects, also addressing nearly all of the research questions of Section 1.3.

### **Key words:**

Industrialization, Lean Construction, Productivity, SCC, Prefabrication, Reinforcement

### **Background and Purpose:**

The industrialization level is low in the construction industry. The purpose is to study how philosophies according to Lean Construction could support the development of a more industrialized process especially for cast in place concrete construction.

### **Methods:**

Application of Lean Construction philosophies on two full scale bridge construction projects. Documentation of methods used during the design and planning phase of the first full scale project, and documentation of the production methods used at both construction sites. Comparing and verifying of achieved results at the first full scale project with the second project.

### **Summary of main contents:**

The implementation of SCC together with to new reinforcement and form techniques makes it possible to increase the degree of industrialization at construction sites markedly. Lean Construction principles prove to be important utensils to realize this during the planning and design phase as well as during the construction of full scale projects. For the first full scale project where the new techniques were applied, it was concluded that the production time at site could be reduced with up to 20 % and that the number of workers could be reduced by virtually 25 %. The second full scale project showed more the impact of the self compacting concrete.

### **Research results and scientific contribution:**

The full scale projects was 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 second case, 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 change were limited. Thus, there were only a few roles of rebar carpets used and the higher strength of the concrete was not considered in design.

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.

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, but had there 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. 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 to not increase the total costs all the benefits of SCC needs to be implemented.

The research showed that 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.

Finally, it was concluded in the project that, 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.



## 6 DISCUSSION

### 6.1 Concluding remarks and research questions

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 a larger part of a highway project 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.

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. 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.

Important findings from the project are that the working environment was recorded to be three times healthier when prefabricated reinforcement and SCC was used. Moreover, 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.

An important conclusion of the project is 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. Without establishing the Lean Design Team, applying Lean tools, the success level of the first project had not been that high.

Initially in this thesis, five research questions were formulated, and it is concluded that by utilizing the Lean construction philosophies and the experiences from the studies, answers can be given to each question as follows:

1. How can the entire (construction) process for constructing bridges be industrialized?

Introduce “new” production methods and design for constructability as well as establishment of a Lean Design Team early in the project.

2. Which benefits can be generated by industrialization?

Shorter construction time, improved working environment, less wastage in material and time. An increased profit margin and increased quality.

3. Are there any hindrances to an industrialization of the process?

An improper design phase initiated late in the process. Lack of long term relationships between involved actors. Rules and regulations might be a hindrance.

4. How can “new” production methods be implemented in the design process, and how can this be encouraged?

Clearly market the new methods by successful reference objects and elucidate economical benefits and improvements of the working environment.

5. How does SCC contribute to industrialization in construction?

SCC encourages faster casting procedures, less workers needed, and a clearly improved working environment. Also, a new organization on the construction site can be established.

The research questions are further developed in the papers.

## 6.2 Future research

Most important for future research is that the findings of this project need to be verified at a larger number of civil engineering projects of different sizes and structural types. Especially, the potential of a larger project with a several involved bridges where beneficial effects of standardization and repetitive work can be studied.

However, according to the authors opinion also the following research issues are of large interest in future research:

The robustness of SCC is one prerequisite for industrialization as well as clearly the defined criteria; this should be further examined and developed in future research.

Methods for a scientific grading of the working environment (work posture, force and repetition) like the used ErgoSAM model, should be further verified for the construction industry.

The potential of prefabricated reinforcement should be examined for other types of structures than bridges.

Left form systems have shown a large potential in house construction which can be anticipated for civil engineering and needs to be examined.

A model for how the Lean Design Team should be established and function during all the stages of a civil engineering project. Possible tools for the Lean Design team should be concretised.

The use of 3D and 4D planning tool (also BIM Building Information Model) for industrialization in civil engineering needs to be developed and analysed.

Models and methods applying Lean tools on site can be established e.g. for documenting waste, value flow and value creation.



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## **PUBLICATIONS**



**Paper I**



# EVALUATION OF A GPS SUPPORT SYSTEM FOR FLEET MANAGEMENT CONTROL

Peter Simonsson<sup>1</sup> and Jonas Carlswärd<sup>2</sup>

## ABSTRACT

Delivery precision and fleet optimisation are highly prioritised within the ready mix concrete industry. Introducing a Global Positioning System (GPS) system for logistic steering and planning provides a tool to make improvements on these areas. Such a system is presently under evaluation at a ready mix concrete supplier in Stockholm, Sweden. The system consists of GPS receivers in the trucks that send relevant information via the General Packet Radio Service (GPRS) net to a server.

A direct effect of implementing a GPS system is that the plants and the order central will be able to better control the whereabouts of the concrete trucks. As a result it will be possible to decrease the waste time at the plants. Another result is that the ratio of usage of concrete trucks will increase, leading to cut-downs in the truck fleet. It is further believed that the lead-time at work sites can be reduced as the delivery precision is improved. By eventually letting the contractor be a part of the system the possibilities for a good production planning at the work site will increase and the non-value adding activities will decrease due to reduced waiting time.

The article presents findings from a pilot study in Stockholm, Sweden. An important ambition is to find out if the system gives the expected benefits. The customer value is evaluated through interviews and time measurements.

## KEY WORDS

GPS system, Waste time, Fleet Optimisation, Non-Value Adding Activities, Pilot Study, Production Planning.

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<sup>1</sup> MSc., Department of Civ. and Env. Eng., Technical University of Luleå, 971 87, Luleå, Sweden, Phone +46 (0)920-491000, peter.simonsson@ltu.se

<sup>2</sup> MSc., Betongindustri AB, Liljeholmsvägen 30, 100 74 Stockholm, Sweden, Phone +46(0)86256200, jonas.carlsward@betongindustri.se

## 1. INTRODUCTION

In recent years the demands have been increasing on the actors of the building industry to develop the building process in order to improve the productivity and cut costs while maintaining or even increasing the quality. Possible solutions have been debated in several reports and surveys in recent years according to Jonsson (2005). A general hypothesis today is that the degree of industrialization within the building process needs to be increased. Inspiration is often sought in the manufacturing industry, e.g. the concept of lean production as described in Womack, Jones and Roos (1990). An important question is how to adopt the concept in the building industry. In other words what is required to achieve an industrialized process?

Main characteristics of an industrial building process are according to Olofsson et al (2004) and Lessing et al (2005) a higher degree of collaboration between partners, design of standardized solutions and technical concepts, an increased use of pre-manufactured highly processed components, improved effectiveness of the logistics and adoption of information technology. It can thus be concluded that industrialization is not synonymous with the utilisation of pre-manufactured components assembled at the building site, even though the association is common. However, there are increasing concerns within the ready mix concrete industry that market shares will be reduced as large contractors take efforts towards industrialization. The only way of survival is then to join the development according to Emborg (2005).

A number of developments that will take the in-situ cast concrete in this direction are pointed out in Byfors (1999). Examples are to increase the degree of prefabrication by replacing traditional formworks with non-removable ones in which the reinforcement has been pre-installed, to minimize the reinforcement work at site by adopting the steel fibre concrete technology, to increase the degree of mechanization regarding the handling of concrete at site and to eliminate the compaction work by using self compacting concrete. Some of the suggestions, such as non-removable formworks, steel fibre reinforced and self-compacting concrete, are used successfully today on a regular basis while some are still to come. This means that measures have already been taken to establish a more industrialized process for site-cast concrete.

However, in order to be competitive in the future it is further essential for a ready mix concrete firm to be more cost effective. Considering that transport costs are the most significant after the cost for materials it is realized that rationalizing the transports is a high priority. It is anticipated that the introduction of a new tool for fleet management control based on the Global Positioning Satellite (GPS) system will have positive effects. Expected improvements are e.g. that the efficiency of transports increases and that waiting times at the production facilities are reduced. Another expected result is that the waste time at construction sites decreases, as real time information on the whereabouts of the concrete trucks is made available.

A GPS system is at the moment under evaluation at the Swedish ready mix concrete producer Betongindustri AB. The analysis is conducted partly on the basis of data collected from an ongoing pilot study and partly on a theoretical discussion on expected effects when introducing such system in full scale. The ambition is to see whether or not the information flow to the company and from the company to the customers can be improved. Also important is to show that the enhanced information results in improved productivity in the supply chain.

## **2. PRESENT SITUATION**

### **2.1 ORGANISATION**

Betongindustri AB is a ready mix concrete company owned by the international building material conglomerate Heidelberg Cement Group. Betongindustri AB operates a total of 41 plants, serving major parts of the Swedish market with ready mixed concrete. The number of employees is approximately 230 and the yearly turnover is around €50 million.

A business concept of Betongindustri AB is to have production facilities close to the customers, which improves the delivery precision and limits the environmental influence by reducing transportation distances. In the Stockholm area there are a total of seven plants run by Betongindustri AB. A positive effect is of course that it facilitates an optimisation of transports in the region, as each concrete order can be placed on the geographically most favourable production facility. At the same time the planning process gets more complex as the number of plants increase, thus implying that more intelligent systems are required for transport coordination.

About 50 trucks each day are utilised by Betongindustri AB for the distribution of concrete on the Stockholm market. Approximately half of the truck fleet is company owned while the rest is hired from transport logistics firms. Betongindustri AB also runs a fleet of concrete pumps, to be used for in-site transportation of concrete. The motivation for keeping a high degree of concrete trucks and pumps within the company, which is unusual in the ready mix concrete market, is to be able to offer customers the best possible delivery service.

### **2.2 SUPPLY CHAIN**

The in-situ placed concrete industry is to a high degree characterised by “pull” behaviour in the sense that the customer controls the delivery chain. This implies that the logistic process of the ready mix concrete producer needs to have a high flexibility. The reason being that concrete is a fresh product that cannot be stored on the construction site. In other words it is necessary for the contractor to be prepared to receive and use the concrete at the moment it arrives at site.

An illustration showing the supply chain that a ready mix concrete company take part in is shown in Figure 1. The first link in the chain is that a customer contacts the order reception, specifying the quality and quantity of concrete to be delivered at a certain place at a certain time. The order reception will check for available resources to meet the specific demands put by the contractor. After acceptance the order is assigned to the most suitable production facility, generally corresponding to the one closest to the site of delivery. The order is further registered in FNG (Fabian Next Generation), the order and invoice system used at Betongindustri AB. A truck-planning list is then established, containing information on the number of trucks as well as to which plant each truck should report the following day. The information on the list is recorded on an answering machine and made available to the drivers the evening before delivery.

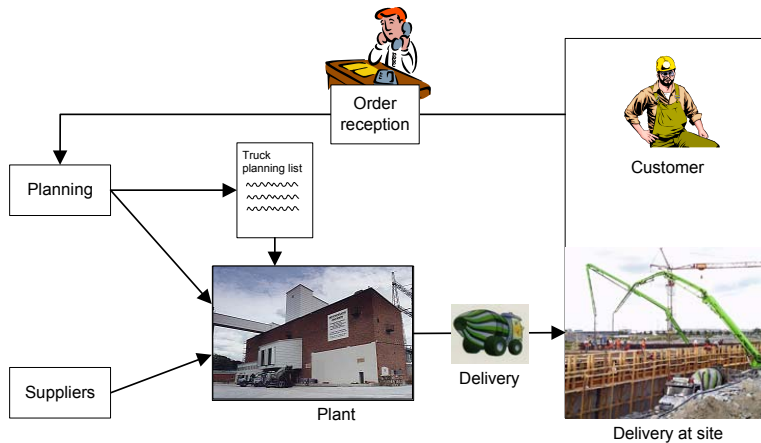


Figure 1: Illustration of a typical regional supply chain for in-situ placed concrete.

Each production unit then has the responsibility for the local planning, in other words to see that the required materials for the production are available in sufficient amounts and to utilise the designated transport resources as effectively as possible. Regarding the inbound supply of raw materials to the plant it can be said that it mainly consists of large amounts of cement and aggregates, the main constituents of concrete besides water. Moreover there are numerous additives and additions, such as fillers, fibres, plasticisers, air-entraining agents, shrinkage reducers etc, which may be utilized in order to achieve specific qualities of the concrete. The large amount of materials that can be used is one of the reasons as to why there are up to and sometimes even above 200 recipes at a production unit. Depending on the type of concrete produced the time required to mix a batch of concrete is between 5 and 10 minutes.

Upon acceptance the plant manager assigns a specific recipe to the order, after which it can be delivered. The computer system utilized at the plant today is connected to the order system, in which relevant information regarding the deliveries is stored. This means that the time to start mixing a batch of concrete is automatically estimated based on mixing time for the specific type of concrete and the transport time required to the construction site. In case of a delay in a delivery consisting of more than one truck, the computer system will recalculate the initiation time for the next batch so that the delivery interval can be kept.

Important to mention is further that the real time planning of the fleet is manually controlled today, implying that it to a high degree relies on the experience of isolated individuals. Contacts between plant personnel and truck drivers are provided for through radio communication units.

### 2.3 ANALYSIS OF THE LOGISTIC PROCESS

As mentioned previously Betongindustri AB has production facilities at several positions in the Stockholm area. This can be seen as a strategic advantage as compared to most of the competitors, thus implying that transport costs can be reduced as the average distance to the customer decrease. The nearness to construction sites also reduces the sensitivity to

traffic disturbances implying that supply safety can be improved. There are furthermore environmental aspects that are worth mentioning in the context.

However, in order to be able to draw full benefit from the situation it is essential to be able to optimize the truck fleet, preferably on a real time basis. This is not possible today, mainly due to the lack of information in the various parts of the supply chain. The nature of the information that is missed as well as a discussion on how a Global Positioning System (GPS) is expected to contribute is provided in the following sections. Most of the information provided in the following sections is based on a previous report of Ögren (2004).

### 2.3.1 Order reception

As mentioned previously the order reception has the responsibility to assign orders and transport facilities to the plants at least a day in advance. A problem that the planners meet is the daily variations in the demand. The distribution of loads in percent over the day as obtained during the pilot study is shown in Figure 2. Ordered delivery times are compared to actual or measured. It can be seen that the ordered deliveries has a maximum early on and is then successively decreasing during the rest of the day. This means that more trucks are generally required in the morning than later on. Thus in order to be able to fulfill the early transports on time it is necessary to plan for excess capacity during the remaining day, if optimization is only conducted at plant level. However, when comparing with actual delivery times it can be seen that there is rather a lack of capacities early on. Approximately 36 % of the daily deliveries were actually carried out between 6 and 9 am to be compared with the ordered ratio of 45 % during the same period. This means that in average 9 % of the deliveries were postponed, possibly due to a lack of trucks.

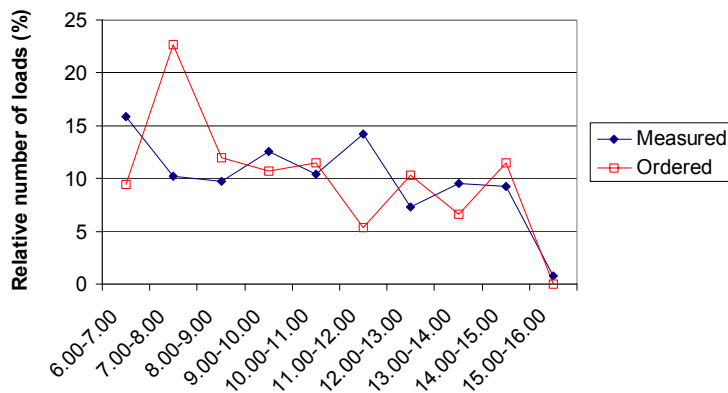


Figure 2: Variation of delivery times over a day evaluated during a four-week period. Ordered times are compared to actual measured delivery times.

The only way of solving this situation is to increase the cooperation between the production units aiming at minimizing the waste time for the trucks. In other words if resources are available at a plant while a lack appears at another trucks should be redirected. This is rarely the case today as the main objective for the plant manager is to

first make sure that sufficient resources are available to be able to provide good service to the customers of that specific plant rather than sharing the resources with other plants.

A more advanced system for fleet planning is required in order to steer the transport facilities in real time. The focus must be to take care of the interest of the company as a whole rather than at each plant as an isolated unit. It is anticipated that the GPS system will provide such possibilities, implying that the productivity of the transport fleet can be increased.

### **2.3.2 The production process**

The responsibility of the production unit is to produce and deliver concrete to the customer using the resources made available the day before by the order reception. As a concrete truck is expensive to hire there are rarely excessive trucks available on the plant yard. This implies that the logistic process is extremely sensitive to disturbances. There are further a number of variables that makes the planning at the production unit rather complex.

A transparent overview of the truck fleet is not provided by the present system for information sharing. A consequence is that mixing cannot be initiated until a truck has arrived back to the plant, which results in unnecessary waiting times. The considerable number of concrete recipes available as mentioned previously is another variable that affects the planning. Thus, when a truck returns from a delivery it is necessary to first check if the truck carries any excess concrete. In case of, the truck container needs to be cleaned before the truck is available for a new batch, a process that requires a time of approximately 10 minutes. The exception is when the old concrete is of a similar concrete quality as the new one, in which case it may be possible to fill the truck directly. The solution is clearly a system that gives continuous information on the position, identity and status of trucks.

