LICENTIATE THESIS

Mapping the Concept of Industrialized Bridge Construction

Potentials and Obstacles

Johan Larsson

LULEÅ UNIVERSITY OF TECHNOLOGY

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"I can´t understand why people are frightened of new ideas.
I´m frightened of the old ones."

- John Cage

PREFACE

The research this thesis is based upon was conducted during two and a half years at Luleå University of Technology's Division of Structural and Construction Engineering – Structural Engineering. I would like to take the opportunity to thank some people and organizations that greatly assisted me during the work.

First I want to express my gratitude to my head supervisor at LTU, Prof. Mats Emborg, for supporting and putting up with me, despite my sometimes "too" strong determination, and my co-supervisors Prof. Thomas Olofsson and Dr Martin Nilsson for believing in my ideas and helping me through the last hectic couple of months.

Further, I like to acknowledge my former colleague Peter Simonsson for your mentorship and interest in my research.

The research was supported by the Swedish Transport Administration (STA), NCC, SBuF, Betongindustri and Abetong. All these contributors are gratefully acknowledged.

I would also like to express my gratitude to the reference group who provided me with empirical material and useful input during meetings and other activities. I would particularly like to acknowledge Magnus Alfredsson (NCC) for his time and support, especially in the study of Highway 50. To be able to work closely with a company is inspiring and probably necessary for me to avoid insanity.

My colleagues at Structural and Construction Engineering have provided great help and support in times of confusion and stress. I highly appreciate you. I would like to especially acknowledge Gustav Jansson for our inspiring discussions and thrilling squash matches.

Many people have been of help during this journey, but the greatest source of inspiration has been to come home to my family after an exhausting day at work. The three people I want to acknowledge the most are therefore my beloved family: Lisa, Oliver and Elsa. What would I be without you?

Johan Larsson
Luleå, December 2012

ABSTRACT

Improving productivity is a central challenge in all industries, but particularly in construction where improvements have been slow, as highlighted by governmental reports and research publications from many countries (e.g. the UK and US). In Sweden the urgency of improving productivity and client satisfaction in the construction industry have initiated a number of government investigations.

Recommendations arising from one of these investigations include improving the planning of procurements for projects, increasing the numbers of turnkey contracts and raising the industrialization of the sector. As a response, the Swedish Transportation Administration (STA) has launched a research and innovation program to foster an industrial mindset and identify ways to increase the standardization of products (among other desired changes). However, increasing industrialization has been difficult to achieve in the project-based construction industry, except in the process-based housing sector.

Thus, the aim of the research this thesis is based upon was to identify the most important components and processes that can be industrialized to make bridge construction projects more efficient. For this purpose, empirical data have been collected through questionnaire surveys, workshops and case studies. Analyses of the data have been presented in four appended papers, which contribute to reach the overall aim by mapping key aspects of the industrialization concept.

One of the interesting aspects highlighted by the empirical results is that the practitioners and industry experts have a multi-facetted view of industrialization, a concept involving elements like prefabrication, standardization and processes. Many of the identified core elements of industrialization are related to processes (long-term) rather than projects (short-term).

Several major barriers for industrialization have been identified, including: lack of repetition possibilities, strict norms and rules, Design-bid-build contracts, government regulations, and conservatism in the infrastructure sector. Interestingly, three out of these five major barriers could be traced back to the client's role. Hence, the clients (e.g. the STA in Sweden) must address these barriers in order to facilitate increases in industrialization. The long-term research and innovation program launched by the STA, where increasing industrialization throughout the value chain and standardization of products are on the agenda, is a first step towards breaking down the barriers, thus enhancing the possibilities for increasing productivity.

Furthermore, the results show that standardization of components and products is a possible way of decreasing complexity in on-site construction. The case studies performed have shown that massive time savings can be achieved by utilizing prefabrication instead of traditional on-site construction. However, standardization and prefabrication will not become more common until identified drawbacks, like aesthetics issues and assumptions that they reduce quality, are recognized and addressed by practitioners. In addition, the opportunities for applying large-scale production processes and repetition are currently limited, and must be expanded, before standardized parts and products can be more frequently used.

The general conclusion of this research is that massive time savings can be achieved by utilizing more industrialized methods and techniques during the construction of concrete bridges, but substantial barriers must be tackled before long-term productivity increases can be achieved.

Keywords

Industrialized construction, infrastructure, concrete bridges, prefabrication, standardization, construction process

SAMMANFATTNING

Att förbättra produktiviteten är en central utmaning i de flesta branscher, så även inom byggbranschen. I många länder som exempelvis Storbritannien och USA har statliga rapporter och vetenskapliga artiklar visat på byggbranschens långsamma produktivitetsökning. I Sverige har detta utretts i ett antal statliga utredningar.

I en av dessa rekommenderas bättre planering avseende upphandlingar av projekt, ökad andel totalentreprenader och att byggbranschen måste bli mer industrialiserad. Som svar har Trafikverket startat ett forsknings- och innovationsprogram där ett ökat industriellt tänkesätt och standardisering av produkter finns på dagordningen. Med undantag för den processbaserade husbyggnadssektorn har ökning av industrialisering emellertid varit svårt att åstadkomma inom den generellt projektbaserade byggbranschen.

Målet med forskningen i denna avhandling är att hitta och utreda de viktigaste delarna och processerna som kan industrialiseras för att göra brobyggandet effektivare. Empiriska data har samlats in genom två enkätundersökningar, en workshop och två fallstudier. Resultatet har analyserats och resulterat i fyra artiklar med fokus på att kartlägga begreppet industrialisering. Varje artikel bidrar till att uppnå målet men fokuserar på olika aspekter av begreppet.

En intressant aspekt av de empiriska resultaten är den mångfacetterade syn praktiker och branschexperter har på konceptet, industrialisering. Detta koncept innehåller delar som prefabricering, standardisering och process-fokus. Intressant är att de identifierade centrala delarna av industrialisering fokuserar mer på processer (långsiktigt tänkande) snarare än på projekt (kortsiktigt tänkande).

Följande hinder för industrialisering har identifierats: brist på upprepningsmöjligheter, strikta normer och regler, utförandeentreprenader, statliga regleringar samt den befintliga konservatism som finns inom infrastruktursektorn. Det har klarlagts att av dessa fem hinder kan tre spåras tillbaka till beställaren. Följaktligen måste beställarna (t.ex. Trafikverket) ta itu med dessa hinder för att öka möjligheten till en industrialisering. Ett första steg mot detta är

lanseringen av det långsiktiga forsknings- och innovationsprogrammet där ökad industrialisering genom hela värdekedjan och standardisering av produkter finns på dagordningen. I detta forskningsarbete anses detta vara ett viktigt steg i rätt riktning mot ökad produktivitet och kundnöjdhet vilket har belysts i ett antal rapporter.

Standardisering av komponenter och produkter har visat sig vara ett möjligt sätt att minska komplexiteten i samband med platsbyggnation. De utförda fallstudierna har visat att omfattande besparingar i form av tid kan uppnås vid användning av prefabricering istället för traditionell platsbyggnation. Standardisering och prefabricering kommer dock generellt inte att bli vanligare så länge de identifierade nackdelarna såsom gestaltning och antaganden om en kvalitetssänkning i och med prefabricering finns tillgänglig i branschen. Även de små möjligheterna för storskalig produktion och upprepning inom dagens brobyggande är hinder mot både standardiserade delar och produkter men också standardisering av processer och ett långsiktigt tänkande.

Den allmänna slutsatsen av denna forskning är att stora besparingar i form av tid kan uppnås vid användning av mer industrialiserade metoder och tekniker vid byggandet av betongbroar. Detta förutsätter att de nämnda hindren måste undanröjas innan långsiktiga produktivitetsökningar kan uppnås.

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Paper I:

Larsson, J., Olofsson, T., Eriksson, P-E. and Simonsson, P.
Industrialized construction in the Swedish infrastructure sector: core elements and barriers. (Submitted for publication in *Construction Management and Economics*, Nov. 2012).

Paper II:

Rwamamara; R., Simonsson, P. and Ojanen (curr. Larsson), J. (2010) Advantages of Industrialized Methods Used in Small Bridge Construction. *Proceedings of the 18th Annual IGLC Conference (International Group for Lean Construction)*, July 14-16 2010, Haifa, Israel.

Paper III:

Larsson, J. and Simonsson, P. (2012) Barriers and Drivers for Increased Use of Off-site Bridge Construction in Sweden. *Proceedings of the 28th Annual ARCOM Conference,* September 3-5, Edinburgh, UK.

Paper IV:

Larsson, J. and Simonsson, P. (2012) Decreased Complexity of Bridge Construction through Prefabrication: A Case Study. *Proceedings of the 20th Annual IGLC Conference (International Group for Lean Construction),* July 18-20, San Diego, USA.

APPENDICES

Appendix 1: Questionnaire survey – Questions (In Swedish)

Appendix 2: Workshop – Questions and summary of results (In Swedish)

1 INTRODUCTION

This chapter presents an introduction to the topic and the background to the studies the thesis is based upon. It then describes the aims, objectives, research questions and delimitations of the research. The chapter ends by outlining the disposition of the thesis.

1.1 Background

Improving productivity is a central challenge in all industries, but particularly in construction where improvements have been slow, as highlighted by governmental reports and research publications from many countries including Great Britain, USA and Australia (e.g. Egan 1998; Teichholz, 2004; Blismas and Wakefield, 2009). In Sweden, the urgency of improving construction productivity and client satisfaction has initiated a number of government investigations (SOU, 2002, 2009 and 2012).

Several productivity studies (e.g. Horman and Kenley, 2005; Mossman 2009; Simonsson 2011) have also shown that large amounts of waste are generated in traditional on-site construction projects. Such wastes - of material, time and other resources - are clearly detrimental to productivity. Furthermore, various authors (e.g. Bertelsen, 2003; Dubois and Gadde, 2000) have shown that conditions in on-site construction are highly complex and unpredictable, often due to the uniqueness of each project, one-of-a-kind production, and loosely coupled supply chains.

In other industries, waste reduction and productivity improvements are achieved by continuous, long-term improvements of industrialized processes (e.g. Winch, 2003). Accordingly, researchers and practitioners argue that the construction industry could learn from other industries, especially manufacturing sectors such as the automobile industry (Gann, 1996). Identified strategies, for the construction sector, that can enhance industrialization include standardization and prefabrication, which can minimize the variation in industrialized construction processes (Björnfot and Stehn, 2005), and lean philosophy. These strategies have been successfully applied in Japan and Sweden, especially in the detached single family house market (Gann, 1996; Bergström and Stehn, 2005). Indeed, housing production companies in Sweden have worked with industrialized processes and prefabrication for decades, resulting in continuous productivity improvements (e.g. Höök and Stehn, 2008; Segerstedt and Olofsson, 2010; Lessing, 2006). New industrialized building concepts for multi-family residential housing have also been introduced by construction companies in Sweden during the last decade (Segerstedt and Olofsson, 2010), although at a relatively modest pace (Söderholm, 2010). However, the construction industry is far from homogeneous in this respect. In other sectors of construction, such as the construction of bridges, other major infrastructure projects, and complex industrial or commercial buildings, increases in industrialization have been slow and difficult to achieve, according to Winch (2003).

1.2 Concrete bridge construction in Sweden

The infrastructure sector is a major component of the construction industry, and is project-oriented in the sense that unique, one-off products are generally produced during limited timeframes. As part of this sector, concrete bridge construction shares these characteristics, and is based on traditional on-site methods. The general production strategy applied in such infrastructure projects can be formally described as concept-to-order (CtO), one of four main production strategies described by Winch (2003), as illustrated in *Figure 1.1*. For explanation of the four production strategies and process flow described by Winch (2003), see Section 2.3.4.

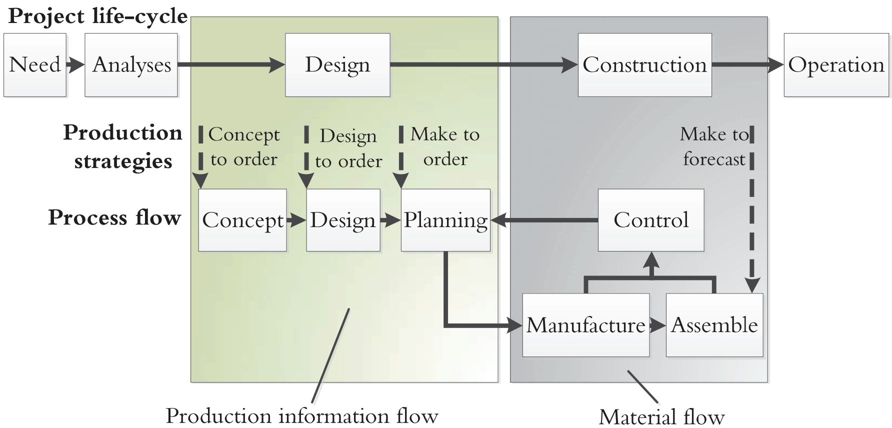

Figure 1.1 *Traditional project life-cycle, and the production strategies and process flow adapted from Winch (2003)*

Bridge construction is a typical CtO context, in which no production is initiated before the client enters the process. Concrete bridges are usually constructed on-site today, meaning that both manufacture and assembly are performed at site. A typical infrastructure project is initiated by the client, whose first action is to design the project in cooperation with a designer, see *Figure 1.1*. Furthermore, the contractor often enters the project late in the planning phase, when most of the design is complete and difficult to change to facilitate construction. This description applies to traditional Design-bid-build contracts, which are the most common type of contract in the Swedish infrastructure sector to date.

Bridges, designed before the contractor enters the process, are often tailored for on-site construction, mostly because this has been, and still is, the common way of constructing bridges in Sweden. However, this approach is hindering inclusion of the vast experience of contractors in the design process. Furthermore, it gives contractors no incentives to invest in products and processes that could increase the overall productivity of projects.

A recently published 30-year retrospective study shows insignificant increases in productivity when applying traditional measures for concrete operations such as formwork, reinforcement, and pouring (Bröchner and Olofsson, 2012). Furthermore, newer bridges have consistently more concrete cover and reinforcement per square metre of useful surface area. Hence, the productivity per unit of useful bridge area has actually decreased, since the amounts of concrete and reinforcement used have increased. However, it is important to note that, because of this, newer bridges arguably have higher quality in a life-cycle perspective (Bröchner and Olofsson, 2012).

For the successful implementation of new methods and techniques in bridge construction, Simonsson (2011) argues that new processes involving all stakeholders in the building process must first be implemented. In addition, Gibb (2001) argues that conflicts between standardization and flexibility need to be resolved for successful introduction of industrialized construction. So the key issue are: can bridge construction be industrialized, and if so how?

The Swedish Transport Administration (STA), as the main client of infrastructure projects in Sweden, has been assigned the task of creating conditions that improve productivity within the infrastructure sector. A recent investigation of government clients' actions for improving productivity and the level of innovation in infrastructure projects has recommended that actions are needed to: improve planning regarding procurement for projects, increase the percentage of Design-build or turnkey contracts and enhance industrialization of the sector (SOU, 2012). In response, the STA has launched a long-term research and innovation program to identify ways to increase industrialization throughout the value chain and the standardization of products (Trafikverket, 2012). Actions to increase the productivity of infrastructure projects are especially important from a societal perspective since public money is spent on investments that are crucial for the development and economic growth of a country.

While large-scale clients are keen to see industrialization, there is an identified lack of knowledge among both practitioners and academics about the concept of industrialization in the context of infrastructure. The purpose of the studies underlying this thesis were therefore to fill this knowledge gap using survey studies, workshops and case studies to investigate the potential for industrialized bridge construction and obstacles to its implementation.

1.3 Research aim and questions

The aim of the research this thesis is based upon was to identify the most important components and processes that can be industrialized to make bridge construction projects more efficient.

To meet this aim the following three research questions were posed and addressed:

Question 1: What are the elements of industrialized civil engineering, and in particular concrete bridge construction?