It is also important to mention the high degree of customer control, which puts high demands on the flexibility of the planning at the production unit. Changes of the specifications of an order, regarding for instance volume or unloading time, can be made just prior to or during a delivery. Today such changes often result in disturbances. The use of a more transparent planning tool would give the plant manager possibility to check for available resources at other plants and thereby minimize the disturbance.

With the present manual communication system it is further not possible to give customers real time information on the exact positions of the trucks. Considering that a contractor relies on high precision in the deliveries of concrete this is a major drawback. In case of adopting a GPS system it will be possible for customers to access the digital map via Internet and check for the positions of the trucks. The waste time at the construction site may then be reduced, as less time will be spent on waiting for the concrete delivery.

## **2.4 CUSTOMER VIEW**

When analyzing the efficiency of the logistic process it is further essential to consider the opinion of the customers. A customer survey is conducted every other year at Betongindustri AB, in which about 300 customers are asked for opinions on a number of issues. A selection of results from the enquiry conducted in 2003 is shown in Figure 3. Diagram (a) illustrates performance and importance while diagram (b) shows the so-

called GAP-values, corresponding to the difference between performance and importance. The GAP-value is a measure on how well the performance of Betongindustri AB coincided with the importance as perceived by the customer. In the context it is important to mention that a GAP-value of between  $-0,5$  and  $0,5$  is recommended. A value that falls outside the limits simply implies that the service is either unnecessary high or low. Importance-performance analysis has previously been utilized to evaluate the supply chain performance of the transport logistics industry, Lai et al (2003). In the study it was found to be useful for assessing the service effectiveness of transports.

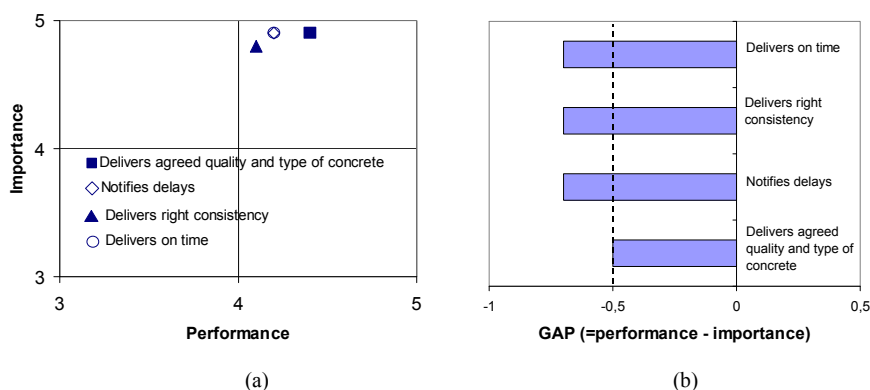


Figure 3: Selected results from a customer survey conducted in 2003. Performance and importance are shown in (a) while the GAP-values are shown in (b).

When studying the results shown in (a) Betongindustri AB appears to perform rather well as 4 equals fairly good performance/fairly important and 5 equals very good performance/very important. However, based on the GAP values shown in the other diagram it can be seen that an even higher service degree should be strived for.

To improve the service level on deliveries and consistence is thereby continuously highly prioritised. Nevertheless it has proved to be extremely difficult to improve the GAP-values. One reason is most certainly that the present system for information exchange in the logistic process is not sufficient.

### 3. THE GPS SYSTEM

The utilisation of GPS-systems is common in businesses such as grocery and material delivering firms, taxi companies, police and ambulance transport etc. There are further examples of ready mix concrete companies in e.g. France, UK and the US that have introduced such system.

The experience within the building sector in Sweden is more or less restricted to a theoretical evaluation on the utilisation of GPS in different applications, Nilsson et al (2003). A result of the study was that a mobile support system based on GPS was introduced to increase efficiency of asphalt deliveries at the Swedish contractor NCC. For the ready mix concrete industry in Sweden however such systems has not yet been adopted even though several firms are evaluating different possibilities at the moment.

### **3.1 TECHNICAL FUNCTION**

The mobile support system under evaluation consists of GPRS-modules and GPS-receivers that are placed in the concrete trucks. The GPS-receiver determines the vehicles position and transmits the information to the receiving unit, e.g. a concrete plant.

### **3.2 MOBILE MAP SUPPORT**

Construction sites and plants are symbolized on a digital map transmitted via Internet as zones that are introduced in order to be able to sort out valuable information. When a truck passes a boundary to a zone a message is sent to the receiving computer with information on truck identity and status. Automatic data is then collected regarding transportation time, time of arrival at the construction site, waiting time at the construction site and time for unloading.

Typical status reports are “towards customer”, “towards ready mix plant”, “towards ready mix plant carrying excessive concrete”, “not accessible”, “disabled truck” or “available resource”. Such information will clearly give the involved personnel a better real time overview of the fleet. An anticipated result is that the planning at plant level becomes better as reliable information is made available on the status of the trucks. It will also be easier for plants to share resources and for the order central to make changes in the fleet in real time when necessary. The statistics regarding the use of the transport fleet will further be more correct in the future. It should be mentioned however that in the pilot study positioning and identity are the only services provided.

### **3.3 ADVANTAGE OF A GPS SYSTEM**

The main motivation for introducing so called wireless fleet management solutions is typically to increase the efficiency of a transport fleet and to improve customer satisfaction. For instance, in an internal periodical report Ralph (2003) states that optimisation of delivery efficiency while maintaining a high level of customer service is an expected effect of introducing a satellite-based truck tracking system at the US concrete producer Lehigh. It is expected that the amount of non-productive time spent waiting in the yard or at site can be reduced so that more time is available to actually deliver and pour concrete. The positive effects are believed to come from the fact that more accurate information is made available when and where it is needed. The ability of the system to actually increase productivity has further been verified by the French producer RMC Beton. After introducing a wireless truck tracking system including status reporting a remarkable increase in efficiency of each truck was noticed. Instead of four deliveries a day each truck could take on five.

Thus, more value is added and more relevance is given to the information, factors that will make the company more effective. In order to fully benefit however it is necessary to also include the order and invoice system. Combined with equipment that enables printing and electronic signing at site this would reduce the administration significantly. In the long run it is further likely that a mobile support system is introduced in the whole logistic chain from raw material supplier all the way to the customer.

In Ögren (2004) an analysis has been conducted to estimate the time to recover the investment. It is assumed that the implementation of the system in full scale will result in a reduction of the truck fleet by one truck each month, which is a rather low estimate. This results in an ROI (Return On Investment) time of approximately 10 months. The

relevance is further verified by follow-ups conducted by the Canadian firm Ocean Concrete in Vancouver. After one and a half year of using a GPS based system it was concluded that the investment was recovered in only about 13 months as compared to the expected ROI time of 24 months.

#### **4. PILOT STUDY**

The pilot study was conducted at one of the ready mix concrete plants of Betongindustri AB in Stockholm. Six concrete trucks were involved along with a few service vehicles. As mentioned previously the pilot study, which went on for a four-week period, only enclosed positioning and truck identity. Rather than showing the advantages the intent was to verify the function of the system, consisting of software, GPRS modules, GPS receivers and hand computers. Another ambition was that some of the staff should be given the opportunity to evaluate it during a few weeks.

Nevertheless data regarding e.g. usage of the trucks during the evaluation period was actually collected although any major positive effects were not expected at this stage. The intent was rather to show that there are deficiencies in the present system for logistic steering.

##### **4.1 GATHERING OF DATA**

A substantial amount of information is generated in the GPS-system. Data regarding the position of a truck is gathered every 20 sec. However, only a minimum of the information is relevant. Thus, the zone system as mentioned previously was adopted to be able to sort the data. This means that construction sites and concrete plant have been predefined with a position and a radius on the digital map. Data on times when trucks passes into and out of a zone can then be stored and analysed. Examples of results from such analysis are transportation time, unloading time and time at ready mix concrete plant.

##### **4.2 EVALUATION OF DATA**

###### **4.2.1 Delivery efficiency**

A high degree of usage of the concrete truck fleet is clearly a high priority. Follow-ups conducted in 2003 indicated that the average effective time of a concrete truck, i.e. transport + unloading time, is only just above 4 hours per day. A considerably higher degree of usage was obtained in the pilot study as shown in Figure 4. The reason is however more likely to be due to experienced staff and a favourable order distribution over the day rather than due to the GPS system. In the diagram the average effective time of trucks equipped with GPS is compared to the corresponding time for trucks without GPS at the same plant. In order to be able to make such comparison the data used was collected from the present system, i.e. based on manual registration of times. It should be mentioned that the automatically obtained data from the GPS system gives an average time that is 30 minutes longer. This indicates that the effective time is typically overestimated today.

When studying the results shown in the diagram an average usage of approximately 6:30 hours was obtained for the trucks equipped with GPS at the end of the study as compared to only 6:00 hours for trucks without GPS. This indicates that although not fully implemented the GPS system has contributed to an increased usage.

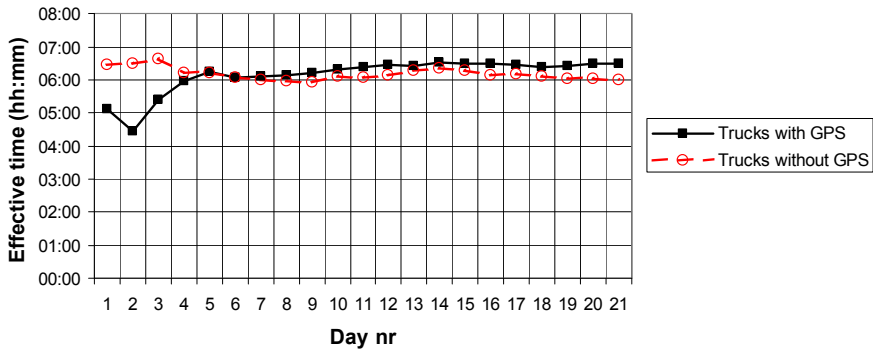


Figure 4: Average effective time, time at site and transport time of the trucks involved in the pilot study.

#### 4.2.2 Waiting times

An expected result of the introduction of a GPS based planning system in full scale is that the waiting times can be minimized. This is mainly due to the more transparent planning provided, which makes it easier to prepare for upcoming loads. Waiting times at the plant for the trucks included in the pilot, i.e. equipped with GPS, were compared to the corresponding times for trucks without GPS at the same plant and during the same period. As in the previous section the comparison was enabled using the existing system for data collection, which means that times registered by the drivers were used. Results showed that the average waiting time for trucks with GPS was 5 minutes shorter, 28 compared to 33 minutes. This is yet another indication that the productivity was in fact slightly increased in the pilot although this was not the prime intent.

#### 4.2.3 Delivery precision

With the term delivery precision the intended interpretation is to which extent a product or service is delivered to the intended customer at the agreed point in time. As Betongindustri AB to a high degree is working with customer order steering such measurement is of great importance. Delivery precision is a parameter that is and will be relatively easy to measure. Today the precision is obtained simply by interpreting noticed time for arrival and departure from the construction site on the invoice. In the future however this kind of information can be achieved directly from the GPS-system, when fully implemented.

Transportation deviations in the pilot study show that there are problems with maintaining agreed delivery times, Figure 5. A positive deviation is a delay while a negative value indicates that the truck arrived early. It is important to note that a deviation does not necessarily imply that the truck arrived at the construction site at the wrong time. Particularly in case of extreme deviations it is more likely that an unregistered agreement has been made between contractor and plant manager.

Nevertheless, rather poor results were obtained in the pilot study. Only about 30 % of the deliveries arrived within the interval set up by Betongindustri AB, i.e.  $\pm 5$  minutes, compared to an ambition level of 95 %. Approximately half of the remaining 70 % of the

trucks was late. Disturbances in deliveries early on in a day are a possible explanation for the delayed loads. This would cause problems even for later deliveries due to reduced transport capacity. Based on evaluations conducted within the study it was also concluded that actual unloading times were in average 10 minutes longer than ordered. This is another reason as to why it is difficult to keep the agreed delivery times for succeeding loads.

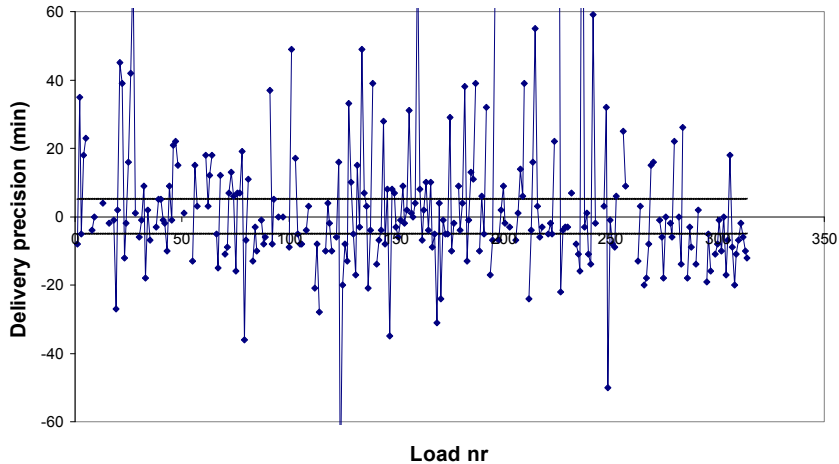


Figure 5: Transportation delays for trucks involved in the pilot study.

Contrary to the results shown in Figure 5 it is a general opinion at Betongindustri AB that the delivery precision is rather good. For instance, in follow ups conducted in recent years the goals have typically been reached, i.e. 95 % within  $\pm 5$  minutes. It is thus suspected that incorrect data is frequently entered in the present manual system, as was also indicated in section 4.2.1. A possible reason is that delivery precision is bonus related.

## 5. DISCUSSION AND CONCLUSIONS

Next after cost for raw material the most significant cost for a ready mix concrete firm is the ones associated with transportation. Delivery is further an important part of the product and the associated service. An ambition is to maintain a high degree of service and make it as efficient and cost effective as possible. It is anticipated that this is achieved when introducing a GPS based system for fleet management control.

Expected positive effects are e.g. an increased degree of usage on the trucks and concrete pumps and a higher number of deliveries at the agreed time. The system is further expected to bring more valid information to the customers giving them real time notification on the positions of the trucks. A positive effect is that the customer will be able to see at an early stage if a delivery is delayed. Thereby it is possible to make a change in the planning of the personnel activities. This gives Betongindustri AB a better customer focus and will lead to better productivity at the construction site due to less waiting time. The map system will further aid the drivers in planning the route to the construction site, thus resulting in less transportation time and better delivery efficiency.

Although the intent of the pilot study was more or less to verify the functionality of the soft- and hardware some conclusions can be drawn based on results from the rather limited pilot study. Firstly, it was shown that the efficiency of concrete deliveries was slightly increased, possibly due to the GPS system. The average usage time was approximately 30 minutes higher for trucks with GPS as compared to trucks without. Secondly results showed that waiting times were in average 5 minutes shorter per delivery for trucks equipped with GPS. For a single truck this may not seem much. However, it can result in savings corresponding to one or several trucks considering a fleet of 50 trucks that are delivering up to 5 or 6 deliveries a day.

Important to mention is also the fact that the automatically generated data in the GPS based system is more reliable than the manually obtained as used today. This is important since many decisions are based upon statistics analysed from the data.

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**Paper II**



# **INDUSTRIALIZATION IN SWEDISH BRIDGE ENGINEERING: A CASE STUDY OF LEAN CONSTRUCTION**

**Peter Simonsson<sup>1</sup> and Mats Emborg<sup>2</sup>**

## **ABSTRACT**

The purpose of the project has been to evaluate and possibly improve the degree of industrialization and productivity when constructing bridges in full scale. Earlier theoretical studies have indicated that, if prefabricated reinforcement, self compacting concrete (SCC) and permanent formwork are used the degree of industrialization can be increased markedly. To be able to realize this, Lean Construction principles prove to be important utensils during the planning and design phase as well as during the construction of a full scale project.

Throughout the design and planning of this first full scale bridge project, intensive contacts between designer, contractor, client and material suppliers were established. The design team concluded that the production time at site could be reduced with up to 20 % and the number of workers could be reduced by virtually 50 % during almost half the project. This was realized by planning with Last Planner ideas, and designing the project properly using modern construction tools and materials. The design team also concluded that if the concrete class increased some of the very dense shear force reinforcement could be left out.

The evaluated outcome of the demonstration project, i.e. potential productivity improvements, structural quality improvements, immediate feasible waste and cost reductions and the positive impact on the working environment, shows that the predicted benefits made were fulfilled.

**KEY WORDS** Bridge design, Concrete, Productivity, Industrialization, Lean, Waste, Logistics, Full scale test, Prefabrication, Reinforcement

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<sup>1</sup> Ph.D. Student, Div of Structural Engineering, Luleå University of Technology, 971 87 Luleå, Sweden  
Phone +46 920 493140, FAX +46 920 491913, Peter.Simonsson@ltu.se

<sup>2</sup> Professor, Div of Structural Engineering, Luleå University of Technology, 971 87 Luleå, Sweden (see above), Head, research and development, Betongindustri AB, SE 100 74 Stockholm, Phone +46 8 6256200

## INTRODUCTION

The productivity of the building sector has been low when compared to other sectors, e.g. the manufacturing industry. *Industrialization* is often mentioned as the measure to be taken to increase the productivity and its definition is frequently debated in literature. It is agreed however 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 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 (Olofsson et al, 2004) and (Byfors, 1999). Now, strong efforts are being taken by contractors towards industrialization and, the introduction of new methods to improve the design and planning processes as well as the production process are of great interest.

The platform for Lean Construction is simple: to deliver what the customer wants when he needs it in the quantity that he requires. A key issue is then the focus on the well known “muda”, i.e. any human activity that absorbs resources without creating any value (Womack and Jones, 2003). 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. Another key criterion for Lean Construction is that downstream actors are involved upstream in decisions and vice versa. This means that stakeholders must involve contractors, material suppliers etc. as early as possible in a project maintaining a good contact throughout the entire project. This contact ensures that products and processes are designed in collaboration between partners.

Several tools and methods are 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 (Olofsson et al, 2004).

For the industrialization of construction with in-situ cast concrete focus must be on the following six components, (Figure 1):

- Improved concrete qualities and optimal construction e.g. SCC.
- 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.

## OBJECTIVE OF THE RESEARCH PROJECT

The following general research questions have been defined of the PhD research project “Industrial concrete bridge construction” at Luleå University of Technology:

- Who owns the industrialization question?*
- When should the industrialization process start?*
- How should industrialization be implemented in the design and construction phase?*
- What are the existing problems, if any, hindering the introduction of industrialization?*

-What are the main obstacles for introducing Lean Construction, and can industrialization be introduced applying lean construction in civil engineering?  
 -Where can we find new solutions for existing problems?

Further more it is known that the earlier in a projects design and execution phase industrialization ideas can be introduced, the greater the influence will be, Table 1.

Table 1: Typical process for construction of larger civil engineering structures, e.g. bridges, and necessary early introduction of industrialization.

Phase	Preliminary study	Feasibility study	Design plan	Purchasing	Building documents	Execution	Operation/maintenance
Remark	Needs, demands etc	Alternative routes	Designing the layout	Entrepreneur involved	Detailed design		
Outcome		Collaborate bridge types  Aesthetics within limits  Create conditions for industrialization	Geometrical prerequisites, Banking → cambering etc  Create conditions for industrialization  Aesthetics etc	Supply conditions Matrl conditions	Documents	Building process	Continued collaboration between contractor and client?
Possible influence industrializ		Important step for industrialization! Most influence	Important step for industrialization! Less influence	Important step for industrialization! Less influence	Might be too late!	Too late	

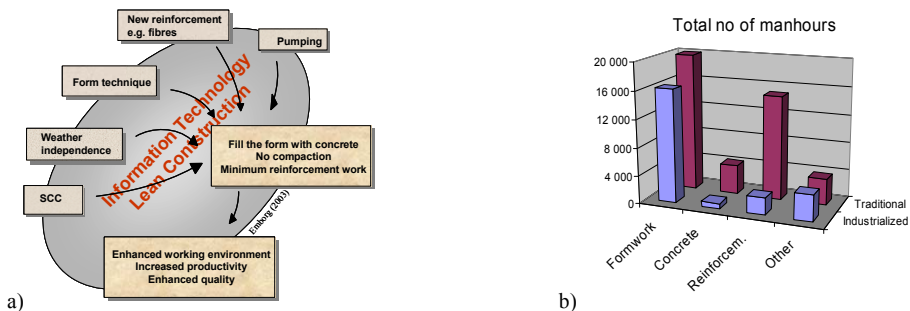


Figure 1: a) Industrial site cast construction by integrating material and production techniques with IT and Lean Construction (Emborg et al, 2005) b) Theoretical on-site time savings when applying industrial construction on bridge projects in Sweden (permanent formwork only partly).

## THEORETICAL PILOT STUDIES

One focus of the research is to see which parts of a bridge that can conveniently be prefabricated and which parts that must be manufactured traditionally on site. Therefore the project was initiated by following up some already constructed in-situ cast concrete bridges to identify areas where major advancements in production can be achieved. 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 (Simonsson and Emborg, 2005). The other 50 % of the costs is related to general establishment at the building site, foundation, pile driving, asphaltting, railing etc. From a purely theoretical viewpoint, the implementation of industrialized construction methods can reduce the manpower substantially for these bridges, Figure 1b. For instance, if

prefabricated reinforcement is used in the foundations and superstructure, the on-site construction time can be reduced with up to 80 %.

More over, besides the reduction of the number of man hours needed (Figure 1b), applying SCC will also increase the casting rates, and improve the working environment (Skarendahl, 2001).

## THE FULL SCALE BRIDGE – LEAN CONSTRUCTION PLANNING

### GENERAL

This part of the research, i.e. the full scale project is mainly dedicated to the two last research questions mentioned above, i.e. to examine what kind of possibilities of industrialization Lean Construction principles can provide when applied to civil engineering, and particularly to an in-situ cast concrete bridge project.

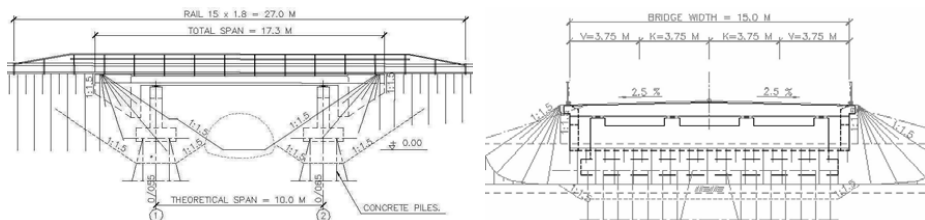


Figure 2: Full scale object in elevation and section (no scale).

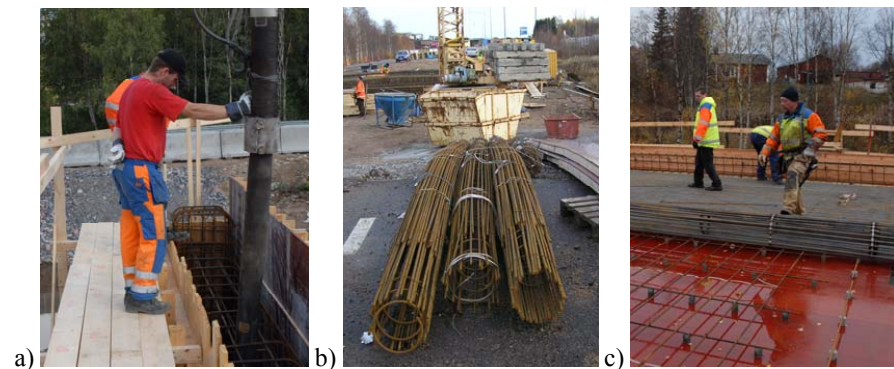


Figure 3: a) Filling the plate structures with SCC, b) Carpet reinforcement for the superstructure, c) Mounting the carpet reinforcement on the superstructure.

The studied bridge “*the industrial concrete bridge*” consists of a span of 10 metres with a width of 15 metres, Figure 2. A key for the success was that the owner, contractor, material supplier and designer cooperated during the complete project. Thus, already during the design phase the partners agreed that SCC and prefabricated reinforcement for the foundations and for some of the superstructure should be used. It was also decided that carpet reinforcement (Figure 3 b and c) were to be used for the super structure and that Lean Construction principles should be utilized during both design and construction phases.

## **BRIDGE DESIGN FOR CUSTOMER VALUE**

Customer value and satisfaction are central points in all types of production; as a result it is of great importance to understand customer needs and expectations before starting production. Crow and Barda, (2004) found in a study that contractors, designers and suppliers often focus on making profit instead of focusing on providing the end user service, this instead repeatedly has the opposite effect and results in economic losses.

According to Karlsson et. al (1998) it is important to implement/transfer customer needs and wishes into specifications for a product and let these specifications greatly influence the design phase of a project. The design documents ensure that the product will function as the customer requires. Considering customer value for a typical highway bridge project, the primary customer is the public. Specified value for a highway bridge is among other things: It should be trafficable, safe and comfortable at an appropriate velocity, have sufficient carrying capacity, and during construction cause as little disturbance on traffic as possible. It should be designed so that future inspection, maintenance and management are economical and easy to perform. The bridge should also be flexible for changes in traffic demand and it should harmonize with the surrounding landscape.

## **DESIGN PROCESS**

When establishing a team meeting these criteria, i.e. a Lean Design Team, for the proper planning and design of the bridge, it is of great importance to include all areas of interest for the studied project. Therefore, knowledge from production, design, management, customer, suppliers and 3D and 4D modelling should actively be implemented in the design phase together with a close relation to the customer. The project team has a few design aids and technical solutions mentioned above i.e. prefabricated reinforcement and SCC to choose from.

The main designer, the prefabricated reinforcement designer/supplier and the concrete supplier worked together in cooperation with the contractor 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, leading to a redesign of the bridge in order to find alternative solutions for improving the construction.

Concerning the superstructure, carpet reinforcement hasn't been used in bridges in Sweden earlier, since rules and regulations do not allow welding of the reinforcement exposed to stress variations over 60 MPa. It is however possible to calculate where those conditions are valid and redesign the bridge allowing for partly welded, and partly clenched carpet reinforcement as well as the shear reinforcement.

## **LEAN CONSTRUCTION PLANNING WITH A CROSS FUNCTIONAL WORKING TEAM**

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 for the project 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 both formwork and reinforcement as well as casting of concrete. This is of course dependent on the size of the project and for this

rather small bridge, the prerequisites for the workers were simply that they had to be multi-skilled.

### CONSTRUCTION PROCESS AND VALUE FLOW

Important for realizing industrialization is to identify the process and even out the flow, see Figure 4, where the process has been subdivided into four main parts: foundation, plate structures, superstructure and finishing works.

To be able to utilize the benefits of the different production methods evolved from the design phase, accurate planning is essential. Therefore Last Planner ideas, (Ballard, 2000) was considered to be valuable assets and also directly applicable in the project.

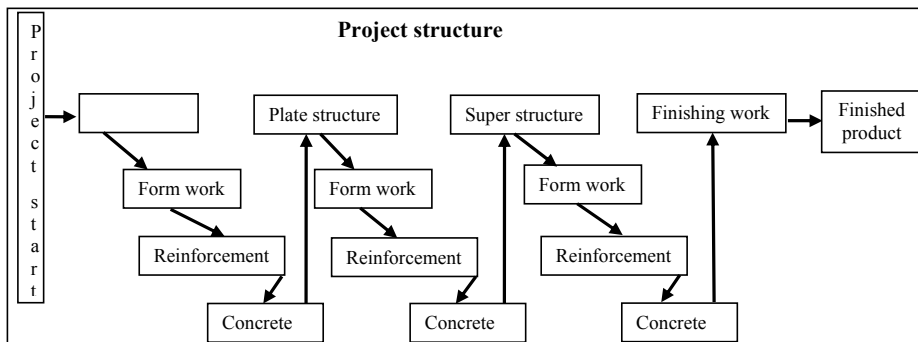


Figure 4: Project structure and activity flow scheme.

The contractor commenced construction of the full scale project in august 2006, and it was completed in November 2006 as according to the timetable. The involved number of workers shifted from 3 to 5 during the projects different stages.

As the contractor used a cross functional working team the instructions for the different working moments is of great importance. Therefore, standard operating procedure documents (SOPD) were created for everyone to use. Nakagawa (2005) suggests that SOPD is of importance for familiarizing the work in advance to the workers, for achieving the target duration and quality.

### RESEARCH ACTIVITIES AT SITE

To be able to follow up the activities at site, various measurements and observations were conducted. For instance the ability of the suppliers to deliver the ordered goods on time was measured; hence the logistics of the involved parties was examined especially the prefabricated reinforcement and concrete deliveries.

Another interesting measurement in the full scale project was the productivity measurement of particular workers during a few typical working days. Every other minute short notes were taken on what the worker was doing and why, giving a more exact picture of how much time on a typical working day the worker was adding value to the product and how much of the time that was type one or type two muda. Type one muda creates no value but is necessary with current technologies and the type two muda creates no value and is immediately avoidable according to the definition by Womack and Jones (2003). The actual time and personnel usage needed for the different working

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

## RESULTS AND EXPERIENCE FROM THE FULL-SCALE TEST

When arriving at the construction site the prefabricated reinforcement for the *foundations* were lifted and mounted directly into the formwork taking approximately one hour for both foundations together, see Figure 5a. Immediately afterwards the connecting reinforcement between the foundation and plate structure was mounted. A few hours later the same day the first foundation was ready to be cast with SCC and around lunchtime the subsequent day the second foundation was ready to be cast, see Figure 5b. All together this made it possible to save almost a week in onsite production time; see Table 2.

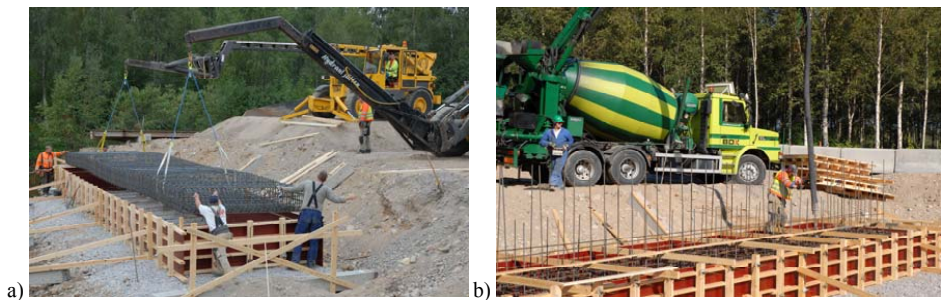


Figure 5 a and b: a) Placing the prefabricated reinforcement into the form work, and b) Casting of self compacting concrete for one of the foundations.

Table 2: Time needed for industrialization concept and traditional production for the foundations.

Foundation	Reinforcement		Concrete	
	Traditional	Industrialized	Traditional	SCC
Prodtime at site	5 days	1 hour	4,5 hours	3 hours
Craftsmen	2 persons	2 persons	4 persons	1 person
Total	80 hours	2 hours	18 hours	3 hours

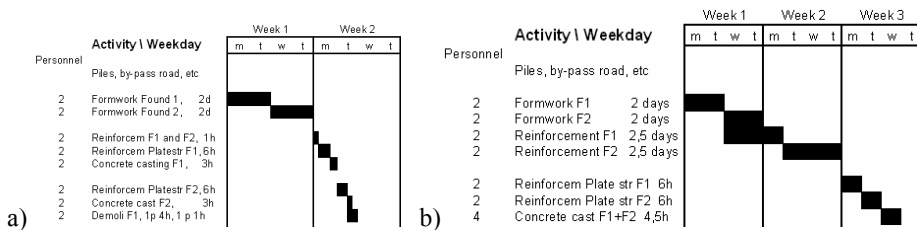


Figure 6 a and b: Gantt charts for the foundations, a) prefabricated reinforcement and use of SCC, and b) using traditional methods.

Casting the foundations with SCC released 3 persons for 4,5 hours in total 15 man hours in comparison with the traditional casting methods, see Table 2. These persons were able to make upcoming work ready for execution.

The reinforcement for the *plate structures* was constructed traditionally on-site and SCC was used reducing the workforce with 10 man hours in total.

The *superstructure* was constructed with carpet reinforcement both in bottom and top utilizing the benefits of new design of the shear reinforcement and the higher strength concrete. This resulted in a clear productivity increase during mounting of the reinforcement at site. Table 3 demonstrates the difference in time for carpet reinforcement and traditional reinforcement. The production time at site was totally only 5 hours for three persons as compared to 2,5 days for 4 persons which is thus a considerable improvement of the industrialization.

Table 3: Time needed for industrialization concept and traditional production for the super structure. \* = only reinforcement able to be changed to carpet reinforcement.

Superstructure	Reinforcement*		Concrete	
	Traditional	Industrialized	Traditional	SCC
Prodtime at site	2,5 days	5 hours	10 hours	7 hours
Craftsmen	4 persons	3 persons	4 persons	2 persons
Total	80 hours	15 hours	40 hours	14 hours

Furthermore SCC was used for the superstructure which released 2 persons and a total 26 hours, see Table 4, making it possible to divide the workers into two teams, working shift. The first team is responsible for casting the concrete and the second team is responsible for the curing. This guarantees that no tired workers are performing the curing of the concrete ensuring optimal quality of the end product. The reduction in resources needed for the concrete is 26 hours i.e. a 65% reduction in man hours and equipment usage e.g. rental costs and pumping costs in comparison to casting the concrete traditionally. Despite the large improvements on productivity achieved it seems that the degree of industrialization could be even higher. For example, during mounting of the rest of the reinforcement of the superstructure there were quite a number of wasteful activities performed. Hence the productivity study at site revealed that only 31% of the average workers day involved contributing to the finishing of the project, the rest of the time was divided into type one muda 26% and type two muda 43%, Figure 7.