Question 2: What are the benefits and constraints of prefabrication and on-site construction?

Question 3: How does prefabrication affect the efficiency of concrete bridge construction?

1.4 Delimitations

One limitation of the research this thesis is based upon is that the studies only consider Swedish infrastructure and in particular small- to medium-span concrete bridges. These bridges were selected as objects for investigation because they are the most common in Sweden. The focus has been primarily on issues related to formwork rather than reinforcement and concreting.

Structural design issues have been ignored, because they are beyond the scope of the aims, and products are considered more from a production process perspective than an engineering perspective. Case studies of standardized bridges have been performed, but no full-scale tests of new bridge concepts have been performed within this research project.

1.5 Thesis disposition

The thesis comprises six chapters outlining various aspects of the research (see below for details), and four appended papers, which are summarised in Chapter 4.

Thesis chapters

Chapter 1 introduces the reader to the research field, then describes the project's aim and delimitations.

Chapter 2 presents theories of industrialisation in construction. Terms like lean, complexity, prefabrication, standardization are considered from an industrialized perspective.

Chapter 3 presents the research design and describes the methods used for collecting empirical data.

Chapter 4 summarizes findings presented in the four appended papers, in separate sections. Other papers that the author contributed to are also briefly presented.

Chapter 5 analyses and discusses the findings presented in all appended papers in relation to the theoretical framework.

Chapter 6 concludes the main findings in relation to the stated research aims and questions, and discusses the research quality. It ends with general conclusions and suggestions for further research.

2 THEORETICAL FRAMEWORK

This chapter presents the theoretical frame of reference, which includes reported work in the following fields: Industrialized construction, characteristics of construction, Lean philosophies, Prefabrication and Standardization.

2.1 Introduction to theoretical framework

The purpose of the theoretical framework is mainly to identify potential strategies for industrialization and productivity improvements, based on published theories and philosophies. However, this chapter starts with a general discussion of the concepts and terms used in the work. This is followed by insights into why construction is often regarded as considerably different from manufacturing and how its peculiarities affect the potential for industrialization. Finally, strategies for industrialization used and analysed in the thesis are presented.

Most literature concerning aspects of this theoretical framework deals with industrialized housing production, while studies on industrialization of infrastructure are scarce. With few exceptions, e.g. Simonsson (2011) and Harryson (2002), little has been written on industrialization in the context of civil engineering (or infrastructure) projects, especially concrete bridge construction. Hence, one must always be aware of differences in the two contexts and try to adapt findings from housing studies to infrastructure projects. Two major differences between the contexts in Sweden are that the Swedish infrastructure sector has only one main governmental client (the STA), while the housing sector has a huge array of clients (Levander et al., 2011), and the infrastructure sector is more tightly controlled by government rules and norms. Almost all of the characteristics of traditional construction (as opposed to industrialized construction) highlighted in the literature cited in Section 2.2, are valid for the infrastructure sector generally, and concrete bridge construction particularly.

It should be noted that there may be differences between industrialization of construction and industrialized construction, as argued by several researchers (e.g. Olander et al., 2011; Lessing, 2006; Harryson et al., 2006). However, this is debatable, and in this thesis they are only considered to be different terms covering all activities performed to increase productivity in construction.

Lessing (2006) described eight characteristics that collectively comprise the concept of industrialized housing construction, as illustrated in *Figure 2.1*. In the figure these eight characteristics are surrounded by continuous improvements, to symbolize the process focus that prevails in industrialized house building. These characteristics were selected with input from historical descriptions, the present understanding and with inspiration from production paradigms and concepts. Experts in the field of industrialized house building were interviewed to verify the model (Lessing, 2006).

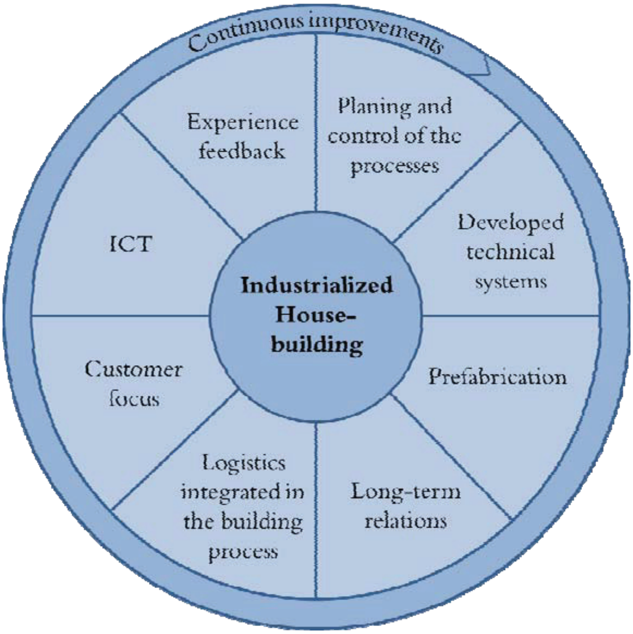

Figure 2.1 *Industrialized House-building Process Model, from Lessing (2006)*

Furthermore, another term that is used in the thesis and should be explained is productivity. According to various authors, e.g. Tangen (2005), the term incorporates both efficiency and effectiveness, where efficiency essentially means doing things right, while effectiveness essentially means doing right things.

In other industries, waste reduction and productivity improvements are addressed by long-term continuous improvements of industrialized processes (Winch, 2003). Accordingly, researchers and practitioners argue that the construction industry could learn from other industries, especially manufacturing sectors such as the automobile industry (Gann, 1996).

Some characteristics of construction and industrialization strategies (lean philosophy, lean construction, product standardization, prefabrication and process standardization) are presented in the following two sections.

2.2 Characteristics of construction

Construction is said to be conservative, risk-adverse and wasteful (Styhre, 2010; Teo and Loosemore, 2001). Koskela (1992) attributed the peculiarities of construction, e.g. one-of-a-kind products, temporary organization and on-site production, as reasons for its inefficiency observed compared to manufacturing production systems. Bertelsen (2004) and Kenley (2005) pointed out that construction has to be seen as a non-linear complex system that cannot be planned and managed like a regular linear and predictable manufacturing process. Three complicating aspects of the non-linear system are identified and discussed by Bertelsen (2004): 1) the non-linearity of the world outside the project, 2) the involvement of several actors with different goals in many projects, and 3) the deployment of temporary project teams, often hired from different subcontractors by the main contractor. Dubois and Gadde (2002) and Hughes et al. (2010) confirm that on-site construction often involves numerous suppliers and subcontractors in temporary networks.

On the other hand, Koskela and Howell (2002) suggest that construction projects can be seen mainly as linear processes and that successful management is based on sound strategies founded (either implicitly or explicitly) on conceptual frameworks such as Transformation, Flow and Value generation theories. Uncertainties like the weather, material and component deliveries, and other surrounding problems, do not make construction impossible to plan and manage. Moreover, a project team should minimize the degree of uncertainty by planning the process as well as possible, according to Sardén and Stehn (2009). By focusing not only on reducing on-site activities and variation, but also engaging participants early and putting more effort into design, the outcome of the construction process will become more predictable. Thus, measures for improving productivity in the construction industry have been identified (e.g. prefabrication and standardization), but they have not been widely adopted. One reason for this, according to Kadefors (1995), is that the construction industry is subject to strong institutionalization due to the need for coordination and communication in complex project organizations, explaining why innovations in individual projects seldom bring about long-term changes.

The peculiar relationship between design and production in Design-bid-build contracts complicates relationships between the client, the principal designer and the main contractor since they share the role of system integrator (Lambert et al., 1998; Segerstedt and Olofsson, 2010). Frödell et al. (2008) also found symptoms of "customer co-production", which are typical in service-oriented industries, in a study of the impact of Swedish construction clients' ability to take decisions on the success of projects. Furthermore, Fox et al. (2002) found that "designers participate in customer-led location-specific design", and that this results in "little, or no, repetition of post-order design certainty." Thus, many work tasks that are similar, but not identical, have to be performed manually, since it is not economically viable to invest in machinery that would facilitate more efficient construction. This complicates the link between contractor productivity and client productivity, since construction clients often procure contract work based on detailed specifications (Bröchner and Olofsson, 2012).

2.3 Industrialization strategies

Construction is often compared to manufacturing industries in terms of improvements to productivity and industrialization (Gann, 1996). According to Winch (2003), models for industrialization taken from the manufacturing industry are often seen as solutions to the lack of productivity improvements in construction. However, industrialization involves not only implementing new products and process innovations but also cultural and attitudinal changes, according to Liker (2008).

Similarly, Courtney and Winch (2003) found that improvement issues are often more strongly related to organizational and behavioural factors than to technological factors. Hence, drivers for change and committed actors are necessary for innovations supporting the successful implementation of industrialization in construction (Harty, 2008), and knowledge is probably the most important (and essential) asset within an organization (Dave and Koskela, 2009; Gluch, 2011).

In the following subsections industrialization strategies are highlighted to provide a clear view of the theoretical framework used and discussed in later sections. Four strategies (lean philosophy, lean construction, standardization and prefabrication) are identified as possible solutions to overcome the lack of productivity increases in the infrastructure sector.

2.3.1 Lean philosophy

Lean production was conceptually established in the beginning of the 1990's in the well-known book "The Machine that Changed the World" by Womack and Jones (1990). Lean production is, according to the cited authors, a philosophy that provides increasingly better ways to meet customers' needs using less of everything: less material, fewer working hours, less energy and less space.

The fundamental ideas for the philosophy are derived from the Toyota Production System (TPS). Lean production was conceptualized to transfer the Japanese TPS in a suitable form for Western society. While it was first developed for the automotive industry, Womack and Jones (2003) presented five fundamental lean principles that are applicable in all industries: 1) Value, 2) Value stream, 3) Flow, 4) Pull, and 5) Perfection.

Furthermore, after studying Toyota's system for two decades, Liker (2004) developed the Toyota's 4P model of production, which summarizes TPS in 14 principles and organizes them in four sections, see *Figure 2.2*.

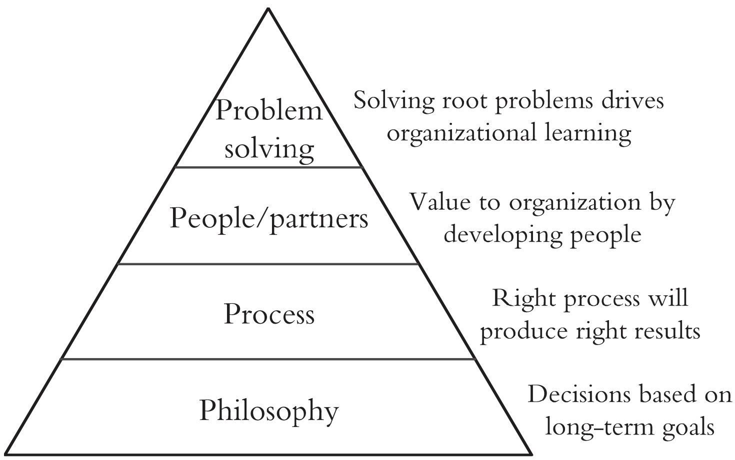

Figure 2.2 *Toyota's 4P model of production, from Liker (2004), simplified by excluding the 14 principles*

Lean production involves not only the application of lean methods, cutting waste from production and continuous improvement, but also changing people's approaches for organizations to become leaner. Of course, lean tools like *Just-In-Time, one-piece-flow, Kaizen* and *Jidoka* (see

Bicheno (2008) for details) cannot be ignored as they are fundamental guidelines, founded in the philosophy of lean production, for the mind-set and strategies that it tries to create, where Liker (2004) is an appropriate reference.

Important elements for the success of Toyota, and its production system TPS, according to Liker (2004), are the abilities to develop leadership, create focused teams and a functional culture, develop appropriate strategies, build partnerships with suppliers and maintain a learning organization.

2.3.2 Lean construction

Koskela (1992) developed a theory known as TVF (Transformation, Flow and Value), which became the main lean production strategy adapted to construction and its prevalent project orientation. Today, this form of lean production is better known as lean construction (e.g. Koskela, 2000; Ballard, 2000). Ballard and Howell (1998) argue that lean production can be applied to parts and components that can be manufactured off-site, while lean construction techniques should be developed to "minimize the peculiarities" of on-site construction.

The basis of lean construction is similar to that of lean production, but with modifications to fit the complexity (or characteristics) of construction presented by Bertelsen (2003). One such modification is the last-planner system, developed by Ballard and Howell (1994) amongst others, to shield on-site construction from variation in flows of work and materials.

Following the modifications of lean philosophy for application in construction, Bertelsen and Koskela (2004) argue that lean construction and its understanding for construction management have progressed “beyond lean”. As often stated, construction is turbulent, complex and unique, involving the production of one-of-a-kind products via the cooperation of a multi-skilled team (Bertelsen and Koskela, 2004; Bertelsen, 2003; Ballard and Howell, 1998). Hence, according to Bertelsen and Koskela (2004), it is impossible to implement the five lean principles (Value, Value stream, Flow, Pull and Perfection), at least without adjustment, in construction because it is so different from ordinary manufacturing. However, Liker (2004) points out that the continuous one-piece-flow concept, a fundamental principle in TPS, is universally applicable for identifying problems and fostering innovation and creativity. Furthermore, as discussed by Ballard and Howell (1998), lean philosophy is a new and important way to manage construction: construction must be seen as a system and efforts must be made to improve all aspects of the process. Thus, in order to change mental models, as Ballard and Howell (1998) called this process, there must be a deeper understanding of lean philosophy among practitioners.

2.3.3 Product standardization and prefabrication

The complexity at a construction site can be reduced by two strategies emerging from lean construction: developing standardized products and prefabrication (S&P), as proposed by Ballard and Arbulu (2004), or by developing standardized on-site construction processes, as proposed by Koskela et al. (2003). S&P is discussed in this subsection, while the development of standardized processes is considered in Subsection 2.3.4. Standardization and prefabrication (S&P) are two ways to produce industrialized products, but they are highly intertwined. Therefore, they are discussed together in this section.

The rationale of S&P is to simplify and minimize work at site and by considering every phase in the delivery process. Use of prefabrication as part of an industrialized construction process provides a way to control unpredictable events, according to Björnfot and Stehn (2005). However, according to Gibb (2001) S&P does not always solve key problems, notably conflicts between standardization and flexibility have not yet been resolved. Gann (1996) believes that balancing standardization and flexibility is a key for success.

Moreover, Gibb and Isack (2003) define four categories of pre-assembly (or prefabrication as this technology is hereafter referred to in this thesis), see *Figure 2.3*. These four are briefly describe below:

1. *Components manufacture & sub-assembly* consists of standardized items like windows, always made in factory.
2. *Non-volumetric pre-assembly* involves pre-assembled units which do not create usable space and often are more complex.
3. *Modular Building* consists of pre-assembled volumetric units which form the actual structure and fabric of buildings like motels and medium rise residential.
4. *Volumetric pre-assembly* includes often fully equipped pre-assembled units, e.g. toilet pods, installed within or onto an independent structure frame.

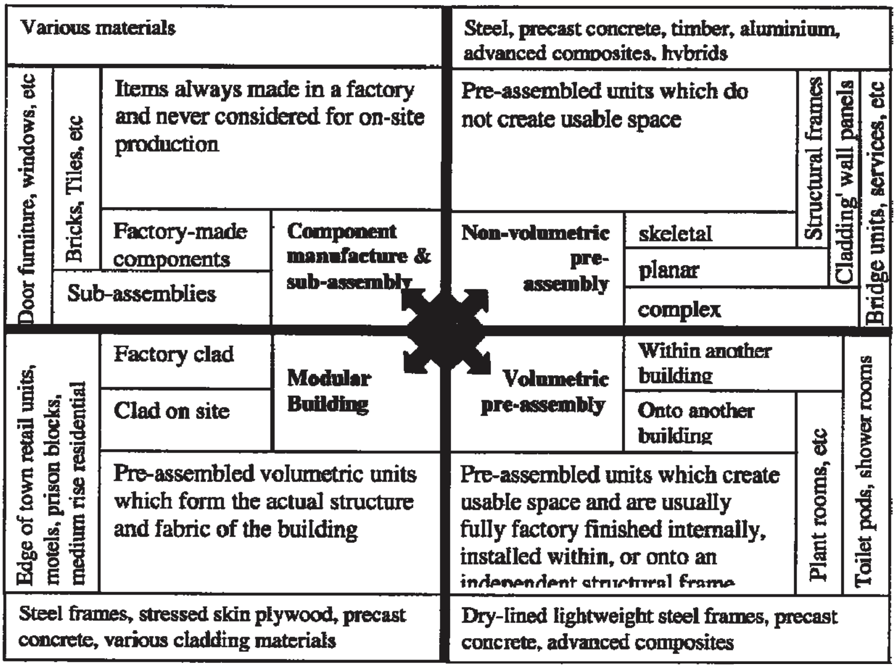

Figure 2.3 *Four categories of prefabrication, from Gibb & Isack (2003)*

Bridge units are examples of non-volumetric complex products that can be produced in factories and assembled on-site. This requires the integration of design and construction, which according to Jensen et al. (2012), demands complementation of the downstream flow of design information to production, with an upstream flow of constraints from production to design. Buildability aspects are, of course, integrated in industrialized construction concepts but can, according to Simonsson (2011), be accomplished by utilizing production competences in the conceptual stages of the project. Product platforms, modularization and configuration strategies have recently been advocated as possible strategies for standardizing products within the construction industry (e.g. Hvam, 2008; Jensen et al., 2012; Segerstedt and Olofsson, 2010).

The standardization of tasks and products is closely related to lean philosophies. In general, S&P has been recognised as a vital element for improving construction in terms of efficiency and productivity (Blismas and Wakefield, 2007). Four major drivers for prefabrication often mentioned in the literature are: time, quality, cost, and health and safety (H&S) (Blismas et al., 2006; Gibb and Isack, 2003).

Barriers for the implementation of prefabrication identified in the literature are mostly related to processes, value, conservatism and knowledge (Blismas et al., 2005). A major drawback for prefabrication in general is that the design of structures has to be established early in each project because of the long supply-chain associated with this technology. Thus, Pan and Sidwell (2011) and Gann (1996) claim that successful prefabrication requires a more complete understanding of the process and cooperation throughout the whole supply-chain. Similarly, according to Nadim and Goulding (2009), both academics and practitioners agree that communication skills, teamwork and problem-solving must play major roles to increase the uptake of S&P.

Many concerns associated with prefabricated bridge construction are the same as those associated with general prefabrication (see above) but a specific concern that must often be addressed is traffic disruption (NCHRP, 2003). However, according to Freeby (2005) and Russell et al. (2005), prefabrication is often assumed to disrupt traffic less than on-site construction.

Other documented drivers for prefabrication of bridges, according to Russell et al. (2005) are: improvements in Health & Safety (H&S), constructability and quality; together with reductions in adverse environmental impacts and life-cycle costs. These correlate well with drivers for prefabrication in general (Gibb and Isack, 2003). However, insufficient attention has been paid, to date, to the barriers and drawbacks that may hinder S&P bridge construction and the degree to which industrialized products satisfy client needs.

Benefits of S&P are well documented, but it is poorly understood by many practitioners, leading to a widespread reluctance to use it (Pasquire and Gibb, 2002; CIRIA, 2000). For a summary of previous S&P research, regarding mostly drivers and some barriers, see appended Paper III, Table 1.

2.3.4 Process standardization

Winch (2003) identified four production strategies for construction projects, see *Figure 2.4* (and *Figure 1.1*). These are briefly described below:

1. Concept-to-order (CtO) where the client enters at the start of the concept stage and nothing happens until client initiate production.
2. Design-to-order (DtO) where contractor already has a basic product portfolio, but significant engineering work is needed to satisfy each specific customer/client.
3. Make-to-order (MtO) where there is a fully detailed product that only has to be configured to suit the specific customer. This production strategy has become known as mass customization (e.g. Jensen, 2012).
4. Make-to-forecast (MtF) where the product is produced for stock and sold afterwards.

Further, Winch (2003) emphasizes the important to focus more on production information flow (e.g. procurement, tender, product development) instead of material flow. Hence, the information flow initiates and controls the material flow (see *Figure 1.1*). Infrastructure projects being characterized as complex, small-volume systems produced mainly using the "CtO” strategy. Standardization should lead to better-defined products and processes, thus complexity and unpredictability should decrease if more standardized production strategies are used.

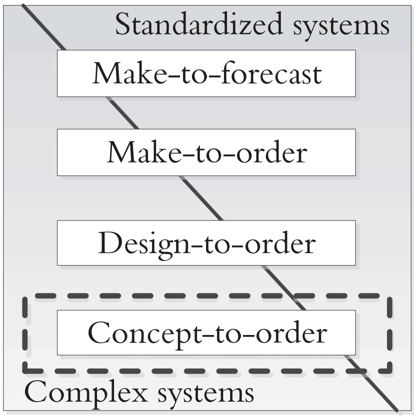

Figure 2.4 *Four production strategies, adapted from Winch (2003), and connection to complexity/standardization*

Winch (2003) identified several reasons for the failure of many efforts to industrialize the construction process, e.g. lack of on-site management control and the frequent exclusion of product design from production control.

The construction industry, including the infrastructure sector, is generally very product-oriented, and process improvements are seen by many authors as the most important step towards productivity improvements. However, there are some exceptions, like the industrialized Swedish housing industry, that focus more on processes than on products (Höök and Stehn, 2008). The industrialized housing industry applies the DtO production strategy, according to Lessing (2006). Firms adopting this production strategy have a basic product concept, but substantial engineering design is needed to meet each customer's specific requirements.

Gann (1996) compared the industrialized Japanese housing industry to automotive manufacturing and found significant similarities in their processes, particularly in a focus on managing the whole production system rather than parts of the process separately. This is relatively rare in construction, including infrastructure construction, where the focus is generally on individual projects rather than long-term processes. Processes are often seen as critical focus in manufacturing industry culture, according to Riley and Clare-Brown (2001), but not in construction, partly because construction has lacked recognized methodological foundations for process improvement initiatives (Hutchison and Finnemore, 1999). Thus, process improvements are required, and they should be characterized by small, continuous step-by-step changes, which have been shown to be effective in (for instance) the industrial housing industry (Lessing, 2006).

In construction concepts and projects, different preparatory work is carried out before the customer order arrives and before realisation of the project. Consequently, more focus should according to Winch (2003) be on the flow of information, rather than material flow that is more common in the construction industry. Different kinds of product specification processes can be identified, which are closely related to the proposed product flexibility, design entry point for the client and the contractual relationship between the client, the principal designer and the main contractor (Winch, 2003; Hvam et al., 2008; Segerstedt and Olofsson, 2010).

3 METHODS

This chapter presents the research strategy and design, describes the methods applied in the studies, and considers their validity and reliability for addressing the research questions.

3.1 Research strategy

Generally, research methods should be selected that are concordant with the overall aims and formulated questions of an investigation (Miles and Huberman, 1994; Yin, 2009). In the studies this thesis is based upon, a mixed method approach was adopted (Creswell, 2002), that is both qualitative and quantitative data were collected, compared and interpreted together, to increase the reliability of the empirical results.

Yin (2009) lists five major qualitative research strategies: experiments, surveys, archival analyses, histories and case studies. Descriptive studies based on surveys are appropriate for addressing "what and which" questions (Yin, 2009), such as the first two research questions listed in Section 1.2 of this thesis. Hence, it was decided that a questionnaire survey, with both quantitative and qualitative elements, should be applied in the first study of the project this thesis is based upon (hereafter the project, for simplicity). It should be noted that qualitative research methods are suitable for acquiring rich descriptions of a studied phenomenon, but only for specific, targeted cases. Hence, conclusions drawn from data acquired using them should be regarded as hypotheses or indications rather than general findings (Denzin and Lincoln, 2005). The first survey was subsequently complemented with another questionnaire survey (see below)

However, qualitative methods can include quantitative elements, which can increase the validity of the data collected (Miles and Huberman (1994), and provide absolute numbers, proportions or ratios that can be generalized (to some degree) to larger populations. Therefore, quantitative elements were included in the questionnaires. In addition, a qualitative workshop was held to further increase the validity of the results.

The last method selected to use in the research was case study, which is often considered the best strategy for exploring problems that require deep contextual understanding (Merriam, 1998). Two single case studies were performed to help address the last "how" research question listed in Section 1.2. A common drawback of case studies is the difficulty in establishing delimitations, which often leads to the collection of very large amounts of data (Denzin and Lincoln, 2005). Applying multiple data collection methods, as in this project, allows general conclusions to be drawn, even when limited numbers of cases are considered, as also pointed out by Gummeson (2000).

3.2 Project description

The initial focus of the project, according to the grant application, was to develop a "new industrialized concrete bridge type" involving both prefabrication and on-site construction. The focus was to be primarily on identifying new solutions for formwork and prefabricated components involved in the new concept. The objective of the project was to optimize production methods, study structural design solutions and standardization, and connect all this with lean construction tools to increase the degree of industrialization.

The interest in developing the whole bridge construction chain (see *Figure 1.1*) has helped the acquisition of a good overview of civil engineering processes in Sweden and the identification of real weaknesses in concrete bridge construction. However, it has made focusing the analysis difficult in some cases, since the field of interests sprawled as the project progressed.

The first action undertaken was to map potential industrialized working methods and prefabricated components used in the civil engineering industry. However, after starting to investigate the industry, a larger knowledge gap was found regarding production- and processes-related issues than in the products themselves. Consequently, the focus shifted more towards production-related questions than product-related issues. Nevertheless, while production has been the primary concern, it is not possible to focus solely on it. Every link in the chain, from design to maintenance, affects all the others in several ways. Thus, to fully understand the concept of industrialization, the whole chain has to be considered. Therefore, a new aim was formulated for the project reflecting this shift (see Section 1.3).

3.3 Research design

A thorough description of the chosen research procedures is vital to enable readers to evaluate the reliability and validity of presented results (Yin, 2003). A research design is an action plan describing how empirical data relate to the aims and conclusions of the research. Accordingly, a thorough research design was established for the project, as illustrated in *Figure 3.1*. Application of the chosen methods within this framework yielded results presented in the four appended papers addressing the aim and three stated research questions.

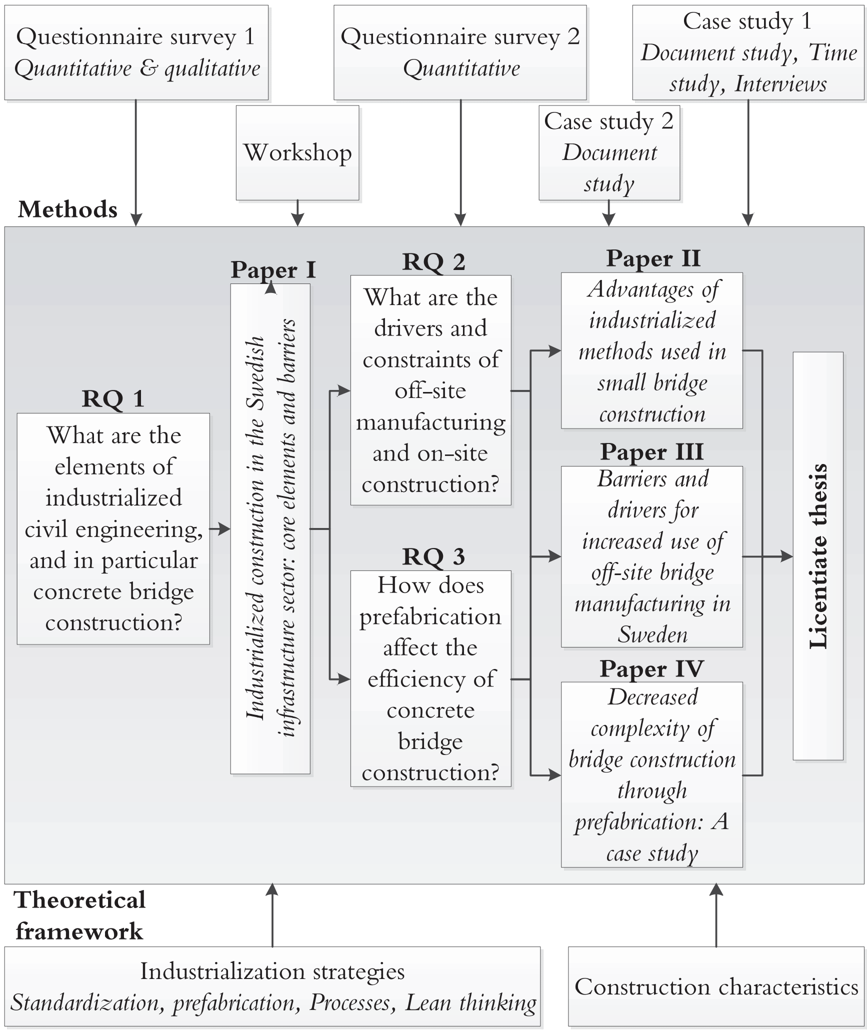

Figure 3.1 *Research design of the research project*

To obtain general insights into the bridge construction industry, the first study (Paper I) examined the infrastructure industry as a whole in broad perspectives. The other three (Papers II-IV) focused on how identified core elements of industrialized infrastructure construction affect the process of constructing bridges.

Papers I and III are based primarily on Questionnaire survey 1 and the workshop. In addition, Paper I includes results from Questionnaire survey 2, which was primarily conducted for The Productivity Committee (Eriksson et al., 2011). Papers II and IV are based on empirical results from two case studies, acquired through document studies, interviews and time studies.

Lean thinking has permeated the whole project work from start to finish, as a philosophy rather than a tool for step-by-step improvements, (see Subsection 2.3.1 for further explanation). Attempts have been made throughout the project, and in the thesis, to capture the very essence of Lean as a philosophy: the continuous striving to improve performance, questioning current methods, standardization of work and products and awareness of long-term thinking and commitment.

3.3.1 Questionnaire survey 1

Objective

The first two research questions were primarily addressed by gathering data using a questionnaire survey to gain a deeper understanding of how general practitioners of civil engineering in Sweden relate to the concept of industrialized construction. The survey was undertaken during autumn 2010 and the last answered questionnaires were received in November 2010.

Questionnaire

Before distribution, the questionnaire was discussed and debated with several people, practitioners and academics, in order to minimize misunderstandings and leading questions (since leading questions and loaded formulations can strongly influence the answers). The questionnaire consisted of both closed and open-ended questions. Responses of open-ended question are more difficult to compile than those of structured survey questions, but provide richer material. Thus, the answers were very information-rich.

The questionnaire included 25 questions covering a variety of subjects, e.g. important factors for bridge construction, contract forms and current conditions in civil engineering (see Appendix 1 for a complete questionnaire in Swedish). A paper version was sent to the respondents by e-mail, enabling it to reach numerous respondents simultaneously.

Sample

Suitable respondents were chosen after discussion with experienced practitioners working in major civil engineering firms and associated companies in Sweden. The sample included clients, consultants, contractors and prefabrication suppliers. Characteristics of the respondents and their experience are summarized in *Table 3.1*. One hundred and fifty-nine questionnaire forms were sent out, and there were 66 responses, giving a response rate of approximately 42%.