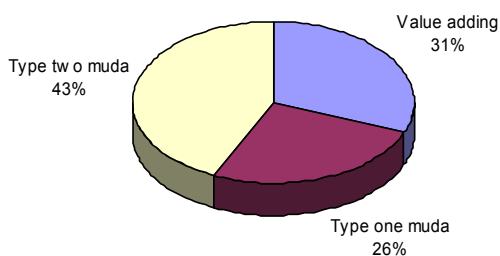


Figure 7: Productivity study superstructure for the reinforcement fixing, subdivided into direct value adding activities, type one muda and type two muda.

## CONCLUSIONS

This bridge could be constructed using less resources, less materials and less construction time both in theory and in reality, e.g. for the actual bridge the production time was

reduced, and the costs for construction were reduced. Moreover the bridge was constructed with a better and less stressful working environment, increased safety and less physical loads. A further discussion on working environment can be found in Simonsson and Rwamamara (2007).

The difference between the two production alternatives is typically demonstrated for the foundation and shows the importance of planning. It is clear that if construction of all structural parts of a bridge is planned and performed as shown in Figure 6 a, large reductions in production time and an increase in productivity is foreseen. To achieve these improvements it is vital to build up a confidence between involved actors to strive in the same direction. It is also important to build up knowledge on the material and processes used in the entire project. For instance, the contractor had no previous experience of SCC which led to some faults during the construction phase of the project, implying that possible benefits were not realized as anticipated.

### **STRUCTURAL QUALITY IMPROVEMENTS**

Overall the structure quality was improved due to less rectification work during construction, better quality of the built in material. The concrete quality was increased from a traditional grade C35/45 to C50/60 giving the designer the privilege of decreasing the amount of shear reinforcement in the superstructure thus reducing difficulties when placing the reinforcement and pouring concrete. As the reinforcement of the foundations was prefabricated and shipped to the construction site, the production of prefabricated reinforcement during settled conditions with accurate manufacturing tools minimized the chance of faults occurring. This was also valid for the carpet reinforcement, especially for the top reinforcement which can be very difficult and complicated to fix and it is also associated with larger risk of injuries for the workers.

### **IMMEDIATE FEASIBLE WASTE AND COST REDUCTIONS**

According to the productivity study, still clear waste reductions were present for the new construction approach that could be taken care of. The shear reinforcement for the superstructure did not fit in its place as it should. It was either assembled wrongly, designed with incorrect tolerances or manufactured with direct faults in the prefabrication plant. The rectification work done was pure waste i.e. of type two muda. No efforts from the contractor were made to clear up the cause of the mistake unfortunately.

Furthermore, the construction workers were uncertain of the best order to fit the reinforcement bars and some reinforcement bars had to be threaded in through holes drilled in the side of the formwork. This could thus easily be avoided if assembly instructions had been provided by the designer. In the future i.e. in the next full scale research project, a specific assembly order for the reinforcement in the superstructure is to be requested from the designer. It is also obvious that all parts involved in the project must take their responsibility to check the validity of drawings and other information before making work ready.

### **ECONOMY OF A LEAN CONSTRUCTION PROJECT**

The main reason for hindering the inauguration of new technologies or new thinking in projects is the uncertainty of the economy in a project. There is often a short period between purchase and commencing construction, and contractors most often give a fixed price on projects and therefore have limited possibilities of altering the production and

still be certain of the outcome of the economy in this short time. Hence, the possibility for new thinking is very limited.

On the other hand if there is no testing there will not be any development at all. Therefore in our research project the economy is of interest. As a summary the reinforcement showed approximately 4300€ in direct profits and a total of 78 man hours saved. Considering the economy for the concrete the benefits were negligible however the project were reduced with over 50 man hours. Indirect profits such as cost for establishment, equipment, better working environment etcetera are off course present but are difficult to estimate. Observing that this was the very first bridge construction of this type in Sweden the result is very positive!

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**Paper III**



# CONSEQUENCE OF INDUSTRIALIZED CONSTRUCTION METHODS ON THE WORKING ENVIRONMENT

Peter Simonsson<sup>1</sup> and Romuald Rwamamara<sup>2</sup>

## ABSTRACT

Traditionally, the working environment has been poor especially when it comes to steel reinforcement and concrete casting on construction sites. Industrialised construction methods such as self compacting concrete (SCC) casting and prefabricated steel reinforcement are creating a basis for an improved working environment. By using these methods, it is assumed that the cost for sick leaves due to ergonomic injuries and accidents are reduced as health and safety risks inherent to the traditional working methods are decreased.

Observations along with video filming and informal interviews were performed. With a sequence-based activity method ErgoSAM, an ergonomic risk analysis was conducted. The analysis showed that industrialised methods reduced ergonomic workload on concrete workers.

The industrialisation of the production process through the introduction of innovative construction methods has benefited the construction workplace environment as well as the customer value in terms of improved material handling, elimination of additional adverse affect on health of handling vibrating tools, reduced on site congestion and reduced over all material costs.

## KEY WORDS

Working environment, Steel reinforcement, Concrete casting, Industrialization, Lean construction

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<sup>1</sup> Ph.D. Student, Div of structural Engineering, Luleå University of Technology, 971 87 Luleå, Sweden  
Phone +46 920 493140, FAX +46 920 491913, Peter.Simonsson@ltu.se

<sup>2</sup> Ph.D. Student, Div of structural Engineering, Luleå University of Technology, 971 87 Luleå, Sweden  
Phone +46 920 492353, FAX +46 920 491913, Romuald.Rwamamara@ltu.se

## INTRODUCTION

The Swedish construction work environment is regarded as the safest in the world on the subject of physical health, working conditions, illnesses and accidents (Flanagan et al., 2001). Nevertheless, there are still work environment related health problems to be tackled. Stress and other mental strains at work present the most dramatic development in recent years in Sweden, but the most common cause of work-related disorders throughout a nine year period 1996-2005, has been the physical strain (e.g. heavy manual handling, strenuous work postures and short, repetitive operations) on the musculoskeletal system. In the construction industry more than one man in five, twice as many as for all men employed, reports musculoskeletal disorders of the musculoskeletal system. This corresponds to 50,000 men in Sweden. Musculoskeletal ergonomics studies concerned with the effects of work postures, working movements, physical loads and other conditions on the muscles and joints indicate that more than 1.5 million workers find their daily work ergonomically strenuous. In the construction industry this experience is shared by over 130,000 men, and it is obvious that musculoskeletal illness is the construction industry's biggest problem (69% of all reported work-related injuries in 2005). These injuries are caused by the so-called ergonomic risk factors, and the most common risk factors are heavy lifting, strenuous work postures and prolonged one-sided work (Samuelsson and Lundholm, 2006; Lundholm and Swartz, 2006). Different occupational groups in the Swedish construction industry are affected by work-related musculoskeletal disorders (WMSDs) at different frequency levels; however the highest relative frequency of reported WMSDs belongs to the concrete workers (Lundholm and Swartz, 2006). The cost to the worker of WMSDs is pain, along with loss of income through being unable to work. This results in significant costs to organisations through sick leave or ill-health retirement, and to the tax payers in general that may have to support a person unable to work (European Agency for Safety and Health at Work OSHA, 2004).

Public debate in recent years has focused increasingly on work environment issues, not least in view of the dramatic rise in the cost of ill-health. Health and safety problems in the form of work-related illnesses and accidents cause relatively high costs influencing the projects. Safety costs will ultimately be paid for by the client either directly or indirectly. The financial, economic, environmental and social costs of deaths, injuries, disabilities and diseases to the industry, in particular, and to the society in general, is colossal (Larcher and Sohail, 1999). Work-related accidents significance for a company reputation and personnel turnover is difficult to measure for construction companies.

Many companies have little knowledge about the costs associated with work environment risks. For example, if only sick-leave costs and social contributions are included in the economic assessment, the cost picture is incomplete. Cost for overtime, decreased production, increased administration, rehabilitation and productivity loss due to reduced working ability need to be taken into account as well (Rose and Örtengren, 2000). Therefore, cutting the sector's high incidence of accidents and work-related illnesses could save for example the EU and its taxpayers up to 75 billion Euros (estimated to be about 8.5 percent of the total construction costs) a year, claims the European Agency for Safety and Health at Work (OSHA 2004).

Direct and indirect costs resulting from a poor work environment have compelled both researchers and practitioners to look for adequate strategies and plan of actions to tackle safety issues in the production planning in the construction process. Koskela (2000) states

that occupational safety is notoriously worse in the construction industry than in other industries and that a number of solutions have been offered to relieve the chronic problem in construction.

The industrialisation of the construction process reflects the use of technology to change the sector's work environment for the better. Industrialised construction methods such as the use of the prefabricated steel reinforcement and the Self Compacting Concrete (SCC) have been introduced into the construction workplace for among other reasons the improvement of the work environment. These methods although often referred to as new, they are not new in principle, as they have had their applications in the industry since the early 1980's.

This paper will share some insights obtained from an investigation study on the use of these industrialized methods impact on the construction site work environment.

## **WORKING ENVIRONMENT AND ECONOMY**

Injury cost estimations, according to the Swedish Social Insurance Agency (2004), the single biggest cause for sick leaves is back pain which accounts for 15 % of all sick leaves among men and 12 % of sick leaves among women. The average of the total back pain illness compensation per case for men (focusing on men which constitutes 92 % of the construction industry's workforce) is about 4 600 €, this cost denotes 45 € per sick leave day. Back pain being the most common illness among men does account for 17 % of all sickness compensations. Considering only the construction industry, Samuelsson and Lundholm (2006) reported that out of all 1582 cases of sick leaves caused by occupational illnesses reported in the year 2004, 1342 cases of sick leaves were caused by ergonomic risk factors (including vibration and noise).

Furthermore, taking into account the 279 cases of WMSDs reported among concrete workers (Lundholm and Swartz, 2006), their sick leave compensations could approximately cost up to 1 280 000 € for the taxpayers. There are of course other direct and indirect costs such as productivity loss and hiring substitute workers that are not often calculated.

## **RISK IDENTIFICATION METHODS**

Risk assessment methods determine the risk level that employees face from exposure to hazards at work and can help establish measures that are necessary to control the risk and to protect workers health and productivity. In the study two risk identification methods were used to complement each other.

## **OBSERVATION AND ERGOSAM**

Observations at the bridge were done in a form of site-walkthroughs, video films of identified steel reinforcement and concrete casting activity work cycles. These observations were the basis for a further risk assessment; the ErgoSAM analysis.

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 (Swedish Productivity Center, 1995). In SAM, the main activities are Get and Put. For each SAM activity, a standard time is given. In addition to the SAM information, the ErgoSAM method considers two additional pieces of information: the 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 (Laring et al, 2005). The output of ErgoSAM is the product of three types of demands namely, work posture, force and repetition (frequency), according to a scientific model, the Cube model (Sperling et al., 1993).

The Cube Model is used on the site observations to acquire the risk of WMSDs on combinations of the variables mentioned (posture, force and repetition). For a specific working task, and for each dimension 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 (Sperling et al., 1993). ErgoSAM is implemented as a macro program in Microsoft Excel.

### FULL SCALE STUDY

A full scale study was carried out on a bridge construction with focus on the industrialised methods and their impact on the work environment. The bridge consists of a span of 10 metres with a width of 15 metres, Figure 1. One objective of the study was to examine the changes on the working environment when “new” construction methods, (use of prefabricated steel reinforcement and Self Compacting Concrete) were introduced. Other objectives presented in Simonsson and Emborg (2007), were to study the productivity at site, site logistics, economics of the changed working methods and planning process.

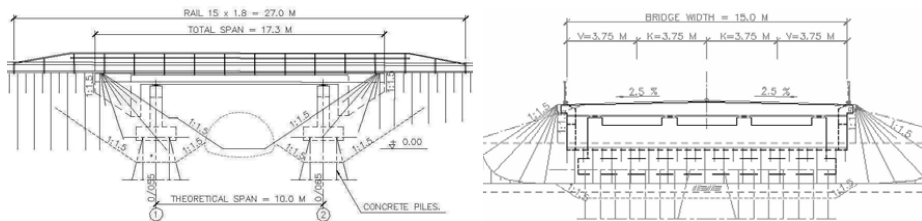


Figure 1: Full scale bridge in elevation and section (no scale).

### CONSTRUCTION METHODS

According to a study by the Danish Technological University, DTU (Nielsen, 2006) some 26 % of a workers average day consists of concrete casting and reinforcement fixing. If this is translated into time, it will be just over 2 hours per working day, or 57 full working days a year. This work is often done in awkward postures with heavy equipments such as the vibrator used to compact the conventional (traditional) concrete or with heavy material when placing the reinforcement piece by piece.

### STEEL REINFORCEMENT

Traditionally, steel reinforcement is fabricated on the construction site at its final destination involving a large labour force and a considerable amount of steel wastage. Current methods for installing steel reinforcement in concrete structures involve interpreting steel positions from plans and installation of individual bars by site workers.

If manufacturing of the steel reinforcement could be moved from its final position, i.e. in the formwork, to a more controllable position, a reinforcement workshop, the working environment could be drastically improved. Prefabricating steel reinforcement cages offers that possibility through the use of scissor lift tables, which makes it possible for the worker to work at the right height all the time instead of a bent posture as shown in Figures 2 a and b. Prefabricating steel reinforcement does not necessary equal manufacturing it in a factory, the reinforcement shop could also be located at the construction site. In this case, the benefit would be that the production flow for the worker can become even and possible waiting times can be eliminated through using this work as a buffer. During the construction of the full scale bridge, the industrial prefabrication of steel reinforcement partly replaced the manual installation on site. The prefabricated reinforcement was easily placed in the formwork, using cranes, before concrete casting commenced, see Figure 3.

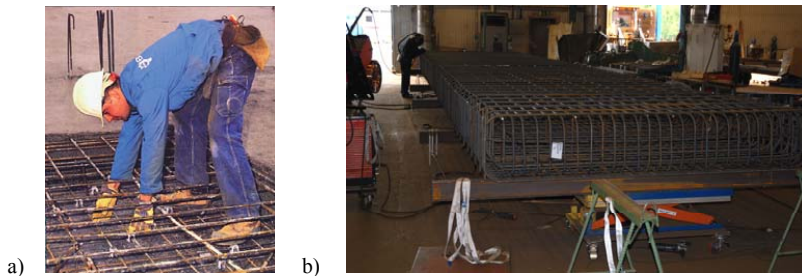


Figure 2: a) Traditional working position when placing reinforcement piece by piece. b) Steel reinforcement prefabricated in the factory and shipped to construction site.



Figure 3: a) Placing prefabricated reinforcement for a foundation. b) Reinforcement carpet lifted into place.

Some of the benefits highlighted when using prefabricated steel reinforcement structures are improved safety and reduced on-site congestion, reduction in site fixing resulting in less exposure time, ease of identification of reinforcement with less stressful situations and improved material handling with less heavy lifting and carrying of material (<http://www.bamtec.co.nz/elements/BAMTECsystem.pdf>).

### CONCRETE CASTING

Traditional concrete casting produces high noise levels and the vibrating tools used for compaction of the concrete often lead to unhealthy working postures (Figure 4a). As

mentioned earlier, a typical concrete worker spends on average 10 % per day casting concrete, thus working in stressful working postures and being exposed to back pains.

Self Compacting Concrete (SCC) is a concrete to which no additional inner or outer vibration is necessary for the compaction. SCC compacts itself alone due to its self-weight and is de-aerated almost completely while flowing in the formwork. For the success of SCC, it is crucial to define the performance of the product, which can, according to the Growth project Testing-SCC (Emborg et al., 2005), be discerned into three main parameters: 1) *Filling ability* 2) *Passing ability* and 3) *Segregation proneness*. For these parameters, criteria should be established to be met by a proper mix design depending on geometry of structure to be cast, reinforcement, form type and, method and local tradition on how to pour the concrete (Figure 4).



Figure 4: a) Worker using a vibrator for compacting normal concrete. b) SCC being pumped into formwork. c) Slumpflow test on SCC measuring approximately 740mm.

In general SCC offers many advantages for cast-in-place construction as well as for the precast and prestressed concrete industry. In regard to the working environment, there is less noise-level i.e. easier communication, eliminated vibration problems, improved quality and durability results in less rectification work and reduced concrete volumes due to higher strength.

## RESULTS AND DISCUSSION

### IMPROVEMENT OF WORK ENVIRONMENT THROUGH TECHNOLOGY INPUTS

With the increasing technology inputs into the construction workplace ergonomic intervention, not only does one enhance productivity but also adds value to the whole construction project. Velasco (1998) states how productivity is brought about by the technical inputs and the quality of the performance of the worker (physiological abilities of the worker (Abdelhamid and Everett, 2002)). Prior to the production start, the main contractor and the client agreed on the technology that will fit workers in the construction workplace. Off-site produced steel reinforcement and SCC were shipped into the construction site and lifted into the site by cranes, thus avoiding any manual material handling. The construction project presented in this paper had basic objectives of production and safety management depending on each other; therefore an integration of Lean Construction and safety management were emphasised on as in Saurin et al. (2006).