Table 3.1 *Characteristics of respondents to Questionnaire survey 1 and their experience*

			Experience				
Dicipline	Resp.	No.	Years	Total	Years	On-site	Off-site
Contractor	Total	27	None		None	1	4
	Men	25	<1		<1		7
	Women	2	1-5	2	1-5	3	6
			5-10	2	5-10	3	1
			>10	23	>10	20	9
Client	Total	21	None		None	2	5
	Men	20	<1		<1		1
	Women	1	1-5		1-5	2	5
			5-10	2	5-10	2	2
			>10	19	>10	15	8
Consultant	Total	13	None		None		
	Men	10	<1		<1		3
	Women	3	1-5		1-5		5
			5-10		5-10	1	
			>10	13	>10	12	5
Off-site (supplier)	Total	5	None		None	1	
	Men	5	<1		<1		
	Women	0	1-5	1	1-5	2	2
			5-10		5-10		
			>10	4	>10	2	3
Total	Men	91%	None	0%	None	6%	14%
	Women	9%	<1	0%	<1	0%	17%
			1-5	5%	1-5	11%	27%
			5-10	6%	5-10	9%	5%
			>10	89%	>10	74%	38%

3.3.2 Workshop

A workshop attended by contractors, clients, consultants and off-site suppliers was held to discuss some interesting results regarding the industrialization context identified in the responses to Questionnaire 1. The workshop was part of a daylong conference on the subject *Research and development within bridges* arranged by CIR (CIB, IABSE, RILEM), held in Gothenburg, Sweden on 31 January 2012. Fourteen participants were invited, based on experience, interest and opportunity to influence the development of civil engineering in Sweden. These influential people were invited to enable the outcome to be transmitted to the rest of the industry. Three groups were formed to discuss five specific topics during the first hour of the workshop. Issues covered were:

1. What elements are included in industrialized thinking?
2. What is customer satisfaction and how do we increase it?
3. How do we create collaboration earlier in a project?
4. What are the common features of civil engineering projects, and thus have potential for standardization, using (for instance) experience feedback?
5. How do we increase the willingness to change in civil engineering?

Results from the group discussion were compiled and discussed jointly during the last hour of the workshop. For a summary of the workshop see Appendix 2. The number of respondents in Questionnaire survey 1 was too small for the results to be statistically significant. However, analysis of the results from the survey and workshop in conjunction provided opportunities to draw somewhat generalized conclusions, considering both the qualitative and quantitative elements to increase the reliability of the results.

3.3.3 Questionnaire survey 2

Objective

To enrich the empirical results presented in Paper I, the quantitative data gathered in Questionnaire survey 2 (originally for the Productivity committee) were included. This survey was originally undertaken for the Productivity Committee and presented in Eriksson et al. (2011). The survey was primarily based on previous case studies performed by the Productivity Committee, but also partly on findings from Questionnaire survey 1 and the workshop. Three structured questions with fixed responses were asked, regarding: 1) core elements of industrialized construction, 2) barriers for industrialized construction, 3) the products and components that could benefit from standardization and prefabrication. The objective was to quantify the opinions of practitioners with explicit interest in, and experience of, industrialized construction in the civil engineering sector. Information acquired from responses to all three questions was included in the study presented in Paper I to help map the concept of industrialized construction in civil engineering. Detailed information about the survey is presented in Eriksson et al. (2011).

3.3.4 Case study 1

Objective

The objective of this case study was to investigate whether using prefabrication instead of traditional on-site construction makes the bridge construction process less complex to manage and control (and thus, help to address primarily research question 3 outlined in Section 1.3). Value Stream Mapping (VSM) was used to map construction of both a semi-prefabricated superstructure (future state) and a superstructure constructed on-site (current state). VSM was also used to identify shortcomings that arise when a new construction method is introduced.

VSM

VSM is an effective method for identifying activities at a construction site and mapping manufacturing flows (Alvarez et al., 2009; Mehta, 2009). This is because the risks of sub-optimizing a process are reduced by analysing (and adjusting) the continuous flow rather than focusing on machines, transportation and personal utilization, according to Ballard et al. (2003), Arbulu and Tommelein (2002).

A traditional VSM includes two steps: 1) mapping flows in a "current state" to obtain a clear view of the existing construction process, and 2) mapping a "future state" in which root causes of waste are eliminated (Rother and Shook, 2004). The latter in this specific case study already existed, but had not been previously mapped; a prefabricated bridge, which is a rare feature in Sweden and hence was regarded as a "future state".

Simonsson (2011) lists and considers non-value-adding activities associated with traditional on-site construction. Some of these activities were omitted from this VSM, to make it more general, e.g. transportation and waiting time, which differ strongly between projects. Numerous minor activities are performed during the construction of a bridge and to make the VSM manageable only activities that last more than 10 hours were taken into account.

Studied object
The bridge studied in this research (STA bridge number 5-1243-1) spans the river Skenaån, 20km outside Motala in Sweden, *Figure 3.2*. The current state is represented by a traditional bridge constructed on-site, where all activities like constructing formwork, fixing and mounting rebar and concrete casting are performed on site, *Figure 3.3*.

Figure 3.2 *Completed semi-prefabricated bridge*

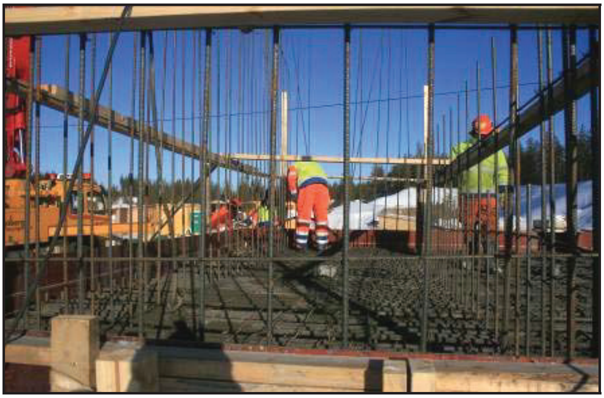

Figure 3.3 *Example of reinforcement fixing at on-site construction*

The focus was on mapping the future state and investigating how this rare construction method (in Swedish civil engineering), affects the construction process. Consequently, only this concept is studied at site and described in detail. This is a semi-prefabricated bridge concept called NCC Montagebro, developed for rapid, easy construction, making it suitable for bridges spanning water bodies, railways or busy roads where traffic disruption must be minimized. The substructure consists of foundations, plate structures and wings constructed on-site, *Figure 3.4*.

Figure 3.4 *On-site constructed substructure*

Prefabricated beams, edge beams and bridge slabs are placed on top of the substructure, when it has been constructed on-site, to form permanent formwork for the superstructure, *Figure 3.5* and *Figure 3.6*. Edge beams and beams are also included in the bearing system, reducing the amount of reinforcement and ready mixed concrete that needs to be added on-site.

After prefabricated parts have been mounted, the required reinforcement and complementary formwork is mounted into the superstructure. Finally, ready-mixed concrete is cast on the remaining formwork to create a continuous superstructure.

Figure 3.5 *Prefabricated beams on top of substructure*

Figure 3.6 *Placing prefabricated bridge slabs between beams*

Time study

A time study was used to map the future state, more specifically the mounting of the prefabricated part of the superstructure, which was done during two working days by the prefabricated structures suppliers' own workers. The time taken by each activity, e.g. crane work, mounting of slabs and reworking was monitored during these two days.

Document study and interviews

In order to map and compare the two construction methods accurately, calculated values from a suggested alternative bridge constructed on-site in the tender was used as the current state. This bridge was never actually built, so this part of the study was based on associated documents (e.g. drawings and calculations) and interviews. Activities that would have occurred during the hypothetical construction of the alternative bridge, constructed on-site, were discussed in interviews with project managers and practitioners. The activities were then placed in the correct sequence, and a value stream map was created for the on-site construction process. Calculations for the current state are regarded as reliable because it is the most common method of bridge construction in Sweden, and the data are based on key values from the company.

The future state (construction of the semi-prefabricated bridge) was primarily mapped by a time study, but data for some activities in the VSM were collected by studying documents such as timesheets, and by interviewing site managers.

Follow-up

After completion of the semi-prefabricated bridge, problems and shortcomings of this "future state", and root causes of the problems, were considered in follow-up discussions with the contractor, supplier and consultant. Findings from the case study were also presented and discussed during the follow-up to validate some of its important results.

3.3.5 Case study 2

Objective

The objective for Case study 2 was to investigate if standardization and simplification of both structural design and construction processes reduce costs related to building materials and manpower working hours. This case study helped to answer research questions 1 and 2 (Section 3.2).

Studied object

When the Swedish government decided to relocate the European highway E4 around a major city (Uppsala), 115 bridges had to be constructed, in addition to the new road. The whole construction project was to be carried out during approximately a five-year period.

The material examined in the case study included documents concerning the construction of small bridges on the 70-km long section of the rerouted E4 highway between Uppsala and Mehedeby.

Document study

The data examined in this case study were collected by reviewing internal company documents and previous case studies on the industrialized construction of bridges. The study focused solely on the construction of rigid frame concrete bridges during this major road project.

4 SUMMARY OF APPENDED PAPERS

This chapter describes the contributions of the author to the four appended papers, and summarizes both those papers and others written by the author.

4.1 Appended papers

Paper I: *Industrialized construction in the Swedish infrastructure sector: core elements and barriers*

This paper was written by Johan Larsson, Per-Erik Eriksson, Thomas Olofsson and Peter Simonsson. It was submitted, in November 2012, for publication in a special issue of the peer-reviewed journal, *Construction Management and Economics*, concerning industrialized building, with a planned publication date of 1 August 2013. My contributions were to formulate the fundamental ideas together with the co-authors, conduct one of the two involved questionnaire surveys, organise the workshop and lead the writing.

Paper II: *Advantages of Industrialized Methods Used in Small Bridge Construction*

This paper was written by Roumuald Rwamamara, Peter Simonsson and Johan Ojanen (curr. Larsson), and was published in Proceedings of the 18th Annual IGLC Conference, July 14-16 2010, Haifa, Israel. The conference proceedings have been subjected to peer review, by two referees, to ensure high standard. I co-planned the paper and contributed to both the research and writing related to formwork and health & safety.

Paper III: *Barriers and Drivers for Increased Use of Off-site Bridge Manufacturing in Sweden*

This paper, written by Johan Larsson and Peter Simonsson, was published in Proceedings of the 28th Annual ARCOM Conference, September 3-5 2012, Edinburgh, UK. Papers presented at this conference are peer-reviewed by at least two reviewers. I contributed to collecting data, formulating the fundamental ideas, major part of the writing and also orally presentation at the conference.

Paper IV: *Decreased Complexity of Bridge Construction through Prefabrication: A Case Study*

This paper was written by Johan Larsson and Peter Simonsson, and published in Proceedings of the 20th Annual IGLC Conference, July 18-20 2012, San Diego, USA. All papers presented at this conference are peer-reviewed to ensure high standard. My contribution was performing the case study and orally presentation at the conference and, together with Peter Simonsson, formulating fundamental ideas and writing.

4.2 Additional papers

A Study of the Future Concrete Bridge Construction in Sweden

This paper, written by Johan Larsson and Mats Emborg, was published in Proceedings of the XXI Nordic Concrete Research Symposium, May 30-June 1 2011, Hämeenlinna, Finland. My contributions were in conducting the questionnaire survey, analysing the survey data and formulating fundamental ideas together with Mats Emborg, and performing major part of the writing.

Future Development Potential for Concrete Bridge Construction in Sweden

This paper was written by Johan Larsson and published in the Czech journal TKS Beton (August 2012), which reaches out to academics and participants in the Czech Republic, after translation into Czech by the journal's editor. I was responsible for all of the reported work, including the data collection, data analysis and writing the paper.

4.3 Summary of papers

The summary of papers is presented in A3 format, inspired by Lean management (Shook, 2010). Many years ago, Toyota discovered that every task in a company can be summarized in a single A3 spread. This gives every person the opportunity to observer each task through the same lens. An A3-analysis will always fit into standard ISO A3 paper size (297x429 mm) and follow the same line of thoughts, but the content is flexible to fit companies' unique needs.

I have summarized each appended paper in a separate A3 presentation, to provide a good overview of its content. However, since the thesis is printed in S5 format, each paper is presented in a single S5 spread. All summaries include the following headings; Introduction, Results and Discussion & Conclusions. However, the focus is on presenting the main findings, which are subsequently used in the cross-analysis of data and conclusions presented in all of the appended papers.

4.3.1 Paper I: Industrialized construction in the Swedish infrastructure sector: core elements and barriers

INTRODUCTION

A recent investigation of governmental clients' actions to improve productivity and innovation in infrastructure projects has urged the sector to become more industrialized. As a response, the Swedish Transportation Administration (the largest governmental client in Sweden) has launched a research and innovation program to foster an industrial mindset and identify ways to increase the standardization of products (among other desired changes). Consequently, the aims of the study presented in this paper were to improve understanding of the concept of industrialization and investigate the barriers to its implementation in infrastructure projects. This was done by collecting data from two survey studies and a workshop to gauge the opinions of clients, consultants and contractors involved in the Swedish infrastructure sector.

RESULTS

Core elements of industrialized infrastructure construction

The findings show that knowledge about industrialization varies widely among practitioners, and have multi-facetted views of the concept. Five core elements of industrialized construction in infrastructure have been identified in the surveys and workshop; see *Table 4.1.*

Table 4.1 *Core elements*

1. Planning for efficient production	4. Prefabrication
2. Integrated design and production	5. Automation
3. Continuous improvement	6. Standardization & repetition

Barriers to industrialized infrastructure

Barriers to implementing industrialized construction were investigated by analyzing responses to the questionnaires used in the surveys, and six major barriers were identified, as summarized in *Table 4.2.*

Table 4.2 *Barriers to implementation*

1. Lack of repetition posibilities	4. Strong focus on lowest bid price
2. Norms and rules of STA	5. Design-bid-build contracts
3. Government rules regarding plans	6. Conservative industry culture

Suitable products and components for standardization and prefabrication

Concrete bridges were used as examples to identify products and components that may be suitable for standardization and prefabrication, and hence for industrialization. The results show that complex components like superstructure (or parts of it), and small bridges, are commonly regarded as being suitable by practitioners.

DISCUSSION AND CONCLUSIONS

Core elements of products and processes, barriers to the implementation of industrialization, and the main factors contributing to the barriers, were identified (*Figure 4.1*) by analysis and summarization of all the results. Some core elements and barriers are assembled as they are closely tied to each other.

An important contribution to the literature on industrialized construction is the identification of the core elements of industrialized infrastructure construction. Three are related to the process (Planning for efficient production, Integrated design & production, Continuous improvement) while only one (Prefabrication & automation) is directly related to the product. The fifth core element, Standardization, is related to both the product and the process. The existing product focus has to be shifted towards a more process focus to achieve a long-term productivity increase in infrastructure construction.

Three out of five barriers for industrialization (lack of repetition, norms and rules, procurement strategies) are controlled by the main client in Sweden (STA), so the STA has major responsibility for its implementation. The study confirms previous findings that a conservative culture in the construction industry is a barrier to innovation Kadefors (1995).

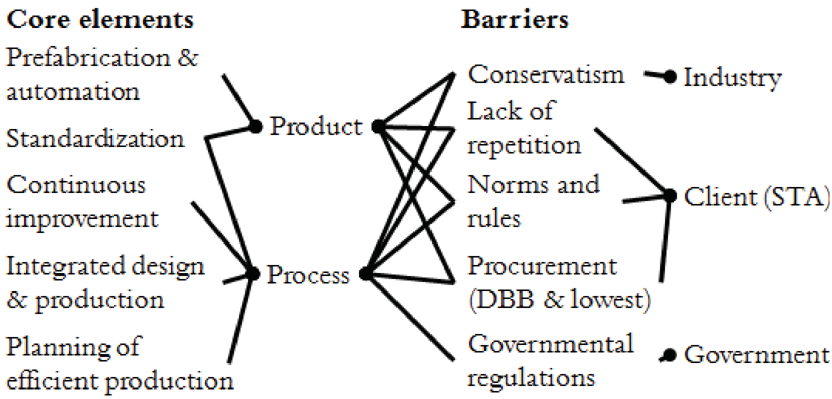

Figure 4.1 *Core elements of the products and processes, and barriers to the implementation of industrialization, in the Swedish infrastructure*

4.3.2 Paper II: Advantages of Industrialized Methods Used in Small Bridge Construction

INTRODUCTION

This paper presents research undertaken in response to the increasing demand for more efficient and competitive ways of constructing concrete bridges. Industrialized construction methods and techniques such as self-compacting concrete (SCC) casting, left formwork and the use of prefabricated reinforcement steel structures, are currently rather rare in concrete bridge construction. Left formwork can consist of structures such as prefabricated shell walls as formwork for supports and wing walls, prefabricated concrete slabs and beams that can collectively provide formwork for a superstructure.