## **ECONOMIC BENEFITS OF 'NEW' CONSTRUCTION METHODS**

From the full scale bridge project it was observed that prefabrication of components allowed a reduction in work time for on-site steel fixing and dedicated labour and minimised the amount of storage space required on what is normally considered to be a congested site. Using prefabricated steel reinforcement elements accelerated the installation process at the construction site and made the construction more economical in terms of material waste. The off-site fabrication of steel reinforcement structures ensured continuous supply regardless of inclement weather which meant the structures was ready for immediate transportation to site to complement the construction process.

The cost related to the reinforcement can be viewed from two perspectives, the production cost of the reinforcement and the construction cost for placing the reinforcement before casting concrete. For the full scale bridge carpet reinforcement, the placing cost varied from 0,02€ to 0,04€ per kilogram (bottom and top reinforcement respectively of the superstructure), the traditional price for reinforcement fixing on the superstructure is approximately 0,65€ per kilogram. The purchase price for the carpet reinforcement rose with approximately 50% in comparison with traditional reinforcement bars, but still some 35% of the total costs were saved.

Concerning the use of SCC, not only workers were pleased to have a non-vibrating and noise-free work environment, but also costs related to the concrete compaction equipment use were eliminated and vibrators are often used inefficiently. They often run wastefully, or at a reduced efficiency, for about 70 % in total of their operating time, this being made up as follows (Hong Kong City University, 2007): out of concrete and left running 15 %, wrongly positioned in the concrete 35 % and vibrating already compacted concrete 20 %. This means that the vibrator is doing useful work only 30 % of the time.

## **ERGONOMIC ANALYSIS, ERGOSAM RESULTS**

After several weeks of observing concrete workers performing their jobs on the construction site, and after informal interviews with concrete workers, it became obvious what were classic work cycles for different methods of steel reinforcement and concrete casting. Based on this information, video films were taken and analyses of representative short work cycles were performed to identify any risks for WMSDs for concrete workers performing their tasks using different construction methods namely conventional and industrialised methods. Results of the analyses for representative work cycles are presented in Figures 5 and 6, where different loads on concrete workers are represented by Cube values.

The Cube value or the load level falls within three levels; where under 6 is acceptable, 6 to under 9 is conditionally acceptable and 9 and above is unacceptable. For example, the work cycle mean value of 7.4 obtained in ErgoSAM analysis in Figure 5 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.

When the worker performed tasks with the manual steel rebar work. The concrete worker is exceedingly exposed to WMSD risk factors which contribute to very high cube values with a mean value of 21. This number denotes almost three times higher risk exposure to WMSDs when working with the traditional rebar reinforcement than when working with the prefabricated steel reinforcement with 7.4 for a mean value (figure 5).

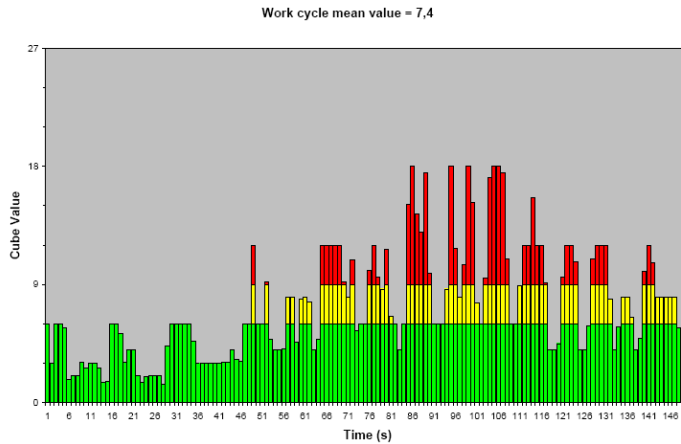


Figure 5: ErgoSAM analysis of a short work cycle of a concrete worker working with prefabricated steel reinforcement. A cube value under 6 is acceptable, 6 to under 9 is conditionally acceptable and 9 and above is unacceptable.

The work cycle mean value of 5.7 was obtained in the ErgoSAM analysis in the case of SCC casting (figure 6), thus making these work tasks acceptable as far as the workers work-related musculoskeletal health is concerned, and hence entails no risk factors for WMSDs.

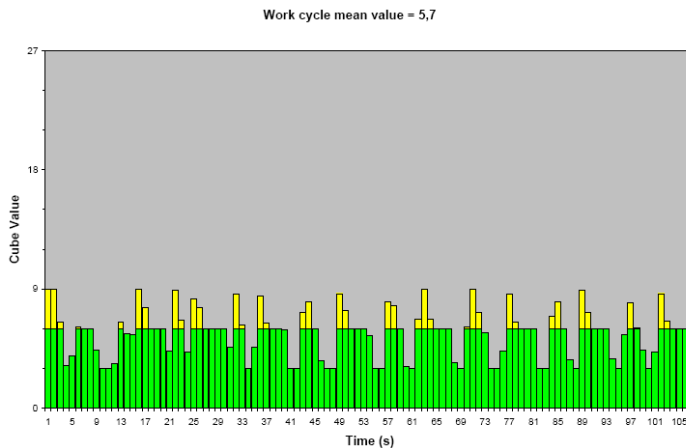


Figure 6: ErgoSAM analysis of concrete worker's short work cycle during SCC casting.

When the traditional concrete casting work cycle was compared to that of the SCC casting, the ErgoSAM analysis showed a mean value of 18.2, thus it became obvious that the normal concrete casting work exposed the worker to WMSD risk factors, over three times higher than working with SCC casting.

## CONCLUSIONS AND FURTHER COMMENTS

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 due to the elimination of physical strain due to the common risk factors that are generally part of the traditional methods of rebar reinforcement and the use of conventional concrete.

The prefabrication of steel reinforcement structures allowed a significant reduction of on-site steel fixing and associated labor costs as well as providing a much safer working environment without risk factors such as heavy lifting and working in bent, awkward and repetitive postures. The SCC cast into a frame of reinforced steel without the need for the labor intensive mechanical vibration usually associated with concrete placing, has led to the improvement of construction work environment and the promotion of health and safety of concrete workers. In a project such as a bridge construction in areas with heavy traffic, the project completion time can be extremely important. As the new steel reinforcement was prefabricated, there was higher quality control than the traditional rebar system. The off-site fabrication of steel reinforcement accomplished difficult construction tolerances, improved handling as well as it contributed to the speed of construction and minimized wastage of material. All mentioned above contributes to the customer value, in this case to the National Road Administration in Sweden.

The use of SCC in the full scale project offered many benefits to the construction: the elimination of the compaction work resulted in reduced costs of placement, a shortening of the construction time and the number of involved workers during casting, and therefore in an improved productivity. Considering the economics of SCC, the material cost was higher than traditional concrete; however the total cost was slightly lower for SCC. The largest benefit though was the reduction in man hours used for casting the concrete, man hours that can be used for preparing upcoming work.

Finally, when working with these industrialized and innovative working 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.

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**Paper IV**



## Industrialized construction: benefits using SCC



Peter Simonsson  
Ph.D. Student  
Luleå University of Technology (LTU), Luleå  
971 87 Luleå, Sweden  
E-mail: Peter.Simonsson@ltu.se

Mats Emborg  
Professor LTU / Head R&D Betongindustri AB  
LTU, 971 87 Luleå, Sweden  
Betongindustri AB 100 74 Stockholm, Sweden  
E-mail: Mats.Emborg@Betongindustri.se  
Mats.Emborg@ltu.se

### ABSTRACT



As known the product SCC comprises many advantages compared with traditional concrete, but yet it has not changed the market of cast in place concrete as expected. This relates to some robustness problems of the concrete and to a general opinion that the product is considered to be expensive. However, manufacturers have improved their quality vastly and SCC has become more robust over the last few years.

To increase the use of SCC, the actors of the building trade need to be informed and convinced how to benefit from all the advantages of SCC: i.e. the working environment the health and safety of the workers, the productivity etc.

This paper deals with full-scale examples on the use and the realization of SCC obtaining several benefits during a projects whole construction time. Specially, the economics and the working environment are treated.

**Key words:** SCC, benefits, economy, productivity, working environment, robustness

### 1. INTRODUCTION

Self-compacting concrete (SCC) is an important link in the development of the industrialization process of civil engineering projects; if managed properly it can, decrease the number of workers needed during casting and become economically profitable as well.

What happened with the expected development of SCC? In the late 1990's many specialists argued that they expected SCC to have more than 50 % of the total concrete market within a five year period. Today, almost ten years later however, the market shares of SCC in EU nations are clearly below 10 % with large variations from country to country. For instance Cussigh [1] reports that only about 3 % of all ready mixed concrete in France is SCC while in Denmark the

SCC market share is as high as 25 %. In Sweden, the SCC market share is about 10 % with very large local variations.

According to recent international findings [1], [2], SCC is on the cutting edge of scientific and technological developments, and it is essential to introduce the technique in a broader manner in cast in place concrete construction. However, still the adoption of SCC is very low and one important reason is, according the authors above, the economy. The need for high quality constituents of materials in SCC results in a more expensive product that not compensates for the possible economical benefits.

Thus, it is essential to clearly document all the direct and indirect benefits using SCC and this article is a contribution in this topic dealing with economic questions, working environment and industrialization possibilities in projects were SCC has been used.

## 2. OBJECTIVE OF THE PH D PROJECT

The research project “Industrialized civil engineering with in-situ cast concrete” at Luleå University of Technology aims at evaluating methods to increase the degree of industrialization in bridge construction. One of the objectives is to investigate possible productivity benefits using SCC at in-situ cast construction sites. Other objectives are to examine the economic potential of the product and the impact on the working environment.

## 3. ROBUSTNESS AND TARGET VALUES OF SCC

### 3.1 Benefits and hindering factors of SCC

Among the positive effects of SCC, the improved working environment and reduced noise level, easiness of placing, productivity enhancements, higher strength, faster construction and less man hours needed for production, can be especially mentioned.

Regarding civil engineering projects, there are certain parts where SCC is superior to traditional vibrated concrete: high walls, columns or plate structures [3]. Most often, when casting these structures with traditional vibrated concrete, concrete workers have to climb down inside the form to be able to carry out the compaction of the concrete properly resulting in low productivity and poor working environment.

However, according to Shah et al. [2] there are some issues hindering the introduction of SCC on a broader front; questions regarding the development of formwork pressure, problems related to static and dynamic segregation resistance, rapid loss of slump flow and doubtful robustness. Cussigh [1] has other explanations for the low adoption of SCC in Europe; the need for high quality materials, which in turn results in costs for SCC materials, clearly exceeds the traditional concrete, an insufficient accuracy of concrete production equipment, as well as a lack of quality control requirements and standards.

Another factor hindering the introduction of SCC is that it is especially important to establish a quality assurance system for difficult castings, especially when the structural section is narrow or the reinforcement is very dense as in most bridges today [4]. However, such systems are seldom established in praxis.

### 3.2 Robustness

Two reasons why SCC is not being used more frequently are the relatively large quality variations and the difficulty in keeping SCC robust. Though, concrete manufacturers in recent time have improved the quality and hence the robustness of SCC, still these negative effects are present with the result that contractors calculate the risk of using SCC to be too high. Therefore, the contractors simply do not use the product even though both costs and time can be saved.

According to Taguchi [5], robustness generally is defined as insensitive against disturbance. For SCC the disturbance can occur in the form of fluctuations of properties of the concrete constituents, mixing procedure and transport conditions. Thus, one important feature of SCC is the ability of the concrete to maintain its fresh properties and structure during transport and casting of a single batch or multiple batches, [6] and [7]. According to the European guidelines for SCC [8] a well designed and robust SCC can typically tolerate a variation of 5-10 liters/m<sup>3</sup> in mix water content, which in practice is about 3-6% of the total water content per m<sup>3</sup>.

### 3.3 Target values

Different target values are preferable for different structural parts in a structure. For civil engineering applications this implies that concretes for slabs compared with concretes for columns or foundations have different properties. Figure 1 show possible target values and allowed variations of the filling ability expressed by slump flow and T50. The slump flow for bridge foundations, columns or walls should be greater than for a bridge slab. Hence, with a bridge slabs horizontal extensions a slightly less fluid concrete is preferred creating opportunities for its proper form filling.

Another example of target values has been suggested by Walraven [9], Figure 2, stating nine consistency classes for SCC regarding slump flow, T50, V-funnel time, segregation and passing ability. As seen the consistency class depends on the construction type, e.g. ramps, walls, floors. Walraven concludes that SCC can be tailor-made for any kind of construction including fairly steep inclination (up to 30°).

It is thus evident that, it is important to design and modify the concrete for a specific project and also for specific structural parts within the same project.

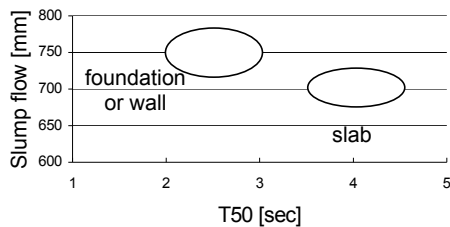


Figure 1. Examples of criteria for SCC for walls and slabs in a workability diagram (slump flow vs. T50), where the ellipse represents target value and tolerance.

Viscosity (sec)				Stability / Passing ability
VS > 2.5 VF 10 -25	Ramps		Tall and slender	Specify passing ability, for SF1 & 2
VS > 2.5 VF 6 -9	Walls			
VS < 1.5 VF 3 -5	Floors and slabs			Specify SS for SF 2 & 3
	SF 1	SF 2	SF 3	
	Slump-flow			

Figure 2. Properties of SCC for various types of application [8], [9].

#### 4. INDUSTRIALIZATION AND SCC

##### 4.1 Possibilities for an enhanced concrete construction

Experience has shown that SCC not alone automatically implies a clear step into industrialization. Therefore, within the research project at LTU, feasibility studies were carried out to grade various measures for industrialization of bridge construction. Ten already constructed concrete bridges were followed up regarding unit times and costs for reinforcement, formwork and concrete and it was identified where major advancements in production can be achieved. Figure 3 shows estimations of effects on man power requirements if industrial methods regarding formwork, concrete and reinforcement theoretically were applied to these bridges.

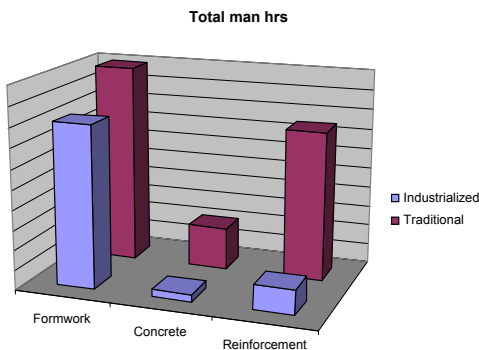


Figure 3. Possible reduction of man power requirements if industrial methods are applied to concrete bridge construction. Theoretical estimations based on follow ups of ten Swedish concrete bridge objects 2003 – 2005 (i.e. “traditional” in the figure).

A large man power reduction was achieved with a more effective handling of reinforcement – a well known circumstance. Different solutions for effective reinforcement fixing can thus be applied at various parts of bridges. At e.g. geometrically more complicated parts, reinforcement can be traditionally placed piece by piece in the formwork. For major parts of the structures the

reinforcement can be prefabricated into cages in a controlled environment in a factory or at a manufacturing location at the production site and lifted directly into the form. Reinforcement can also be prefabricated into rebar carpets and rolled out at site (Figure 4), preferably at superstructures of the bridges, see e. g. [10].



Figure 4: a and b) Manufacturing of carpet reinforcement in a controlled factory environment. c) Placing of carpet reinforcement on the superstructure.

The formwork can be designed to be permanent on the construction, which often is the case in house production. Preferably, this method of production can be applied for foundations, columns and/or plate structures but a larger use of permanent formwork for bridges is rather complicated to realize.

Considering the potential for SCC, apart from largely reducing the number of man hours needed, as shown in Figure 3, the concrete also increase the casting rates, and improve the working environment, see e.g. Skarendahl [11].

#### 4.2 Productivity according to Lean Construction

Another important component of industrialization is to change the organisation at the site and the attitude of the personnel. Philosophies of Lean Construction can thus be a useful tool. In Lean Construction waste (in Japanese: *muda*) plays a central role, whose definition is any human activity that absorbs resources without creating any value [12]. Two types of *muda* are defined: Type one *muda* creates no value but is necessary with current technologies while the type two *muda* creates no value at all and is immediately avoidable. Increased productivity is dependent on how much the *muda* can be eliminated.

Considering the concrete from this point of view, the vibrating moment is not waste when casting traditional concrete, but on the other hand not very productive either. Therefore, the compaction of the concrete can be graded as type one *muda* according to the definition above. On the other hand, in the case of SCC, the vibrating moment should be regarded as type two *muda*, because it creates no value at all and should immediately be avoided.

When using SCC, concrete workers are being released from their traditional assignment of vibrating the concrete and free to perform other tasks during the form filling. For example, the workers can fix reinforcement and prepare formwork for next section to be cast, i.e. a leap in productivity is near at hand.

Regarding the reinforcement a similar reasoning can be made. When traditional reinforcement is mounted for the bridge foundation for instance, the worker fetches and fixes each reinforcement bar at the correct location piece by piece. Traditional placing of reinforcement involves a lot of movement and carrying of reinforcement which can according to above be considered as type

one muda, since it is necessary with this technology but does not create any value. Using prefabricated reinforcement cages or rebar carpets, the element of movement/walking is reduced to a minimum or completely eliminated on site. If this still is done, the reinforcement handling ends up as a type two muda, i.e. a waste that creates no value and can immediately be avoided.

The productivity could consequently be improved simply by choosing the correct components, materials or prefabrication level to work with. Another method of improving the productivity is to increase standardisation, making structural parts more similar. It can be as simple as limiting the types of distance blocks for keeping the correct concrete cover layer, or to design foundations, columns or superstructures similarly in larger project to make them repeatable.

### **4.3 Working environment Ergonomic analysis through ErgoSAM**

According to a study at the Danish Technological University [13] some 26 % of a workers average day consists of concrete casting and reinforcement fixing ((approximately 10 % and 16 % respectively). If this is translated into time, it will be just over 2 hours per working day, or 57 full working days a year. This work is often done in awkward postures with heavy equipment such as the poker vibrators for the traditional concrete or with heavy material when placing the reinforcement piece by piece.

Today construction workers is one of the most exposed groups of employees when it comes to noise level, heavy lifts, poor ergonomics and varying weather conditions [14]. The conclusion is that a chance of improving the working environment often is denied because of the contractor only considers the short term prize for material and man power and not the total possible long term cost reduction from e.g. an enhanced working environment.

The difference in working environment between traditional casting of concrete and casting SCC has been debated recently; see e.g. Geel et al. [15], Nielsen et al. [16], Lecrux et. al. [17] to name a few; who all, debate the importance of introducing SCC in the workers point of view. However, there are few researchers presenting numbers which actually show the environment when casting traditional concrete compared to SCC.

To be able to perform the comparison between different working methods a model is needed. The ErgoSAM model [19] together with the Cube model [19] is such a tool. The ErgoSAM is based on the Cube Model that has been used on site observations to acquire the risk of Work-related Muscular Skeletal Disorders (WMSDs) in combinations of the variables; work posture, force and repetition. For every work task and for each variable separately, demand levels may be defined as low, medium, or high. The demand criteria are chosen so as to discriminate between good or poor work ergonomics, and assigned weight factors 1, 2, and 3 respectively. The combined value representing the load level or exposure level is obtained by multiplying the result of the three variables as illustrated in Figure 5, and the product determines the acceptability of the task [19].

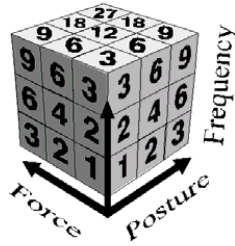


Figure 5. The Cube model combining the variables; work posture, force and frequency [19].

Combinations of these demands will largely decide whether a work situation entails risks of strain injuries or musculoskeletal disorders [18]. The ErgoSAM model has been used by different Swedish companies within the manufacturing industry. For instance, studies have been carried out at Volvo Cars in Gothenburg [20]. At the full scale project in Kalix (see chapter 6.1) the observations were done by construction site-walkthroughs, video filming of identified steel reinforcement and/or concrete casting activity work cycles and interviews with the workers. These observations formed the basis for a further assessment with ErgoSAM, see chapter 6.4.

#### 4.4 Economy

One of the drawbacks with SCC is that it is considered to be more expensive to manufacture compared to traditional concrete, a cost that is difficult to meet by a higher prize [1]. Hence, to be able to make SCC profitable also the casting phase needs to be overlooked. Therefore, the productivity when casting SCC should be high which means that the production system needs to be adapted to the “new” concrete. The difference between the manufacturing cost for the original concrete and the SCC cannot be too large if SCC is to become profitable [21].

There are factors reducing the cost for SCC; reduced energy consumption due to the absence of vibration, lower future maintenance cost, reduced illness of construction workers, as mentioned above [9], as well as lower over-head costs for projects due to decreased rental costs for various types of equipment and shorter construction time.

However, the probably most important factor when considering the economy of SCC is to have the whole life span of the project in mind when choosing material. SCC has an increased strength and durability which should be utilized when considering the reduction of maintenance needed for a project during its life span. This could also be utilised for the possible reduction of shear force reinforcement as well as minimization of the structures cross sections. This of course applies for any high strength concrete if chosen for a project. These factors and the faster casting and less labour needed during casting will result in considerable reduction in costs and risks and it will also reduce any possible traffic disruption during construction.

### 5. LABORATORY STUDIES

#### 5.1 General

As mentioned earlier, to be able to produce a robust SCC product the focus should be on keeping the fluctuations of the different constituents as low as possible and to design a robust

concrete mix. Among possible fluctuations e.g. the quality of the coarse aggregate, cement or additives can be specially mentioned, whereas, the moisture content in the coarse aggregate might be the factor causing the most common and largest variations. Therefore, the recipes of the SCC used in the two full scale projects (chapter 7), were tested in the laboratory regarding sensitivity to fluctuation in water content corresponding to a moisture content variation of  $\pm 0,5\%$  and  $\pm 1,0\%$  without compensating done in the mix. Two test series were performed for mix proportions, according to Table 1. Variations of filler content were performed by adjusting the aggregate content. The fine and coarse grained aggregate curves featured  $\pm 14\%$  deviations from the original curve at the fractions 1 mm. Figure 6 and 7 show documentations of workability (slump flow, T50 and V-funnel) and rheology (shear stress and viscosity) for the mixes.

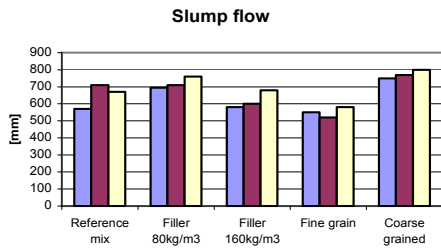
*Table 1. Concrete mix proportions at laboratory tests for two recipes. SCC 1 is the mix used in the Kalix project and SCC 2 is a mix used at the Nynäsvägen project however, here, with the same aggregate as SCC 1.*

Materials (kg/m <sup>3</sup> )	SCC 1	SCC 2
0-8 mm	1012	899
8-16 mm	545	651
Cem	450	430
Limestone filler	122	130
Water	175	172
Superplastcizer	0,8	0,6
Water / Cement ratio	0,39	0,40

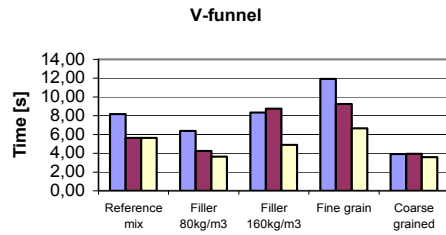
## 5.2 Results

The first studies were carried out on SCC 1. The variations in moisture content varied between  $\pm 1,0\%$  for this recipe, with one exception which is the mixture with the filler content of  $80 \text{ kg/m}^3$  were only  $\pm 0,5\%$  water was added due to considerable separation and an unusable concrete as a result when  $+ 1,0\%$  water was added.

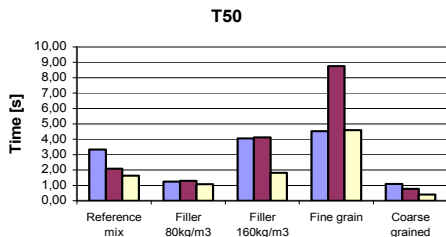
Regarding the slump flow of SCC 1, it is observed that the concrete is not particularly sensitive to the moisture change of the aggregate. However, when studying the V-funnel test results it can be seen, that the flow time is noticeably longer for the drier mix than for the wetter and hence the moisture content clearly affects the concrete for this type of test. It is also observed that, the concrete gets less fluid when the filler content increases. Moreover, the concrete with the fine sieve curve is rather sensitive to moisture, as compared to the insensitiveness of the concrete with the coarse grained aggregate.



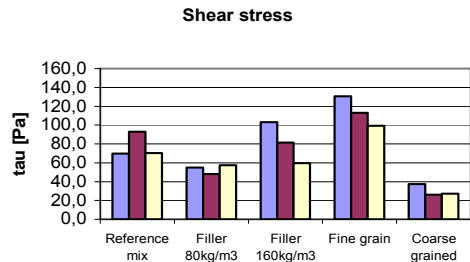
a)



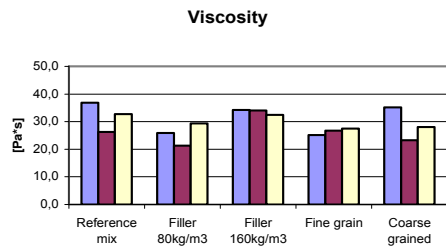
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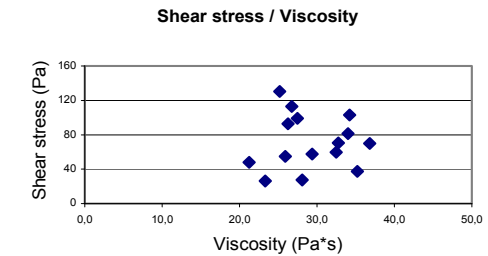
c)



d)



e)



f)

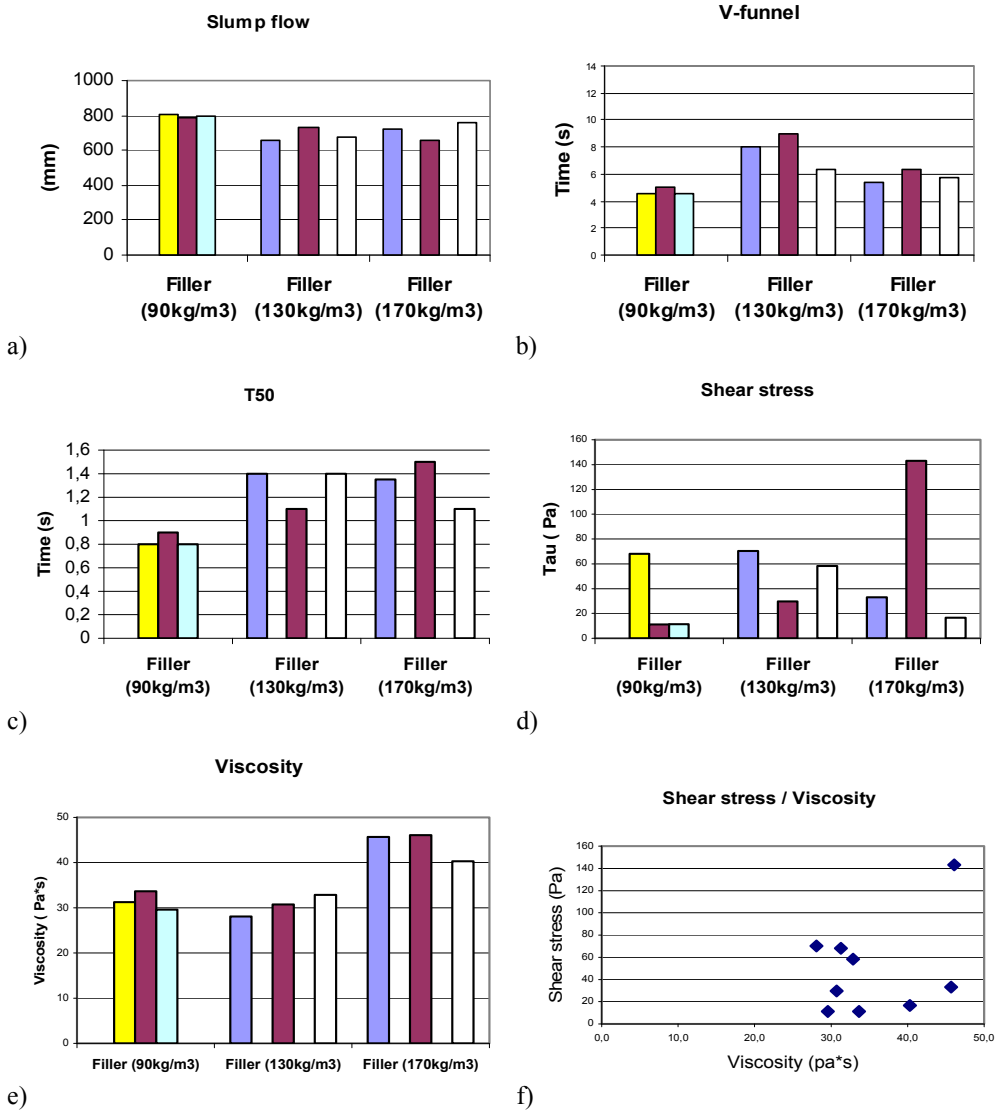
Figures 6 a to f. Workability and rheology tests on SCC 1: slump flow, V-funnel, T-50, shear stress, viscosity and shear stress / viscosity. Variations of moisture content in 0-8 mm; -1% (left) and +1% (right) from reference mix (middle) (80 kg/m<sup>3</sup> filler: ± 5 % variation).

Considering the T50-time it can be seen that the moisture content has a small effect, since the test time is markedly shorter for the wet mix than for the dry mix. Regarding the fine grain mix and T50, the test with reference moisture content was affected by the laboratory equipment and the value is therefore not relevant.

According to the shear stress values of Figure 6d, there is an obvious difference between the fine grain and coarse grained tests. The fine grained material is more sensitive to water content than the coarse grained aggregate.

The test results in Figure 6e (viscosity) and 6f (viscosity versus yield stress) does not show any apparent differences and no specific conclusions can be drawn. However, there is a difference in the filler content; the viscosity is larger with a higher amount of filler. Also, it can be observed that the drier mixes have higher viscosity values.

In the tests with SCC 2, the slump flow and V-funnel, Figures 7 a and b, were rather insensitive to the water content in the concrete. The slump flow for the mix with reference water content is declining with increasing filler content. On the other hand, regarding the v-funnel test, the reference filler content gives a long flow time while both high and low filler content lead to shorter flow times.



Figures 7 a to f. Workability and rheology tests on SCC 2 for filler variations: slump flow, V-funnel, T-50, shear stress, viscosity and shear stress / viscosity. Variations of moisture content in 0-8 mm; -1% (left) and +1% (right) for filler content 130kg/m<sup>3</sup> and 170 kg/m<sup>3</sup> from reference mix (middle). Variations of moisture content for 90 kg/m<sup>3</sup>-0,5% (left) and +0,5% (right) from reference mix (middle).

Considering the viscosity test results, there is probably a break point between filler content 130 kg/m<sup>3</sup> and 170 kg/m<sup>3</sup>, since there is a clear difference between these two test values. The T50 test results are very low and can be said to be within the margin of error and no clear conclusions can be drawn.

Generally, from the laboratory tests it is observed that both SCC mixes are relatively insensitive to the moisture variations studied even though the filler content was increased and decreased from the reference mix. However, SCC 1 is somewhat more sensitive than SCC 2 to the changes of moisture content.

Furthermore, some relation between slump flow and shear stress is present as well as between T50-time, V-funnel time and viscosity as similar observations can be observed for the rheology tests as for the workability tests when varying the mix.

## 6. FULL SCALE PROJECTS

### 6.1 General

Two full scale projects have been studied with two concrete suppliers that had different experience with the SCC product. The first supplier had never delivered SCC to a civil engineering project before and had accordingly little experience and no functioning recipe while the second supplier had more experience and several SCC mixes available as commercial products.

#### *Study No 1: The Kalix bridge*

Near the village Kalix, approximately 100 km NE of Luleå, the most comprehensive studies were carried out. The bridge “*the industrial concrete bridge*” featured a span of 10 m and a width of 15 m. The full scale project comprised “new” reinforcement solutions such as reinforcement cages for the foundations and rebar carpets for the superstructure. Also, prefabrication was chosen for some of the very dense shear force reinforcement and SCC was used for all parts of the bridge. To facilitate the introduction of these new working methods, the design and production planning of the bridge were carried out according to Lean Construction philosophy [22].

In total, the bridge consisted of approximately 280 m<sup>3</sup> SCC cast at four occasions: foundation, plate structures, end walls and superstructure. The superstructure comprised 16 tons reinforcement of which 13 tons were placed using rebar carpets. The reinforcement for the foundation were prefabricated in two sections, one for each foundation plate, each weighing 2,7 tons. The cages were mounted in single pieces directly from the delivery truck into each of the foundation formwork, ready to be cast as soon as the connecting reinforcement had been installed.

#### *Study No 2: The Nynäsvägen bridge*

The project at Nynäsvägen (50 km SE of Stockholm) consisted of two identical bridges next to each other (bridge spans of 18 m and widths of 9 m). The total amount of concrete for the foundations, columns and superstructures for both bridges was approximately 550 m<sup>3</sup>. Each bridge was cast at five occasions and the largest single casting was approximately 210 m<sup>3</sup> for the superstructures. SCC was used for the entire structure.