When the Swedish government decided to relocate the European highway E4 around the city of Uppsala, 115 bridges were to be constructed. During the early design stage, it was decided that the project would require the construction of bridges with 110 different sizes and/or geometries; the question is, was that really necessary? Hence, the objective was to test the hypothesis that standardization and simplification of structural design could reduce costs related to building materials and man-hours.

This study involved examination of designer drawings, information on the amount of time the designers spent on each project, the contractor's perceptions of each project in terms of suggested construction methods, time consumption for most of the work to be carried out and the client's expectations in terms of early design drawings. The study focused on the construction of foundations for rigid concrete frames.

RESULTS

Present conditions

The distribution of total costs for the constructed bridges shows that the material and labour costs for formwork, reinforcement and concrete each accounted for approximately 23% of total costs. Deeper examination of the labour cost showed that formwork and reinforcement accounted for approximately 85% of total labour costs.

Standardization and simplification

The foundations of the bridges could have been divided into sets with certain geometries and load capacities, and consequently standardized. Instead of constructing, for instance, reinforcement cages with 64 different geometries for the bridges' foundations, it would have been possible to use just six geometries. This would have saved more than 22 man-weeks at site and approximately 50% of the anticipated labour costs for reinforcing the foundations.

If traditional concrete had been replaced by Self Compacting Concrete (SCC), there would have been further considerable potential for production time savings at site. Approximately 60 worker-weeks (63% of the total) could have been saved for all concrete casting activities at site, and some 10 weeks for the foundations alone.

Formwork accounted for approximately half of the working hours (740 weeks) consumed in the studied project. If left formwork had been used instead, more than 630 worker weeks at site could potentially have been saved.

DISCUSSION AND CONCLUSIONS

The size of the studied project made it eminently suitable for using industrialized production methods, techniques and standardized components of the bridges. The focus in the design phase in the early stage of the project should have been on standardization, simplicity, communication and (hence) constructability and buildability of the bridges. The study shows that significant savings in both money and working hours could have been achieved by using more industrialized thinking.

Findings from this case study also show that the main factor hindering the introduction of industrialized working methods is the late involvement of the contractor in the project process. According to responses of several contractors during the interviews, "there is simply not enough time for site management to rethink production". Thus, the organizational culture did not seem to be geared to implementing changes during a project at that time.

4.3.3 *Paper III:* Barriers and Drivers for Increased Use of Off-site Bridge Manufacturing in Sweden

INTRODUCTION

As in many countries, the Swedish construction industry has been linked with inefficiency and not meeting client needs. Thus, there is much discussion about the need for change to make Swedish civil engineering more industrialized. Off-site manufacturing (OSM) is seen as a technology to reduce waste and complexity related to on-site construction (Ballard and Arbulu 2004). By implementing OSM in concrete bridge construction, bridges can be constructed more rapidly, using less resources and (hence) increasing client satisfaction.

The objectives of the study presented in this paper were to investigate whether OSM satisfies clients' needs better than on-site construction and to highlight barriers and drivers for OSM and on-site construction. To meet these objectives, the views of 66 practitioners representing all the parties involved in bridge construction (clients, contractors, OSM suppliers and consultants) were surveyed. In addition, a workshop was held, involving 14 people with specific interest and knowledge of industrialized civil engineering. A summary of previous S&P research, mostly regarding drivers and some barriers, is available in appended Paper III, Table 1.

RESULTS

Benefits and drawbacks of off-site manufacturing and on-site construction

Results from the survey indicate that the greatest benefits of OSM are time savings and H&S, which were cited by 59 and 42 respondents, respectively (*Table 4.3*). Poor aesthetic appearance is considered to be the major drawback; respondents often used words like "ugly" to describe prefabricated bridges and stated that they all look the same.

Two major benefits of traditional on-site construction are aesthetic appeal and quality, according to 51 and 41 respondents, respectively, while drawbacks include high time costs and relatively poor H&S. Quality was seen as a minor drawback for OSM bridges by the respondents, and many believed that on-site construction provided superior quality. These results are not consistent with previous findings, presented by Freeby (2005), Blismas and Wakefield (2007), Gibb & Isack (2003), among other authors. There was no significant difference in the responses between experienced and inexperienced respondents regarding this issue.

Client satisfaction

The results indicate that the benefits and drawbacks of OSM are product-related and only become drivers or barriers if they are considered important for the client. Hence, drivers and barriers are important factors to satisfy client needs.

The data presented in *Table 4.3* show that the factors cited by the most respondents as being important in bridge construction were quality (cited by 80% of the respondents), followed by cost (68%), time (33%) and H&S (33%). These four factors are, according to the survey, the most important and hence potential drivers for the different construction methods. Each respondent had the chance to cite up to three important factors for bridge construction, and the responses reveal that different actors have similar thoughts about important factors.

Overall 'client satisfaction scores' for OSM and on-site construction were obtained by multiplying the number of respondents citing each benefit by the proportions who felt that OSM and on-site construction were superior with respect to that benefit, respectively, and then summing the resulting values. The scores for OSM and on-site construction were 60 and 40, respectively, indicating that OSM is likely to satisfy clients better than on-site construction.

Table 4.3 *Benefits, their importance and drivers of the four most important factors for bridge construction*

	Benefits		Importance	Drivers	
	OSM (No.)	On-site (No.)	Proportion of respondents	OSM	On-site
Quality	15	41	0.80	12	33
Cost	21	10	0.68	14	7
Time	59	1	0.33	20	0
H&S	42	1	0.33	14	0
Client satisfaction				**60**	**40**

DISCUSSION AND CONCLUSIONS

OSM is rarely used in Sweden, although it satisfies client needs better than on-site construction. Concerns about aesthetics and the negative attitude among practitioners have to be addressed before OSM can be more common. Discussions during the workshop revealed that elements associated with end-user satisfaction include short construction times, information about disruptions, and minimization of traffic disruption during construction.

Paper IV: Decreased Complexity of Bridge Construction through Prefabrication: A Case Study

INTRODUCTION

Implementing prefabrication is seen by many as a means to improve construction in terms of managing variability and productivity (Ballard and Arbulu 2004). However, in Swedish civil engineering works this has not been adequately documented to date. In the case study presented in this paper VSM was used to document the construction of both a semi-prefabricated superstructure (future state) and an on-site constructed superstructure (current state). The intention of the project was to investigate whether using prefabrication instead of traditional on-site construction makes the bridge construction process less complex to manage and control. Comparing these two construction methods revealed both positive and negative aspects of them both. Here, complexity is regarded as both the amount and difficulty of activities performed on-site, the working hours required at site and lead time.

RESULTS

Current state (Construction of a bridge on-site)

In the current state only one activity is performed parallel, all other are performed one at a time, so the lead time is long. Some activities are complex, e.g. performing framework, mounting reinforcement (see *Figure 4.2* (left)) and constructing edge beams. Only two value-adding activities, reinforcement and casting of concrete, can be identified for current state. Formwork activities are seen as type 1 muda (necessary waste, with the current method). Non value-adding activities account for about 45% of the total lead-time. Total working hours for on-site superstructure amount to 1102 h and the lead-time is 980 h.

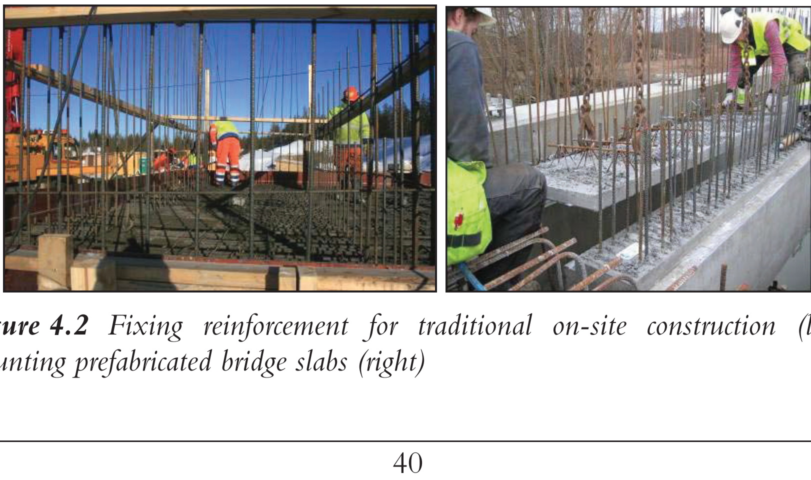

Figure 4.2 *Fixing reinforcement for traditional on-site construction (left), mounting prefabricated bridge slabs (right)*

Future state (Construction of a semi-prefabricated bridge)
Six activities are performed during the construction of the future state and one parallel activity. Furthermore, activities performed on-site are easy and standardized (see *Figure 4.2* (right)). All activities except mounting formwork, which is the parallel activity, can be seen as value-adding. The critical chain does not change if waste associated with the non-value adding activity decreases. Total working hours for the future state amount to 338 h and the lead time is 249 h.

Shortcomings of the future state
Some problems associated with the future state were identified, e.g. reinforcement collision when mounting prefabricated beams and some prefabricated slabs were cast with wrong dimensions, leading to reworking at site. After completion of the bridge, shortcomings of the future state and root causes of problems were considered in follow-up discussions with the contractor, OSM supplier and design consultant.

DISCUSSION AND CONCLUSIONS

Results of this case study show that prefabricated bridges can be more rapidly assembled, on-site activities are easier to perform, the number of on-site activities can be decreased by 50%, and on-site lead time by 75% by applying OSM. On-site complexity, as defined in this paper, is therefore reduced, making the construction process easier to plan and control. Nevertheless, a whole new approach to the construction process is needed before the intended result for standardized bridges can be optimized.

Combining the results of the case study with information from a follow-up discussion (involving contractor, designer and supplier) regarding the future state, three problem areas were highlighted. Firstly, use of prefabrication increases the need for clear communication and cooperation between involved participants, because understanding the process of off-site manufacturing is essential. Secondly, the prefabricated product is less flexible than corresponding products constructed on-site, and late changes are difficult to handle at the construction site. In addition, controlling parameters have to be set earlier, before prefabrication of parts is started (Koskela et al., 2003; Björnfot and Stehn, 2005). The last problem encapsulates all current difficulties and can be essentially stated as follows: a standardized process is required to deliver a standardized product and optimise the outcome.

5 CROSS-ANALYSIS AND DISCUSSION

This chapter presents a cross-analysis of the results and conclusions presented in the appended papers.

5.1 Industrialization

An interesting aspect of the empirical results is that industrialized infrastructure construction is a multi-facetted concept that involves much more than merely prefabrication (as indicated by the responses to the questionnaires). Following analysis of the elements involved in industrialization identified in Paper I, and the survey results, three categories for industrialization were selected for more detailed examination: *standardization, prefabrication* and *processes* (involving the elements continuous improvement, planning for efficient production, integration of design and production, and cooperation), see list below for more detailed description of the core elements:

1. *Standardization* of both processes and products. This is the foundation for industrialization because it is without standardization very difficult to measure how changes are affecting the outcome.
2. *Prefabrication* is a way to increase the control and predictability of the end product. It is easier to plan and control the manufacturing process in a factory than at the construction site.
3. *Continuous improvement* is a good way to handle development of processes. Tools like experience feedback and ICT (Information and Communication Technology) helps the improvements to be efficient.
4. *Planning for efficient production* means to strive for a continuous construction flow, whether it is about mounting together prefabricated elements at the construction site or traditional on-site construction.
5. *Integration of design and production* means having a good cooperation between these two project phases. This gives the opportunity to design the best product from a buildability perspective.

6. *Cooperation* is vital in order to benefit from the collective experience and knowledge that is gathered within a process.

Thus, the aims of the following studies (reported in Papers II-IV) were to assess the effects of these elements on bridge construction. The effects of standardization are considered in Papers II and IV, effects of prefabrication in Papers III and IV, while processes, especially the construction process, are addressed in Paper IV. In the following summary each of the elements, and their effects, is separately considered.

No definition of the multi-facetted concept of industrialized infrastructure is provided in this thesis, and in the literature possible distinctions between industrialization and industrialized construction have been debated, as previously mentioned (see Section 2.1). However, some researchers have tried to encapsulate the term. For example, Lessing (2006) defines industrialized construction as:

"…a developed building process with a well-suited organization for efficient management, preparation and control of the included activities, flow resources and results for which highly developed components are used in order to create maximum customer value."

All three core categories (standardization, prefabrication and process) are included, in some way, in this definition. Further, comparing the eight characteristics (or elements) of industrialized housing noted by Lessing (2006), with the core elements of industrialized infrastructure identified in the studies this thesis is based upon, reveals that the latter include several additional elements, as shown below.

Industrialized infrastructure	**Industrialized house building**
1. Prefabrication	1. Prefabrication
2. Planning for efficient production	2. Planning and control of the processes
3. Cooperation	3. Long-term relations
4. Continuous improvements	4. Experience feedback
5. Standardization	5. Developed technical systems
6. Integration of design and production	6. Logistics integrated in the building process
	7. Use of ICT
	8. Customer focus

Prefabrication is highlighted, in both concepts, as a key for industrialized products. Furthermore, planning is essential for the ability to predict and control the whole process. Planning of the unpredictable on-site production process is especially important in industrialized infrastructure construction, because most activities are currently performed at site. According to Lessing, on-site activities in industrialized house building are mostly related to mounting prefabricated building parts.

Cooperation is closely related to long-term relations among parties involved in the process concerned (e.g. clients, designers, consultants, contractors and suppliers), which are highly important for optimising any process or product (Liker, 2003).

In Lessing's model of industrialized housing, "continuous improvements" is placed in a circle around the eight characteristics (see Section 2.1, *Figure 2.1*), but in industrialized infrastructure it must be integrated as a core element. Experience feedback is one of many tools that can be used to deliver the continuous improvements that characterize the process thinking inspired by Lean philosophies.

Modern ICT is another tool that can facilitate achievement of continuous improvements.

Standardization is probably the most important core element of industrialized infrastructure, and it should be involved in both industrialized products and processes. Without it is extremely difficult to measure the effects of any changes in the process. The term standardization is not visible in any of the eight characteristics of industrialized house building. However, developing a technical system for housing involves a high degree of standardization of both processes and products.

Integrating design and production is according to industrialized infrastructure a way to increase the buildability of the product and thereby improve the satisfaction of client needs.

Characteristics 6-8 of industrialized house building are not included as core elements of industrialized infrastructure, but nevertheless are important features of an industrialized process. However, they cannot be included as elements, in this research, since they were not mentioned as particularly important by either the survey respondents or workshop participants. These two concepts are in many ways similar, but have to be adjusted to the specific context.

5.2 Barriers for industrialization

A major barrier that hinders all attempts to industrialize the infrastructure sector is the conservative atmosphere that prevails in it. Accoridng to the Questionnaire survey 1, people within this industry are conservative and rarely question current non-industrialized methods. However, according to Josephson and Saukkoriipi (2005), there is no evidence that people within the construction industry are more inherently conservative than others. Conservatism is often mentioned as an excuse for avoiding changes to the secure "institutional" existence that, according to Kadefors (1995), prevails today. One respondent (contractor) from Questionnaire survey 1 summarized this by stating:

"Stupid does as stupid says, we are just used to doing what provided documents say [we should do]".

Further reasons for the lack of productivity improvements are opinions about the uniqueness of the industry (unique products, unique projects, unique site conditions) and the consequent impossibility to change practices. The uniqueness barrier identified in Paper I is corroborated (and strengthened) by some researchers arguing that construction must be seen as a complex and non-linear phenomenon and, thus, projects cannot be planned traditionally (Bertelsen, 2003; Kenley, 2005). One respondent (client) summarized this barrier by commenting:

"The basic premise is that construction is constantly changing [in terms of] place of production, product design and that the external physical conditions of production vary from place to place".

Other identified barriers for industrialization are lack of repetition possibilities, norms & rules, and procurement actions. These are all heavily connected to clients (i.e. the STA in Sweden). Thus, the clients must address these barriers in order to enhance the pace of industrialization. The following comment from a respondent (contractor) to Questionnaire 1 summarizes these barriers:

"The industry is tightly controlled by codes, standards and requirements. Late involvement means that the risk (time, cost and acceptance) becomes too great to step outside the frame".

Despite the identified barriers industrialization of bridge construction in Sweden is inevitable, due (among other things) to increasing international competition and accompanying demands from clients for productivity increases, see for instance SOU (2012).

5.3 Standardization

According to Liker (2011) standardization is perhaps the most important element of industrialized construction, as it is a prerequisite for measuring the impact of changes on the output of construction processes. Thus, in order to analyze consequences of changes for industrialized infrastructure you first have to standardize.

According to Lean Construction literature two strategies can be used to decrease construction complexity: developing standardized on-site construction processes, as proposed by Koskela et al. (2003), or developing prefabrication and standardized products, as proposed by Ballard and Arbulu (2004). In both cases standardization is the foundation, either for processes or products. Results from the case studies presented in Papers II and IV show that it is not enough to standardize only one of them. Standardization of products, like the semi-prefabricated bridge examined in Paper IV, requires a well-defined construction process for efficient construction.

Bertelsen (2003) describes, as previously mentioned, on-site construction as a non-linear phenomenon that is too complex to standardize because of its numerous unpredictable components. However, mapping the value stream of the on-site construction process (Paper IV) reveals that the process is relatively linear and that predicting and planning it is possible. The case study presented in Paper IV only considered one small semi-prefabricated bridge, but an important outcome from the associated workshop (see Appendix 2) is that practitioners confirm that at least the construction process is relatively linear and comparable between projects.

However, a whole new approach to construction is required to enable standardization. The standardized product considered in Paper IV requires not only a standardized process, but also increased cooperation and communication throughout the whole process, from early design until the bridge is ready to be taken into use, in order to construct it as efficiently as possible (see also Paper II). The above conclusions are supported by Hvam (2008) and Winch (2003), who note that well-defined processes and products are essential for reducing the complexity of construction previously described by authors such as Bertelsen (2003).

The results also show that contractors currently lack possibilities for repetition due to the commonly used Design-bid-build contracts and project focus in the industry. Incentives for contractors to invest in standardization (and prefabrication) could be increased by implementing more turnkey contracts, based on functional requirements. By increasing standardization, the industry could change its production strategy from Concept-to-order to Design-to-order, see Subsection 2.3.4, *Figure 2.4*. Thus, the design hours needed could be decreased and the buildability of the products increased.

5.4 Prefabrication

A common view among practitioners who responded to Questionnaire 1 is that industrialized bridge construction solely involves prefabrication, and not any of the other mentioned core elements. This could reflect ignorance about the multi-facetted concept of industrialized construction among practitioners within the infrastructure sector (Paper I). Thus, the workshop confirmed that prefabrication and product standardization play important roles in industrialization, but as concluded in Paper IV, standardization of processes is also important.

The results from Questionnaire survey 1 also indicate that the greatest benefits of prefabrication are time savings, followed by health & safety and cost improvements, correlating well with previous research, see appended Paper III, Table 1.

In previous literature quality is often stated to be a major benefit of prefabrication, mostly because of the possibility to construct products in a factory with a controlled environment. However, concerns about poor quality and that prefabricated structures always look the same are mentioned in the responses to Questionnaire survey 1. Hence, these matters must be addressed before prefabrication can be implemented in large scale.

Papers II and IV reveal several other constraints for the implementation of standardization and prefabrication in bridge construction. One important constraint is the need for a whole new approach to construction, involving more cooperation, communication and early involvement of key actors. However, the greatest perceived drawback of prefabrication is that it reduces flexibility (Paper IV). This is consistent with observations by Gibb (2001) and Winch (2003). As bridges are seen as complex infrastructural products, it is important to investigate their components that could be standardized without compromising the flexibility of on-site construction. Standardization of products should also take advantage of the recent development in product platforms, modularization and configuration strategies in the construction industry, see Section 2.3.3.

Given the massive savings in construction time that can be obtained by using standardized and prefabricated products (Papers II and IV), it is easy to conclude that despite their drawbacks they should be considered as alternatives to on-site construction more often. Results presented in Paper III also indicate that reduction in construction times is a major driver for prefabrication.

5.5 Processes

As mentioned above (and in Paper IV) the lack of a standardized on-site production process is currently a major barrier to the supply of standardized products. In the follow-up discussions with the contractor, supplier and designer, after construction of the semi-prefabricated bridge presented in Paper IV, several problems were raised that occurred during the construction, e.g. reinforcement collisions and tolerance errors. It was concluded that root causes of these problems could all be traced to the lack of a standardized construction process, poor cooperation between involved actors and unclear communication channels, i.e. elements noted earlier in the text.

An industrialized bridge construction process should, according to Paper I and also Simonsson (2011), involve elements including: planning for buildability, early involvement of all actors, knowledge feedback and continuous improvement. This is in accordance with the statement by Liker (2004) in *The Toyota Way* that:

"Right process gives right results"

Although Liker described a process developed for manufacturing automobiles, the process-thinking that is essential for Lean production could also be highly beneficial for the infrastructure sector, especially if it moves towards a design-to-order production strategy. Gann (2010) describes how Japanese construction firms have learnt from other manufacturing processes (especially in the automotive industry), implying that the construction process, as identified also in this research, is not as different from manufacturing as some literature about construction complexity claims.

Every infrastructure project includes, according to the workshop participants, the same phases, and to perform them efficiently certain information must be readily available. Also, a strong focus on material and material flows is currently present in infrastructure construction. These finding confirms what Winch (2003) stated, that to facilitate mapping and standardization of the construction process more focus should be on the flow of information rather than on flow of material (see also *Figure 1.1*).

5.6 Concluding remarks

The multi-facetted concept of industrialized infrastructure has been mapped and compared to industrialized house building, as described by Lessing (2006). Many of the core elements (or characteristics) of the two concepts correlates well with each other. From this cross-analysis it can be concluded that since there is only one large governmental client for infrastructure in Sweden, the STA, the client complexity is minimal, as described by Bertelsen (2003). The STA is now focusing on becoming purely a client, refraining from interfering with projects as much as possible and using more turnkey contracts. These measures should give contractors greater incentives to cooperate with suppliers in order to move towards a more standardized production strategy (see Subsection 2.3.4). However, as the construction industry is conservative, the shift from a short-term project focus to a long-term process focus will take time, as concluded in Paper I.

Lean construction describes two strategies to decrease the complexity of construction: developing products or processes. The findings of this research indicate that a combination of both is the optimal way to increase client satisfaction. Early involvement of all actors is thus needed, because all important decisions are taken in early stages of projects, and affect all subsequent stages (as observed in Paper II).

Furthermore, as shown in Paper IV, prefabrication alone could decrease construction complexity. However, by planning projects correctly and allocating more time for considering buildability in design, in cooperation between organizations, the complexity of the whole project can be decreased and probably create a process that increases productivity and satisfies client needs better than current practices.

6 CONCLUSIONS

This chapter presents conclusions based on the cross-analysis and discussion, and the degree to which the aims of the research aims were fulfilled and the questions posed were answered. The research quality, academic and practical contributions are discussed, and finally suggestions for further research are given.

6.1 Fulfilment of aims

A recent investigation of government clients' actions for improving productivity and innovation in infrastructure projects has recommended that planning regarding the procurement of projects should be improved, the numbers of turnkey contracts should be increased and the industrialization of the sector should be enhanced. In response, the Swedish Transportation Administration (STA) has launched a research and innovation program to foster an industrial mindset and identify ways to increase the standardization of products (among other desired changes).

Thus, the aims of the studies this thesis is based upon were to identify the most important components and processes that can be industrialized, and hence increase the productivity of concrete bridge construction. In order to meet these broad aims, three research questions were formulated, each of which is addressed in the following three sections.

6.1.1 Research question 1: What are the elements of industrialized civil engineering, and in particular concrete bridge construction?

This research question was mostly addressed by the Questionnaire surveys and workshop. Core elements of industrialized infrastructure were mapped to increase understanding of the concept. The results indicate that industrialization of the infrastructure sector is a multi-facetted concept involving several core elements. Identified core elements and its relation to either process or product are presented in a model for industrialized infrastructure, see *Figure 6.1.* This model is inspired by the industrialized house-building process model by Lessing (2006), available in *Figure 2.1.*

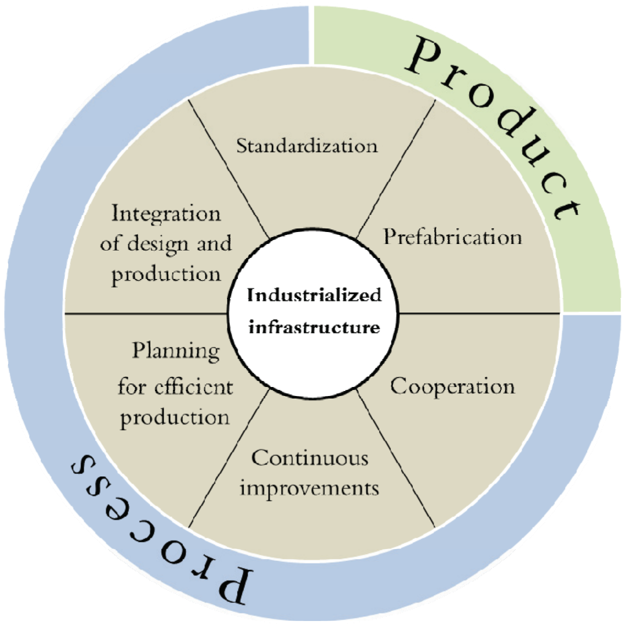

Figure 6.1 *Model for industrialized infrastructure, inspired by Lessing (2006)*

The most important element is standardization, of both products and processes. Processes have to involve cooperation between different actors and organizations in the early stages of projects, when the possibility to affect the outcome is greatest. By involving contractors, designers and suppliers (e.g. prefabrication suppliers) early, it is possible to optimize both the product and the process.

Industrialization of infrastructure projects must also involve the standardization and prefabrication of products (or product components) to meet client needs better than today.

However, the model, *Figure 6.1*, is based solely on findings from this research (surveys and workshop) and therefore not definite. Before the model can be verified, it first has to be evaluated and then tested, this in cooperation with knowledge people and organizations within industrialized infrastructure.

6.1.2 Research question 2: What are the benefits and constraints of prefabrication and on-site construction?

Prefabrication has been identified as a core element of industrialization; hence investigation of its benefits and constraints (as listed in *Table 6.1*) is important. On-site construction, currently the most common way of constructing concrete bridges in Sweden, is also of interest, see *Table 6.1*.

Table 6.1 *Benefits and constraints of identified prefabrication and on-site construction methods*

	Benefits	Constraints
Prefabrication	Time	Aesthetics
	Cost (Life-cycle)	Less flexible
	Health & safety	Lack of knowledge
	Predictability	Increased cooperation
On-site	Flexibility	Time
	Quality	Health & safety
	Aesthetics	Need for skilled workers
	Common method	Environment

The major benefits of prefabrication identified from the surveys of practitioners' views (improvements in time consumption, health & safety and costs) correlate well with those identified in previous research. The cost benefits are mostly reductions in life-cycle costs, due to increases in quality, rather than initial production costs, according to previous publications. However, the surveyed practitioners appear to believe that on-site construction provides greater quality, although it is done in an unpredictable environment. This peculiar result does not correlate well with previous literature, in which quality is seen as one of the greatest benefits of prefabrication.

Not surprisingly, the pros and cons of on-site construction identified from the survey responses and analysis of current and future states are almost mirror images of those of prefabrication. Quality and flexibility are seen as major benefits of on-site construction compared to prefabrication, while time and health & safety are perceived as major constraints. There is no significant difference between responses of experienced and inexperienced respondents regarding this issue, which increases the reliability of the results.

Very strong opinions concerning aesthetic issues were revealed by survey. Comments that prefabricated structures are ugly and always look the same were common in survey answers. These opinions are a major concern for any attempts to promote prefabrication.

6.1.3 Research question 3: How does prefabrication affect the efficiency of concrete bridge construction?

A case study was undertaken to compare prefabrication to traditional on-site construction (where no measures have been made regarding industrialization), by constructing value stream maps showing how the two alternatives affected the construction process at site. Use of the prefabricated alternative decreased the number of activities at site by 50%, it eased the work (by introducing more standardized repetitive tasks), and reduced the on-site lead-time for the studied semi-prefabricated superstructure by 75% compared to traditional on-site construction. The drawbacks of the prefabrication alternative were that it demands greater cooperation between suppliers, designers and contractors, and increases the need for clear communication channels. Some of the problems at site identified for the use of prefabrication in the studied case were strongly connected to it being less flexible than on-site construction. This is consistent with findings in some previous literature that loss of flexibility is one of the major concerns associated with prefabrication.

6.2 Contributions

An important theoretical contribution of the presented research on industrialized construction is the identification of core elements of industrialized infrastructure construction and how many of them are connected more to the process than to the product. Consequently, much greater attention to process development is required to increase the productivity and industrialization of the infrastructure sector.

Mapping the concept of industrialized infrastructure is especially important because it contributes to filling a gap within the concept-to-order production strategy that has been neglected to date. The findings show that even this complex sector, which supplies unique one-of-a kind products, could benefit from implementing industrialization.

These findings contribute to both practitioners' and academics' understanding of this important aspect of the construction industry.

The contributions to practitioners are consequently an understanding of the multi-facetted concept of industrialization of infrastructure construction, and how some of the core elements affect the traditional construction process.

6.3 Research quality

Even the choice of research methods limits the results that can be obtained and conclusions that can be drawn from any study. By using several data collection methods, both qualitative and quantitative, as in the presented studies, the reliability of the results can be increased, but limitations will always be present. One of the limitations of Questionnaire survey 1 was that only 42% of the questionnaires were returned. On the other hand, the results were verified by follow-up discussions in a workshop and a quantitative questionnaire survey, thereby improving their reliability. The multiple data collection method also increases the validity of the results and, consequently, conclusions drawn from the findings can be considered rather general in this particular context.

The results of the case studies are also limited by several factors. Notably, results of case study 1 are limited by the exclusion of time consumed in manufacture of the prefabricated elements. Hence, the analysis focused solely on the construction process at the construction site. Furthermore, some of the data are based solely on calculations made by the contractor, and both the reliability and accuracy of this source are questionable. However, the results show such large differences between the two concepts, in terms of time, that some human calculation errors would not make significant differences to the overall result. Furthermore, as both case studies indicated the same patterns, the conclusions can be considered reliable.

6.4 Further research

The research that this thesis is based upon has highlighted a number of areas that are of interest for further research regarding the industrialization of infrastructure generally and the construction of concrete bridges in particular. As two of the major findings are that standardization and cooperation are both important, it would be of interest to explore ways to enhance cooperation between different actors in order to improve standardization and standardized processes. Another interesting area for further research is how components involved in concrete bridge construction can be standardized and prefabricated while maintaining flexibility.

However, continue the development and verification of the model of industrialized infrastructure is the obvious first activity after completion of the Licentiate.