At these bridges the reinforcement were placed traditionally except some 1,8 ton of the superstructure where rebar carpets were used. The reason for the very low degree of prefabrication was that the possible use of rebar carpets was decided very late in the project and a proper redesign for this solution was not possible in such a short notice.

## 6.2 Documentation of concrete properties

The concrete properties, slump flow and T50, were recorded at the building site on all delivered batches at study no 1, after the pump see Figure 8. At study no 2, slump flow and air content were recorded on nearly half of the batches prior to the pump, Figure 9.

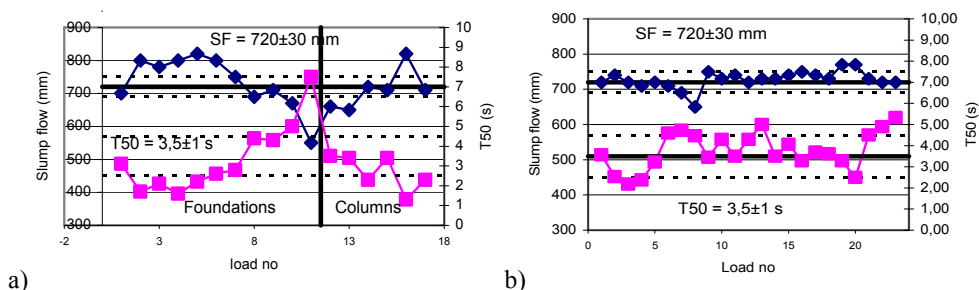


Figure 8 Slump flow and T50 documentation at study no 1. Castings of foundations and columns at two occasions (a). Casting of end walls and superstructure at one occasion (b).

At the casting of the substructures of the Kalix project some difficulties occurred in delivering the concrete with firm properties see Figure 8. This is probably depending on the inexperience of the concrete supplier and the relative small separate volumes. On the other hand, casting of the bridge superstructure was performed with a concrete of an even and high quality, Figure 8 b. Only some batches out of 24 featured properties just outside the criteria e.g.  $720 \pm 30$  mm for slump flow and  $3,5 \pm 1$  s for T50. For the two outlier values above the interval, the measuring can have been affected by disturbance and these two values can be neglected in the context.

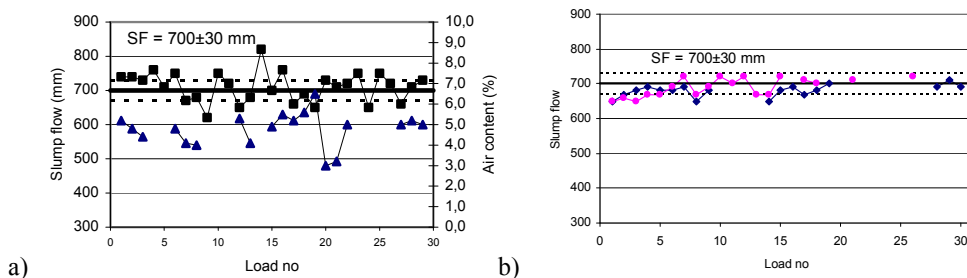


Figure 9. a) Slump flow and air content measured on casting of foundations and columns at study no 2, cast at five occasions. b) Slump flow at concrete plant and at building site, casting of superstructure at study no 2.

At the second study the conditions for the slump flow were changed and the criteria were set to  $700 \pm 30$  mm, T50 was not measured at all in this study. In Figure 9 a, there are five different

castings for the substructure, i.e. foundation and columns, accumulated. Almost 30 % of all delivered concrete batches were measured outside of the set conditions for slump flow (Figure 9 a). Nevertheless, there was only one recorded batch of separated concrete.

The air content is fluctuating during the castings with an average value of 4,8 %. There were never any specific values set for the air content in this project, although the air content for a civil engineering project is generally said to be accepted with in a span of 4-8 % and therefore was the air content acceptable.

Casting the superstructure at study No 2 on Nynäsvägen, Figure 9 b, the slump flow was measured both at the concrete plant and at the construction site. During the delivery from concrete plant to construction site the slump flow has increased in most cases. This probably indicates that the super plasticizer needs to be more thoroughly mixed into the concrete at the concrete plant. Furthermore, the first deliveries had less slump flow than the latter; this can be due to the fact that the buckets of the trucks were dry in the beginning.

It is also noted that very few batches delivered showed slump flow values just outside the criteria and they were accepted by the client.

### **6.3 Economy of SCC**

#### *Study No 1: Kalix project*

As the Kalix project was a local pioneer full scale project, neither workers nor management had experience of working with SCC. Therefore, at the first two cast occasions (foundation and plate structures) the number of workers was too large, see Table 2 showing man power and costs of the full scale project. Also, some concrete delivery problems occurred, implying about 50 % longer casting times than expected. This had however, nothing to do with the SCC mix i.e. these problems would have occurred even if traditional concrete had been used. Thus, the comparison between traditional concrete and the outcome of SCC at these two castings as shown in the table is not representative.

When casting the superstructure at two different occasions the delivery problems were eliminated, and the workers had also become more experienced with SCC. Therefore, the castings went well and the outcome was almost as planned using SCC, see Table 2. Approximately € 1200 was saved at these castings as compared to conventional concrete. However, the concrete was more expensive (about € 15 per m<sup>3</sup>) resulting in a material cost increase of € 2000 and hence the total costs were enhanced with approximately € 800 in total.

On the other hand, the price difference of € 15 per m<sup>3</sup> SCC is rather high, and if the difference had been the same as in the project at Nynäsvägen (€ 8) the result would have come out differently. The increase in material cost would have become roughly € 1100, with the decrease in placing cost of € 1200 mentioned above resulting in minor savings of about € 100.

Table 2. Expected time (h) and costs (€) for casting with traditional concrete, the actual outcome of using SCC at site and theoretical expectations of SCC castings when fully exploited at the Kalix project. Superstructure – left, bridge deck – right.

Traditional casting				
m3	No of workers	proj time	work time	cost €
64	4	5	20	800
36	4	3	12	480
<b>Total</b>		<b>8</b>	<b>32</b>	<b>1 280</b>

Traditional casting (planned work)				
m3	No of workers	proj time	work time	cost €
47	4	4,5	18	720
90	4	6	24	960
<b>Total</b>			<b>42</b>	<b>1 680</b>

Outcome				
m3	No of workers	proj time	work time	cost €
64	4	7	28	1120
36	2	5	10	400
<b>Total</b>		<b>12</b>	<b>38</b>	<b>1 520</b>

Outcome				
m3	No of workers	proj time	work time	cost €
47	1	4,5	4,5	180
90	1	4	4	160
<b>Total</b>			<b>8,5</b>	<b>340</b>

SCC Theoretical				
m3	No of workers	proj time	work time	cost €
64	1	3	3	120
36	1	2	2	80
<b>Total</b>		<b>5</b>	<b>5</b>	<b>200</b>

SCC Theoretical				
m3	No of workers	proj time	work time	cost €
47	1	3	3	120
90	1	4	4	160
<b>Total</b>			<b>7</b>	<b>280</b>

### Study No 2: Nynäsvägen

At the Nynäsvägen project the casting of the foundations and columns included a total of approximately 140 m<sup>3</sup> of SCC. While the traditionally planned casting involved approximately 38 working hours for casting the concrete, the theoretical casting of SCC would contain approximately 8 hours for casting, see Table 3. The actual outcome of the project ended up on a sum of 26 hours for the casting, i.e. a saving of 12 working hours from the planned work schedule could be made. However if the full potential of SCC would have been utilized (SCC theoretical) approximately 30 working hours or 80 % of the planned work time could have been saved. With an assumed construction worker cost of € 40 per hour, the saving in form filling costs is approximately € 500 for the outcome and € 1200 for the theoretical SCC.

For the superstructure the traditional casting was planned to be performed by 9 workers during 15 hours of production, ending up on 270 hours for the two bridges. A theoretical calculation using SCC shows that the actual time for casting can be considerably reduced. Savings of approximately 170 working hours can be realized. With € 40 per hour the saving of man power is roughly € 6800.

The actual outcome for the superstructure ended up in 90 work hour's reduction due to faster casting and some € 3600 in cost savings. However, the material costs increased by approximately € 8 per m<sup>3</sup> for SCC compared with traditional concrete, which resulted in a more expensive concrete for the superstructure of almost € 3400.

Nevertheless, the overall result for the superstructure was positive as compared to a traditional concrete solution even though SCC's potential was not fully utilized, and the total costs were reduced with roughly € 200. Hence, if SCC had been fully utilized as the theoretical calculation in Table 3 suggests the possible savings would become virtually € 3400 for the superstructure.

Table 3. Expected time (h) and costs (€) for casting traditional concrete, the actual outcome of using SCC at site and theoretical expectations of SCC when fully exploited for the Nynäsvägen project. Superstructure- left, bridge deck – right

Traditional casting (planned work)				
m3	No of workers	proj time	work time	cost €
25	3	2	6	240
30	3	2	6	240
35,5	3	3,75	11,25	450
36	3	3,25	9,75	390
10	3	1	3	120
5	2	1	2	80
141,5		13	38	1520

Traditional casting (planned work)				
m3	No of workers	proj time	work time	cost €
206,8	9	15	135	5400
206,8	9	15	135	5400
413,6			270	10800

Outcome				
m3	No of workers	proj time	work time	cost €
25	2	2	4	160
30	2	2	4	160
35,5	2	3,75	7,5	300
36	2	3,25	6,5	260
10	2	1	2	80
5	2	1	2	80
141,5		13	26	1040

Outcome				
m3	No of workers	proj time	work time	cost €
206,8	9	10,5	94,5	3780
206,8	9	9,5	85,5	3420
413,6			180	7200

SCC Theoretical				
m3	No of workers	proj time	work time	cost €
25	1	1,25	1,25	50
30	1	1,5	1,5	60
35,5	1	2	2	80
36	1	2	2	80
10	1	0,5	0,5	20
5	1	0,5	0,5	20
141,5		7,75	7,75	310

SCC Theoretical				
Two teams	No of workers	proj time	work time	cost €
7-14,30	3	7,5	22,5	900
10-16,30	4	6,5	26,0	1040
7-14,30	3	7,5	22,5	900
10-16,30	4	6,5	26,0	1040
			97,0	3880

## 6.4 Working environment

Probably the largest benefit with SCC is, as mentioned earlier, the improvement in working environment. The improvement at our documentation on site is threefold in comparison with traditional concrete casting, Figures 10 and 11. The work cycle mean value is computed to 18,2 in our project if traditional vibrated concrete had been used at the Kalix project as should be compared with the actual outcome of 5,7 for SCC [23]. This when comparing the casting of relatively small and easy to produce plate structures. Considering the case with for instance a 10 meter high plate structure with dense reinforcement, the improvement is possibly even larger due to fact that the worker has to climb down inside the construction carrying the vibrating equipment. This result in exceptionally poor working environment, and also in a probable loss of productivity, due to much lower unit time for casting traditional vibrated concrete.

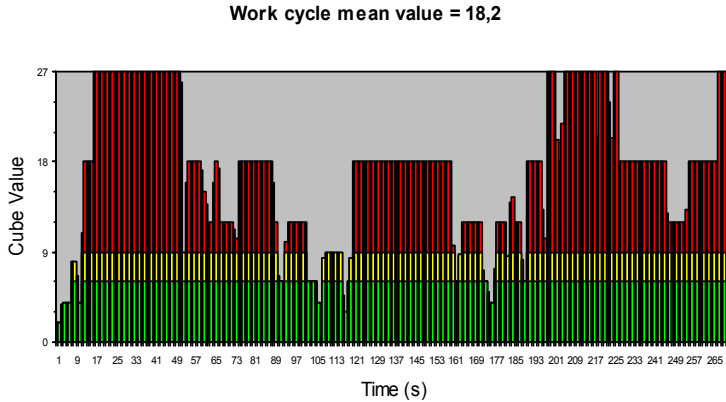


Figure 10: ErgoSAM analysis of concrete worker's short work cycle during casting of traditional vibrated concrete. Below 6 is acceptable, 6 to below 9 is conditionally acceptable and 9 and above is unacceptable.

When the value in the Cube model reaches 27 in Figure 10, the worker lifts the heavy poker vibrator (Force = 3) repeatedly (repetition = 3) in awkward positions (Work posture = 3) resulting in the top value which is unacceptable. When the value reaches 18 in the figure the worker has the value three for two of the variables and the value two for the third variable. These individual values can vary during a work cycle.

The top value of 9 for SCC in Figure 11 is achieved when the worker pushes the pump hose from one place to another, resulting in the value three for force and working position and the value one for repetition.

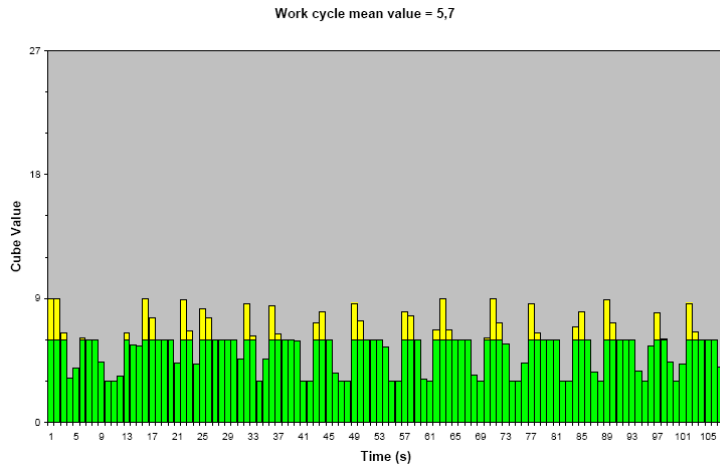


Figure 11: ErgoSAM analysis of concrete worker's short work cycle during SCC casting. The average value for the work cycle is 5,7 which is below 6 and hence acceptable.

Injury cost estimations according to the Swedish Social Insurance Agency [24], show that the single largest cause for sick leaves in general is back pain which accounts for 15 % of all sick

leaves among men and 12 % of sick leaves among women. The average of the total back pain illness compensation per case for men (focusing on men which constitutes 92 % of the construction industry's workforce) is about 4 600 €, this cost denotes 45 € per sick leave day. Considering only the construction industry, Samuelsson and Lundholm [25] reported that out of all 1582 cases of sick leaves caused by occupational illnesses reported for 2004, 1342 cases of sick leaves were caused by ergonomic risk factors (including vibration and noise).

For concrete workers 279 cases of WMSDs were reported and their sick leave compensations is estimated up to 1 280 000 € for the taxpayers [26]. There are of course other direct and indirect costs such as productivity loss and hiring substitute workers that are not often included in such calculations.

Improved working environment also implies an increase in productivity given that the workers are at the site performing work tasks and there are no vacancies or unskilled substitute workers at the production sites.

## 7. CONCLUSIONS

The largest economic benefit from introducing SCC to a contractor in civil engineering projects is probably on the superstructure of a bridge, since the largest number of workers is needed during casting of traditional vibrated concrete and it is therefore associated with large casting costs. Hence, the number of workers needed for casting can be markedly reduced if SCC is introduced and proper planning has been carried out before casting.

However, controversially it is often easier to introduce SCC for foundations, columns or plate structures since these structural parts are less dominant in the construction and the "risk" related to using SCC is small. However, for these smaller less people demanding castings it is more difficult to achieve economical benefits in using SCC.

The overall risk using SCC is that the product it is not robust enough, which might result in the concrete does not enclose the reinforcement satisfactory and rework is needed. Also, after casting, it can be visual lines (inward bends) in the finished construction which is not acceptable. Therefore, most often, contractors calculates the risk enclosed in using SCC to be too high, especially for the more important superstructure and simply does not use the product even though both costs and time evidently can be saved.

The SCC delivered to the superstructures on both projects was robust and was of desired quality. The "risk" involved using this SCC was minimal and the contractors were satisfied with both the delivered product and the order of in which the casting was performed. Hence, the castings of the superstructures on both projects were carried out in shorter time and could have been carried out using fewer personnel than planned with traditional concrete. The SCC delivered to the substructures at both projects was not entirely acceptable, however, the SCC at the two projects differed and the quality was better at study 2.

Probably the largest benefit with using SCC is, as mentioned earlier, the improvement in working environment. Therefore, the economy of the Swedish construction industry and society can benefit significantly from using the right kind of working method during construction. As mentioned earlier, 1342 sick leaves were reported for 2004 due to ergonomic risk factors. If these sick leaves costs as much as expected above e.g. € 4600 per sick case, it suggests that the

total costs ends up on roughly € 6 170 000 annually! This is according to Lean Construction a great deal of muda!

To be able to utilize the redundant personnel during casting of SCC, projects need to be planned and managed properly. Hence, the organisation at the worksite needs to be optimized during the whole project, clear work instructions need to be formulated for all workers involved for all work tasks to be performed. Also, a list of buffer work needs to be logged so that workers can be temporarily occupied with other productive work tasks during casting but still within reach if needed during casting, Ballard [27].