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PAPER I

Industrialized construction in the Swedish infrastructure sector: core elements and barriers

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Industrialized construction in the Swedish infrastructure sector: core elements and barriers

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A recent investigation into government clients' actions for improving productivity and innovation in infrastructure projects has recommended better planning regarding the procurements of projects, increased numbers of turnkey contracts and more industrialization of the sector. In response, the Swedish Transportation Administration has launched a research and innovation program where an increased industrial mindset and standardization of products is on the agenda. With the exception of the process-based housing sector, increased industrialization has, however, been difficult to achieve in the project-based construction industry. This paper aims to improve the understanding of the concept of industrialization and investigate the barriers to its implementation in infrastructure projects. Using two survey studies and a workshop**,** the opinions of clients, consultants and contractors regarding core elements and barriers were investigated. The results reveal opportunities and obstacles related to product standardization, standardization of processes for continuous improvements as well as the relationships between the client and the contractor. We conclude that the concept of industrialized infrastructure construction and its barriers span many different aspects. Hence, the implementation of industrialized construction requires conscious and purposeful project governance at the outset of the project and the rethinking of established attitudes, norms and regulations.

Keywords: Infrastructure, industrialized building, standardization, prefabrication, barriers

Introduction

Improving productivity is a central challenge in most industries and construction is no exception. In many countries, such as Great Britain and US (Egan, 1998; Huang et al., 2009; Teichholz, 2001), government reports and research publications have highlighted the slow growth of productivity in the construction industry. In Sweden, the urgency of improving productivity and client satisfaction in the construction industry has initiated a number of government investigations (SOU, 2002; SOU, 2009; SOU, 2012). Several studies of

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productivity (e.g. Horman and Kenley, 2005; Mossman, 2009) have also identified a large amount of waste generated by traditional on-site construction projects. Such a waste of material, time and other resources is detrimental to productivity. In other industries, waste reduction and productivity improvements are dealt with by long-term continuous improvements of industrialized processes (Winch, 2003). Accordingly, researchers and practitioners argue that the construction industry could learn from other industrial contexts, especially manufacturing sectors such as the automobile industry (Gann, 1996).

The construction industry is, however, far from homogeneous in this aspect. In housing production companies have worked with industrialized processes and off-site manufacturing for decades, resulting in continuous productivity improvements (Höök and Stehn, 2008; Segerstedt and Olofsson, 2010). In other types of production, such as major projects including infrastructure and complicated industrial and commercial buildings, increased industrialization has, however, been difficult to achieve (Winch, 2003). In addition, there is a lack of research on industrialized construction within the context of the infrastructure sector.
The Swedish Transport Administration (STA) has been assigned the task of creating the conditions to improve productivity within the infrastructure sector. A recent investigation of government clients' actions for improving productivity and the level of innovation in infrastructure projects has recommended better planning regarding the procurement of projects, increased amount of Design-build or turnkey contracts and more industrialization of the sector (SOU, 2012). In response, STA has launched a long-term research and innovation program where increased industrialization throughout the value chain and standardization of products is on the agenda. Measures to increase the productivity of infrastructure projects are especially important from a societal perspective since public money is spent on investments that are crucial for the development and economic growth of a country.

While the larger clients are keen to see industrialization, there is a lack of knowledge about the concept of industrialization within the context of infrastructure among practitioners as well as academics. The purpose of this paper is therefore to fill this gap using survey studies and a workshop to investigate attitudes and opinions about industrialized construction among practitioners within the Swedish infrastructure sector. The aim is to improve the understanding of the concept of industrialization and investigate the barriers to its implementation in infrastructure projects.

Literature review

The purpose of the literature review is to identify potential strategies for industrialization and productivity improvements. Most literature on this subject deals with housing production while studies into the industrialization of infrastructure projects are scarce. However, this literature study will start with insights into why construction is often seen as considerably different compared to manufacturing and how these peculiarities affect the potential for industrialization.

Characteristics of construction

Construction is said to be conservative, risk-reluctant and to behave wastefully (Styhre, 2010; Teo and Loosemore, 2001). Koskela (1992) attributed the peculiarities of construction, such as one-of-a-kind products, temporary organization and site production, as reasons for the inefficiency seen when compared to manufacturing production systems. Bertelsen (2004) pointed out that construction has to be seen as a non-linear complex system that is not possible to plan and manage as one would a regular linear and predictable manufacturing process. Also, the complexity has increased since World War II (Baccarini, 1996).

The peculiar relationship between design and production in Design-bid-build contracts complicates the relationship between the client, the principal designer and the main contractor since they share the role of system integrator (Lambert et al., 1998; Segerstedt and Olofsson, 2010). Frödell et al. (2008) also found symptoms of "customers co-production" that is typical within service-oriented industries when he studied the impact of Swedish construction clients' ability to make decisions about project success. Fox et al. (2002) stated that "designers participate in customer-led location-specific design that results in little, or no, repetition of post-order design certainty." Thus, many different work tasks have to be performed, since it is not economically viable to invest in machinery that would assist in more efficient construction. This makes the link between contractor productivity and client productivity complicated since construction clients often procure contract work based on detailed specifications (Bröchner and Olofsson, 2012).

On-site construction often involves numerous suppliers and subcontractors in temporary networks (Dubois and Gadde, 2002; Hughes et al., 2010). Synchronization and flexibility can be more important than supply chain integration for improving the performance of the supply chain (Bankvall et al., 2010). Kadefors (1995) found that the construction industry is subject to strong institutionalization due to the need for coordination and communication in complex project organizations, explaining why innovations in individual projects seldom bring about long-term changes.

Almost all of the characteristics of construction highlighted in the above mentioned literature are valid for infrastructure projects. The major difference between general construction and that of infrastructure is that there is one dominating government client involved in infrastructure projects: the Swedish Transport Administration.

Industrialization strategies

Construction is often compared to manufacturing industries in terms of improved productivity and industrialization (Gann, 1996). Accordingly, models for industrialization taken from the manufacturing industry are often seen as solutions to the lack of productivity improvements in construction (Winch, 2003). Koskela (1992) developed the TVF (Transformation, Flow and Value) theory, which became the lean production (LP) strategy adapted to construction. Today, this form of LP is better known as lean construction (LC) (e.g. Koskela, 2000; Ballard, 2000). The basis of LC is similar to LP but some alterations have been made to fit the complexity of construction (Bertelsen, 2003). Methods such as the last planner system that focuses on variability reduction (Ballard and Howell, 1994) and value stream mapping of work flows (Simonsson et al., 2012) are examples of lean tools that have been applied to make on-site construction more efficient. Egan (1998) advocated lean thinking and the need of radical changes in construction instead of continuous improvements and step by step implementation as proposed by LC.

The standardization of tasks and products is closely related to lean thinking. By standardization and pre-assembly of products, increased predictability and efficiency can be achieved (Gibb, 2001). Bertelsen (2004) identified two strategies for decreasing the complexity in construction: either develops more standardized products or more processes. Waste can effectively be reduced by using pre-assembly (Tam et al., 2006). Benefits often associated with pre-assembly are time, quality, cost, and health and safety (Blismas et al., 2006; Gibb and Isack, 2003). Gibb and Isack (2003) identified four kinds of pre-assembly products where infrastructure elements (e.g. bridges) are categorized as non-volumetric pre-assembly products.

Obstacles to the increased use of pre-assembly are mostly related to process, value, conservatism and knowledge (Blismas et al., 2005). A major drawback is that the design of the structure has to be established early in the projects' lifecycle because of the long supply-chain associated with this technology. Despite the fact that benefits and constraints are well documented, (Blismas et al., 2006; Goodier and Gibb, 2007) pre-assembly and its benefits are poorly understood by many practitioners, leading to a widespread reluctance to use it (Pasquire and Gibb, 2002; CIRIA, 2000). Winch (2003) identified different modes of production in construction, with infrastructure projects being characterized as a complex system, with small volumes and where "concept-to-order" is the dominating production strategy. Several reasons for the failure of the many efforts to industrialize the construction process are also identified, for example, lack of on-site management control and the product design often being excluded from the production control (Winch, 2003).

The industrialized Swedish housing industry has focused more on processes than on products (Höök and Stehn, 2008). Process improvements are seen by many as the most important step towards productivity improvements. Gann (1996) compared the Japanese housing industry to automotive manufacturing and showed significant similarities in their processes. It is about the ability to manage the whole production system rather than focusing on minor parts of the process. This is relatively rare since construction, including infrastructure, often focuses on projects rather than on processes. Processes are often seen as a key focus area within the manufacturing industry culture (Riley and Clare-Brown, 2001). Hutchison and Finnemore (1999) wrote that construction has not had a recognized methodology to base a process improvement initiative on. Its process is characterized by small continuous step by step improvements, which have been shown to be effective in other industries.

Construction concepts and projects also carry out different preparatory work before the customer order arrives and before realisation of the project. Hence, more focus should be on the flow of information, rather than material flow which is more common in the construction industry. Different kinds of product specification processes can be identified, which are closely related to the proposed product flexibility, design entry point for the client and the contractual relationship between the client, the principal designer and the main contractor (Winch, 2003; Hvam et al 2008; Segerstedt and Olofsson, 2010). The balance between standardization and flexibility is believed to be a key for success (Gann, 1996). Better integration between design and construction require that the downstream flow of design information to production is complemented with an upstream flow of constraints from production to design (Jensen et al., 2012). Buildability aspects are, of course, integrated in industrialized construction concepts but can also be accomplished by involving production competences in the conceptual stages of the project (Simonsson, 2011).

Industrialization is not only about implementing new products and process innovations but also involves cultural and attitudinal changes (Liker, 2008). Findings from Courtney and Winch (2003) showed that issues of improvement can be related more too organizational and behavioural aspects than to technological matters. Drivers and involved actors are necessary for innovations to be implemented successfully within construction (Harty, 2008). Knowledge is necessary and probably the most important asset within an organization (Dave and Koskela, 2009; Gluch 2011).

Research method design

This study involves a mixed method design, including both qualitative and quantitative approaches in order to increase the reliability of the empirical result (Creswell et al., 2003). Two survey studies and a workshop were used to investigate the opinions of clients, consultants and contractors regarding core elements of industrialization and barriers to its implementation. In addition, the surveys have identified what parts and components can benefit from being prefabricated and/or standardized. Concrete bridges are a complex product within infrastructure and have therefore been used as an illustration.

Questionnaire survey 1 was first undertaken to record a general view of how the concept of industrialization is perceived by different construction industry actors. The workshop that followed saw some results from this survey discussed with experienced people, more to confirm and clarify findings than to obtain new data. Both these studies are based on a qualitative approach. Findings from Questionnaire survey 1, the workshop and a previous pre-study involving a multiple case study were then used as a basis for the design of the quantitative Questionnaire survey 2. The second survey was undertaken to quantify the importance of core elements and barriers found in the previous studies.

Questionnaire survey 1

This survey involved both quantitative and qualitative approaches with the objective to gain a deeper understanding of how practitioners in the infrastructure sector relate to the concept of industrialized construction. The survey study, which was undertaken during the autumn of 2010, included both structured and open-ended questions. Before distribution, it was discussed and debated with several people, both practitioners and academics, in order to minimize misunderstandings and leading questions, which can greatly influence the answers. The sample, which included clients, consultants and contractors, was selected after discussions with major firms working within the infrastructure sector. 159 questionnaires were sent out by mail and 66 responses were received, giving a response rate of approximately 42%. For a complete summary of respondents and their work experience, see Table 1.

Table 1. *Summary of respondents (Questionnaire survey 1)*

Discipline	Client			Consultant			Contractor		
Num. of resp.			21			13			27
Exp. (Years)	<1	1-5	>5	<1	1-5	>5	<1	1-5	>5
Construction	0%	0%	100%	0%	0%	100%	0%	7%	93%
On-site	10%	10%	80%	0%	0%	100%	4%	11%	85%
Off-site	29%	23%	48%	24%	38%	38%	41%	22%	47%

Workshop

To complement some of the results from Questionnaire survey 1, a workshop involving contractors, clients, consultants and prefabrication suppliers was undertaken. 14 participants were selected based on experience, interest and their opportunity to influence the infrastructure sector in Sweden. Three groups were formed to discuss five specific topics during one hour of the workshop. Topics included: core elements of industrialization, client/customer satisfaction, cooperation, uniqueness of the construction industry and reluctance to change. The topics were based on interesting results related to industrialization identified in Questionnaire survey 1. Results from group discussions were subsequently compiled and discussed jointly during the last hour of the workshop.

Questionnaire survey 2

The purpose of the second survey study was to investigate the opinions of practitioners with explicit interest and experience of industrialized construction in the infrastructure sector. 52 questionnaires were sent to people in the industry who had been invited to and/or registered on a special seminar about industrialized infrastructure construction that took place on 11th October 2011, hosted by The Productivity Committee within The Ministry of Enterprise, Energy and Communications. 33 responses were received from 4 clients, 14 consultants and 15 contractors, giving a response rate of 63%.

The design of the questionnaire, including the selection of response alternatives, was based on a previous multiple case study of three infrastructure projects and also the results of Questionnaire survey 1 and the workshop. The first question investigated core elements: "How important are the following elements of industrialized infrastructure construction?" Six response alternatives were presented in the questionnaire: Repetition and standardization, Automation, Prefabrication, Planning for efficient production, Experience feedback and Integrated design and construction. The second question investigated barriers: "How big are the following barriers to increased industrialization of infrastructure construction?" Nine response alternatives were presented in the questionnaire: Lack of large-scale and repetition possibilities, Norms and rules of the Swedish Transport Administration (STA), Design-bid-build contracts, Impaired aesthetics and monotonous architecture, Severe environmental impact due to long transportation distances, Conservative industry culture, New solutions and methods increase risks, Strong focus on lowest bid price, Government rules regarding plans. The third question investigated the suitability for standardization and prefabrication of 11 identified building products and components in the construction of infrastructure.

5-point Likert scales were used for all three questions where 1 = not important (Q1), not big (Q2), not suitable (Q3), 2 = rather important (Q1), rather big (Q2), rather suitable (Q3), 3 = important (Q1), big (Q2), suitable (Q3), 4 = very important (Q1), very big (Q2), very suitable (Q3), 5 = extremely important (Q1), extremely big (Q2), extremely suitable (Q3).

Empirical results

The results are divided into three parts: 1) core elements of industrialization, 2) barriers to industrialized infrastructure construction and 3) products and components suitable for standardization and prefabrication. Results from Questionnaire survey 1 show that only 10% of the respondents totally agree that infrastructure has become more industrialized over the past few years. 22 respondents commented this question of which 14 were related to that prefabrication has become more common. This indicates that prefabrication is seen by many general practitioners as the major element within industrialized infrastructure. The respondents seem united in thinking that the degree of industrialization will increase in the future. 92% predict that the infrastructure sector will become more industrialized. Comments related to this question mostly concern increased demand for cost and time reduction but also the increased competition from foreign contractors.

Core elements of industrialized infrastructure construction

Results from the workshop reveal seven core elements of industrialized infrastructure construction, see Table 2.

Table 2. *Core elements of industrialized infrastructure construction (workshop)*

Processes	Prefabrication
Standardization	Continuous improvement
Repetitiveness	Experience feedback
Cooperation	

Working with continuous improvements in long-term processes is central to industrialized infrastructure construction. In fact, it can be argued that such improvements span many of the other elements. Experience feedback is, according to all group discussions, an important element when working with continuous improvements. Cooperation between involved actors and the creation of clear communication channels are necessary for increased industrialization.

The workshop participants agreed that standardization is a major part of an industrialization of infrastructure in general. A standardized product is in need of a standardized process, in order to enhance efficient production. Standardized work and standardized products are of great importance in order to gain the advantages associated with repeatability. For that to be possible, similarities between projects have to be recognized and utilized.

Discussions of comparable aspects between projects are mostly concerned with the similarity of the processes which would benefit from standardization, but some participants claim that all types of aspects are comparable among projects. This result contradicts the results of Questionnaire survey 1, that is, that practitioners only see uniqueness among projects. Every infrastructure project might have unique characteristics, but the process of constructing, for example, a concrete bridge, always follows the same process stages. Identifying similarities among projects instead of seeing the uniqueness is a first step towards increased industrialization.