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**Paper V**



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



Peter Simonsson  
Ph.D. student  
Luleå University of Technology (LTU)  
971 87 Luleå, Sweden  
E-mail: [Peter.Simonsson@ltu.se](mailto:Peter.Simonsson@ltu.se)

Mats Emborg  
Professor LTU / Head R&D Betongindustri AB  
LTU, 971 87 Luleå, Sweden  
Betongindustri AB, 100 74 Stockholm  
E-mail: [Mats.Emborg@betongindustri.se](mailto:Mats.Emborg@betongindustri.se)  
[Mats.Emborg@ltu.se](mailto:Mats.Emborg@ltu.se)



## ABSTRACT

The implementation of Self Compacting Concrete (SCC) together with two 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. At the construction of the first full scale project “The Industrialized Concrete Bridge” Sweden built during 2006, the new techniques were applied., It was concluded that the production time at site could be reduced with up to 20 % and that the number of workers could be reduced by virtually 25 %.

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**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 usef for houses. The system of NCC Komplet 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 our 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.

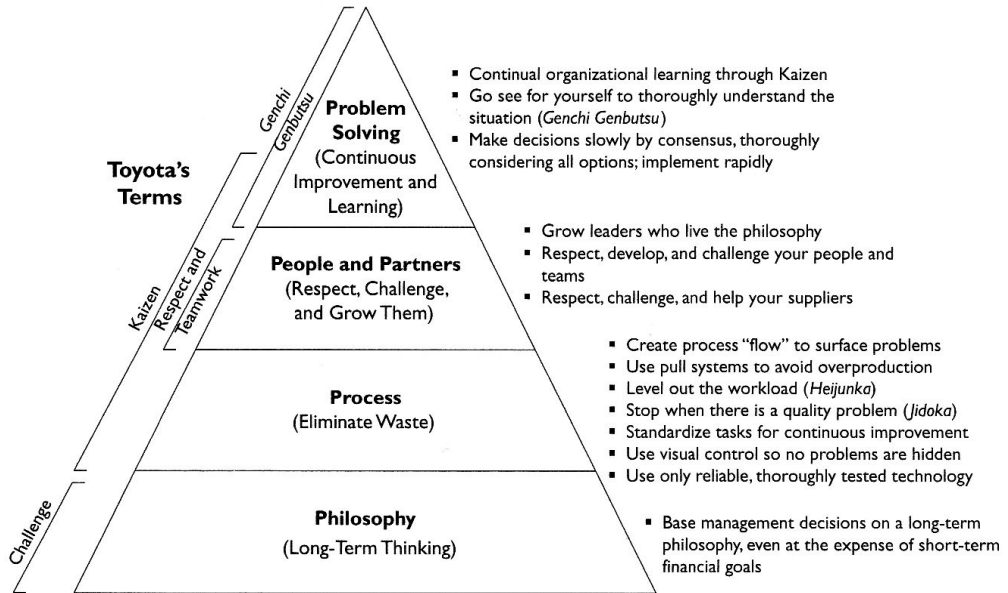


Figure 1 – Toyotas four P's (middle) and 14 principles (right) of production, Liker (2004).

## 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 bidding 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 (SRA-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.

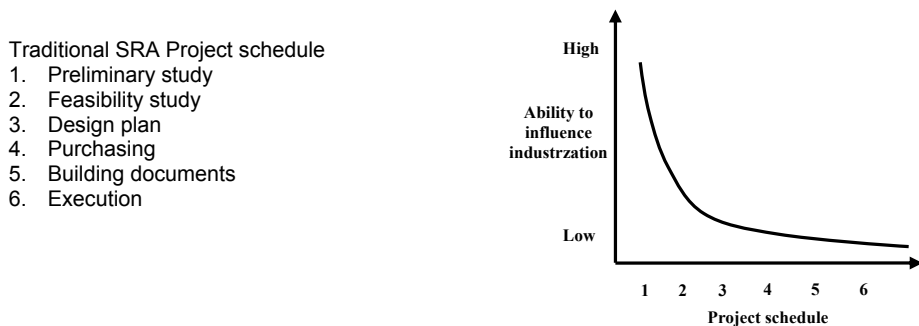


Figure 2. Project schedule of a traditional Swedish National Road Administration (SRA) project and its industrialization possibilities. The earlier the efforts for industrialization the greater impact they have.

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 11<sup>th</sup> principle “respect your extended network of partners and suppliers by challenging them and helping them to improve” you should treat your partners and suppliers as an extension of your 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.

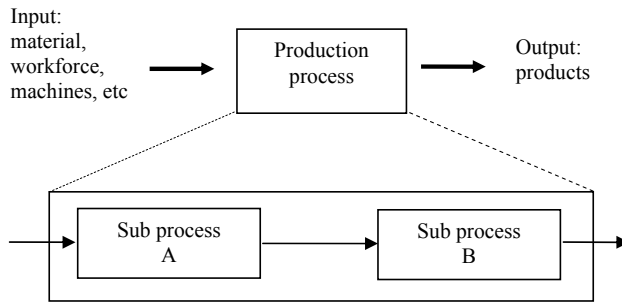


Figure 3. The transformation process of input becoming output according to Koskela [10].

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.

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.

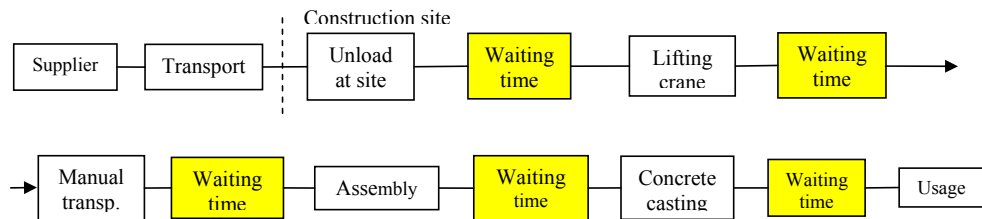


Figure 4. Value stream of traditional handling of single piece reinforcement on a construction site.

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.

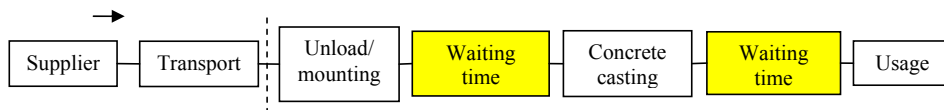


Figure 5. Value stream when handling the prefabricated reinforcement sections for the foundation of the first full scale bridge project.

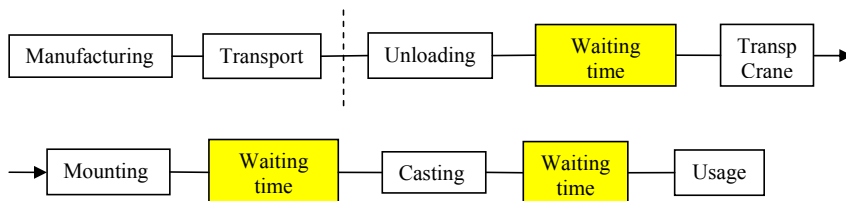


Figure 6. Value stream when handling the rebar carpet reinforcement used at the first bridge project.

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 SRA-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 asphaltting, 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 1. Distribution of time and costs at construction of in-situ cast concrete bridges. Summaries of answers from interviews conducted with personnel from SRA- Production.

	Foundation		Superstructure		Average	
	Time	cost	time	cost	time	cost
Formwork	25%	20%	50%	30%	37%	25%
Reinforcement	45%	40%	35%	35%	40%	38%
Concrete	30%	40%	15%	35%	23%	37%

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, asphaltting, railing etc and mostly performed by sub-contractors.

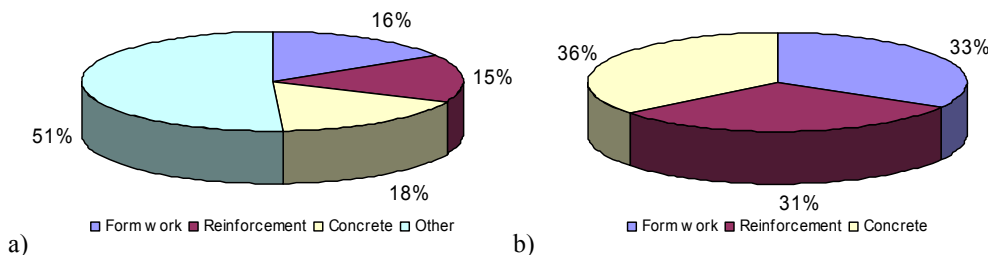


Figure 7. a) Distribution of total construction costs for concrete highway bridges. b) Distribution of costs for formwork, reinforcement and concrete, both figures according to follow up from ten medium sized bridges.

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. Theoretically, only one person is needed during the concrete casting (the concrete pump operator).

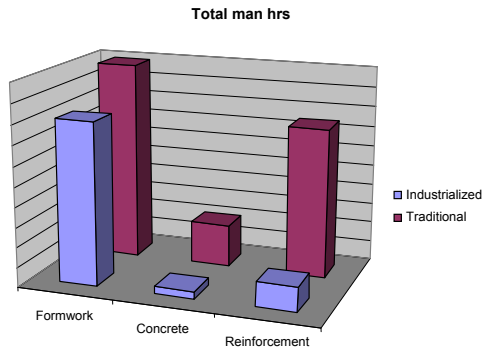


Figure 8. Theoretical reduction of on-site man hours during construction for an industrial process compared with traditional methods.

## 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.

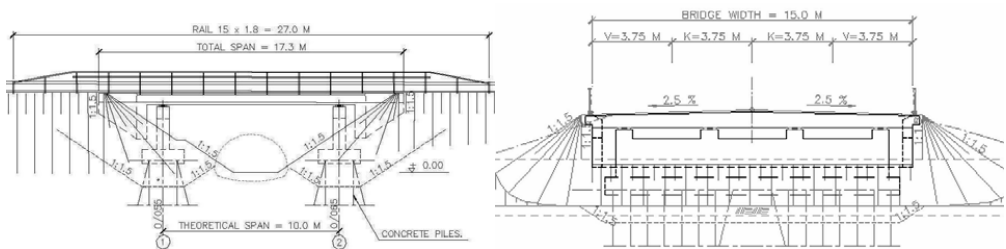


Figure 9. First full scale project with a bridge span of 10 m and a width of 15 m.

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 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.

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.

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.

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



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



*Figure 12: Rebar carpets, rolled out on the superstructure at the Kalix project.*

## 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 site-walk throughs, 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.

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.

*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).*

<b>Kalix</b>	Traditional	Craft hrs/ton	Industrialized	Craft hrs/ton		
Prd time at site	2,5 days	80 hrs	5 hrs	15 hrs		
Craftsmen	4 persons	13,2 ton	3 persons	13,2 ton		
<b>Total</b>	80 hrs	6 hrs 4 min	15 hrs	1hr 8 min		
<b>Boden</b>	Traditional	Craft hrs/ton	Industrialized	Craft hrs/ton		
Prd time at site	4 hrs	8 hrs	27 min	1,5 hrs		
Craftsmen	2 persons	1,48 ton	3 persons	1,48 ton		
<b>Total</b>	8 hrs	5 hrs 24 min	1,5 hrs	1 hrs		
<b>Nynäsvägen</b>	Traditional	Craft hrs/ton	Industrialized	Craft hrs/ton	<b>Kalix</b>	Traditional
Prd time at site	12 hrs	24 hrs	1 hr	3 hrs	Prd time at site	10 hrs
Craftsmen	2 persons	3,6 ton	3 persons	3,6 ton	Craftsmen	4 persons
<b>Total</b>	24 hrs	6 hrs 40 min	3 hrs	50 min	<b>Total</b>	40 hrs
						Optimum SCC
						7 hrs
						2 persons
						14 hrs
<b>House</b>	Traditional	Craft hrs/ton	Industrialized	Craft hrs/ton	<b>Nynäsvägen</b>	Traditional
Prd time at site	12,5 hrs	25 hrs	64 min	3 hrs 15 min	Prd time superstr	20
Craftsmen	2 persons	1,91 ton	3 persons	1,91 ton	Craftsmen	9
<b>Total</b>	25 hrs	13 hrs 5 min	3 hrs 15 min	1 hr 42 min	<b>Total</b>	180
						Optimum SCC
						14
						7
						97

## 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  $\pm$  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.*

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.

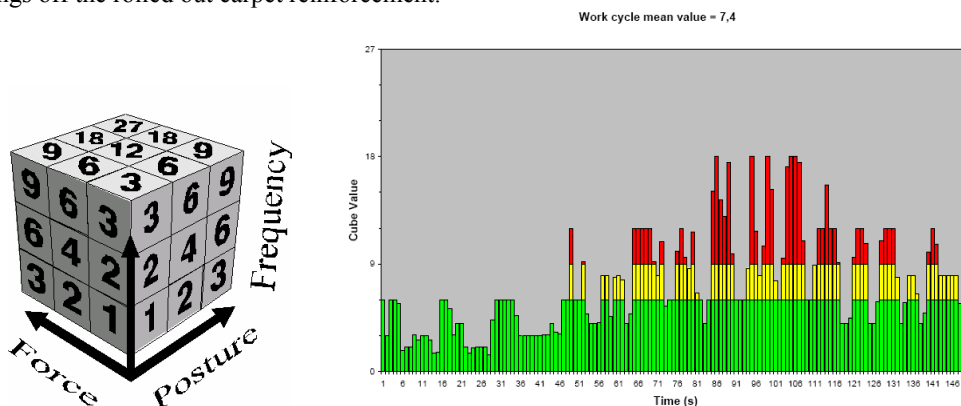


Figure 14: a) Using the Cube model [18] for a specific working task, force, posture and frequency are given weight factors 1, 2 or 3 and then multiplied to be able to discriminate between good and poor work ergonomics. b) ErgoSAM analysis of a short work cycle of a concrete personell working with prefabricated 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.

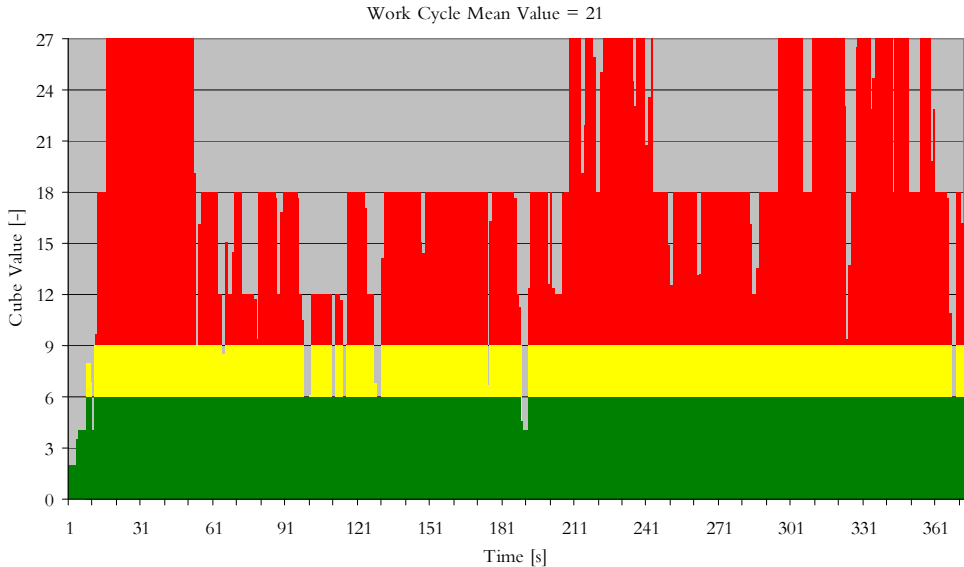


Figure15: ErgoSAM analysis of a short work cycle of traditional reinforcement placing, mean value 21. Below 6 is acceptable, 6 to below 9 is conditionally acceptable and 9 and above is unacceptable.

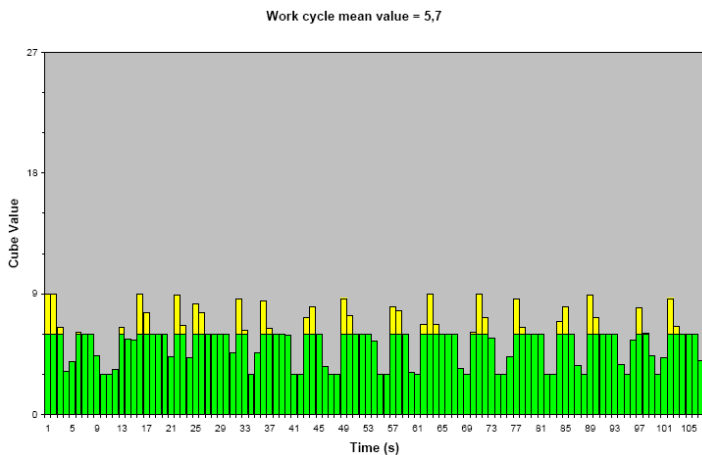


Figure 16: ErgoSAM analysis of concrete worker's short work cycle during SCC casting. Below 6 is acceptable, 6 to below 9 is conditionally acceptable and 9 and above is unacceptable.

## 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.

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.

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