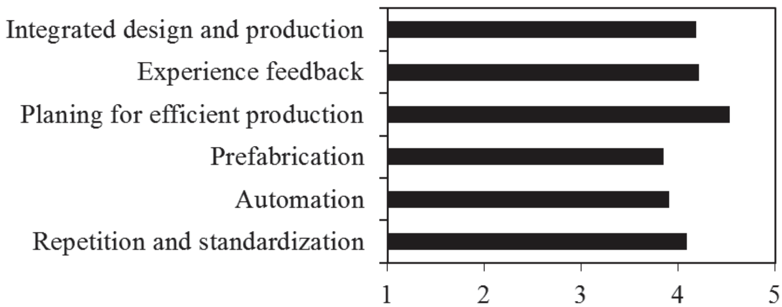

Figure 1. *Core elements of industrialized infrastructure construction (Questionnaire survey 2)*

In Questionnaire survey 2, six core elements were identified from the workshop and the previous multiple case study. Standardization and repetition are related and have thus been merged into one element. Cooperation is especially important during the design stage and therefore re-labelled integration of design and construction. Prefabrication and experience feedback have been kept the same as in the first survey. Automation and Planning for efficient production were identified in the pre-study and included in Questionnaire survey 2.

The results from Questionnaire survey 2 shows that all six identified core elements of industrialized infrastructure are considered very important with mean values ranging from 3.8 to 4.5, see Figure 1. Planning for efficient production was considered most important (4.5) and prefabrication least important (3.8). However, since 3.8 is a rather high mean value close to 4, which is labelled “very important”, all six elements can be considered core to the concept of industrialization. Standard deviations are rather low, ranging between 0.6 – 0.9, which means that the responses do not vary considerably. Hence, the respondents have similar opinions. Furthermore, a compare means test (ANOVA) shows that there are no statistically significant differences between the three types of respondents, indicating that clients, consultants and contractors have similar views on these elements. This strengthens the argument that the respondents agree that these are six core elements of industrialized infrastructure construction.

Barriers to industrialized infrastructure

Barriers are studied in both questionnaire surveys, making it possible to obtain a wider view of how practitioners in the infrastructure sector perceive the barriers to increased industrialization.

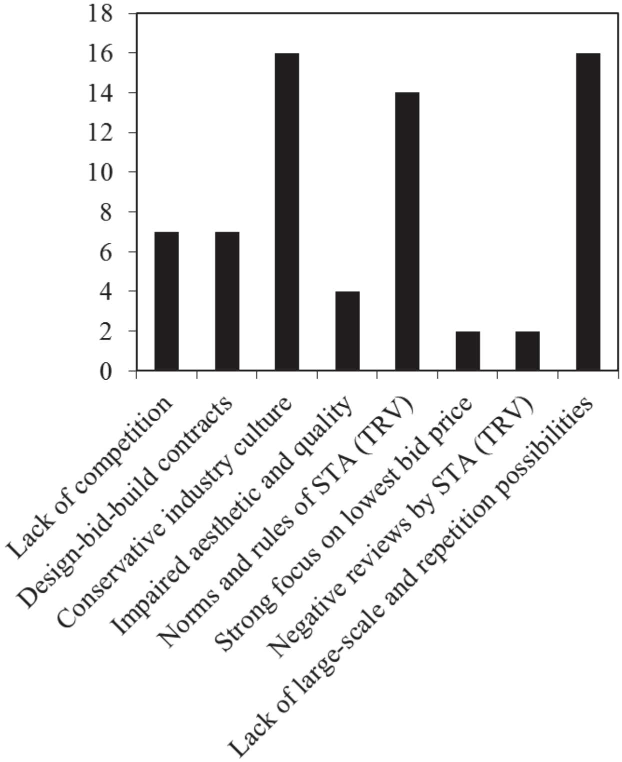

Figure 2. *Barriers to industrialized infrastructure construction (Questionnaire survey 1)*

The barriers to industrialization that were identified, as investigated in Questionnaire survey 1, are shown in Figure 2. This was an open-ended question with respondents able to suggest more than one barrier. The answers have been divided into larger categories comparable with those used in Questionnaire survey 2. The question was answered by 54 persons. Three barriers are mentioned frequently: conservative industry culture, the lack of large-scale and repetition possibilities and norms and rules of STA. Lack of competition (few contractors competing for large projects) in the industry and the use of Design-bid-build contracts are included in 13% of the responses. No significant differences in answers between disciplines were identified.

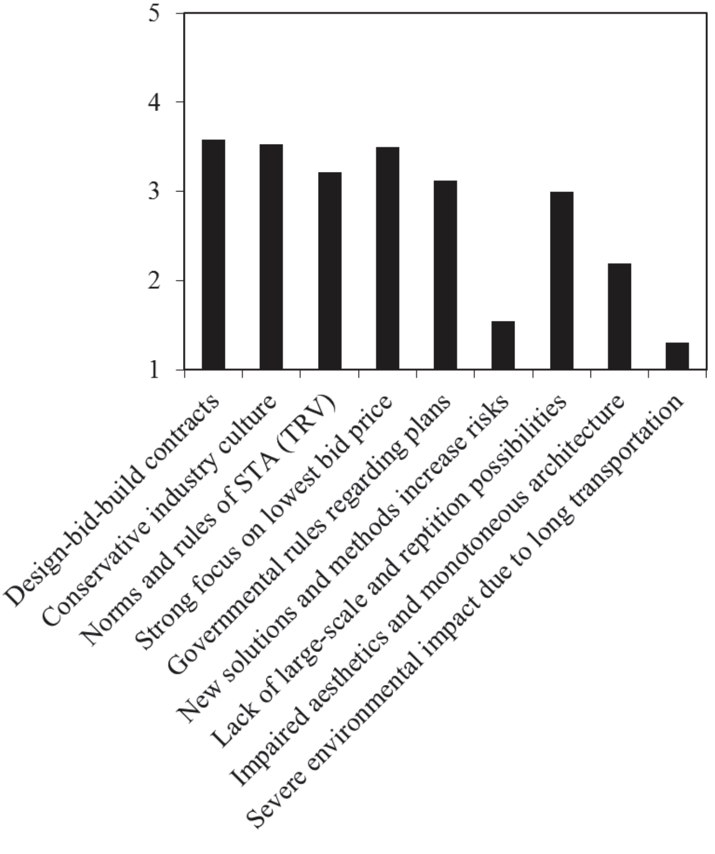

Figure 3. *Barriers to industrialized infrastructure construction (Questionnaire survey 2)*

Based on the results from the pre-study and the results from Questionnaire survey 1, nine categories of barriers were investigated in Questionnaire survey 2. The empirical results show that the respondents consider the nine identified barriers to be of varying importance, see Figure 3. Lack of large-scale and repetition possibilities, Norms and rules of the Swedish Transport Administration (STA), Design-bid-build contracts, Conservative industry culture, Strong focus on lowest bid price and Governmental rules regarding plans are viewed as big or very big barriers, whereas New solutions and methods increase risks, Impaired aesthetics and monotonous architecture and Severe environmental impact due to long transportation distances are viewed as not very big barriers.

Only two barriers (New solutions and methods increase risks and Severe environmental impact due to long transportation distances) have standard deviations below 1.0, indicating that the respondents agree that these barriers are not big. For the other barriers, standard deviations vary between 1.1 – 1.4, indicating that respondents' opinions regarding these vary. These differences in opinions are further shown in compare means tests. Two barriers have statistically significant differences. Design-bid-build contracts are considered to be a very big barrier by contractors (4.1) and clients (3.8), whilst consultants view it to be of less importance (2.9). Contractors also view Governmental rules regarding plans to be a very big barrier (3.9), whilst it is considered to be of less importance by consultants (2.3) and clients (3.3). While not statistically different, differences are also evident for the barrier Strong focus on lowest bid price (contractors 3.8, consultants 3.4, clients 2.3).

Standardized and prefabricated products and components

The prefabrication and standardization of products and components is studied in both questionnaire surveys. Questionnaire survey 2 takes a more general view of infrastructure, while Questionnaire survey 1 investigates concrete bridges as an example of a complex product used within construction of infrastructure. On this issue, the number of respondents was 24 in Questionnaire 2 because 9 respondents felt that they did not have sufficient knowledge and experience on these more technical aspects. Respondents expressed the opinion that almost all identified parts and components were considered to be appropriate or even very suitable to standardize and prefabricate, see Figure 4. Three (Barrier walls, Noise barriers and Reinforcements) of the four most suitable parts and components for industrialization are considered to be standard products.

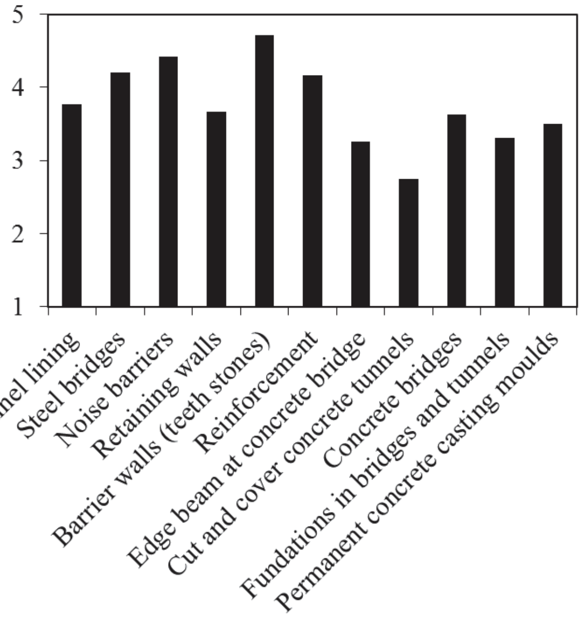

Figure 4. *Products and components suitable to be prefabricated and/or standardized within in infrastructure (Questionnaire survey 2)*

In Questionnaire survey 1, small to medium sized concrete bridges were chosen to illustrate what parts and components have the greatest potential to be standardized and prefabricated into a more complex product. 94% respondents think that it is possible to standardize concrete bridges, or at least some parts of the product. 52 respondents choose to comment on standardized parts, see Figure 5.

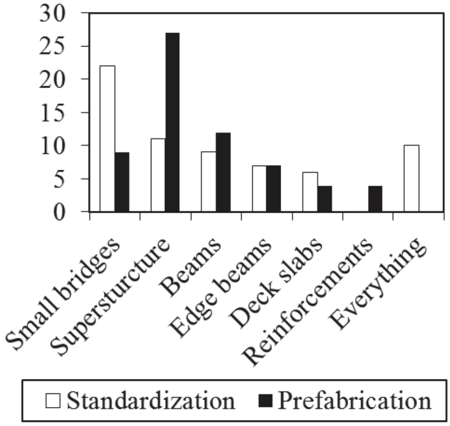

Figure 5. *Parts of concrete bridges to be standardized (left) and prefabricated (right) (Questionnaire survey 1)*

42% think that small bridges should be standardized while the superstructure or part of it (beams, edge beams and deck slabs) is the part most suitable to standardize for medium sized bridges. Survey results show that the superstructure or parts of it are most suitable for prefabrication, Figure 5. Figure 5 shows that the same structures are seen suitable both for standardization and prefabrication.

Discussion

An interesting aspect of the empirical results from the surveys and workshop is the multi-facetted view practitioners and industry experts have on industrialized construction in infrastructure projects, a concept that involves much more than merely prefabrication strategies. Many of the identified core elements of industrialization focus on processes (long-term) rather than projects (short-term). The identified core elements from the workshop with selected industry experts were processes, standardization, repetitiveness, cooperation, prefabrication, continuous improvement and experience feedback. This view was later confirmed in the second questionnaire study where automation, planning for efficient production and integrated design and construction were added to the list of core elements of industrialized infrastructure construction. Many of these elements can also be found in productivity strategies described in the literature regarding the industrialization of products and processes. Standardization is regarded as a major component of an industrialization strategy since a standardized product facilitates the continuous improvement of a standardized process. This finding shows that it is important to switch the product focus to a focus that also involves processes, as suggested by Höök and Stehn (2008).

With respect to barriers, increased industrialization of infrastructure construction is mainly hindered by the lack of large-scale and repetition possibilities, norms and rules of the Swedish Transport Administration (STA), procurement of Design-bid-build contracts based on lowest price, conservative industry culture and governmental regulations and laws regarding the planning process of infrastructure. Literature often includes complexity as a barrier for improvement (Bertelsen, 2004; Baccarini, 1996).

The core elements and barriers in industrialized construction in infrastructure projects are summarized in Figure 6.

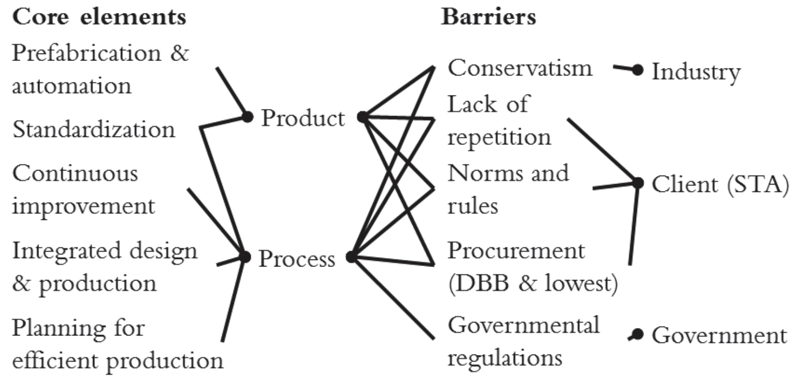

Figure 6. *Core elements and barriers related to products and processes in industrialized infrastructure construction*

Norms and rules of the STA, governmental rules regarding plans and a conservative industry culture hinder new solutions that can be related to repetition and standardization, automation and prefabrication. Design-bid-build contracts with a focus on lowest bid price hinder integrated design and construction, planning for efficient production and experience feedback. Lack of large-scale and repetition possibilities, derived from clients' procurement and contracting; hinder repetition and standardization as well as investments in automation and prefabrication. The study confirms that a conservative culture in the construction industry is considered as a barrier to innovation (Kadefors, 1995). However, three out of five barriers to industrialization (lack of repetition, norms and rules, procurement strategies) are controlled by the main client in Sweden (STA).

With regard to products in infrastructure projects, complete products, subsystems and components were suggested as possible candidates for prefabrication and standardization, see figure 7.

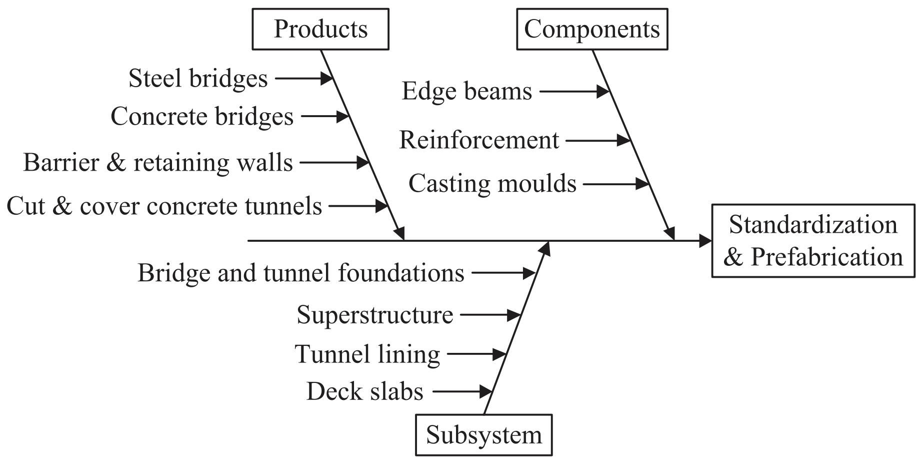

Figure 7. *Standardization and prefabrication of products, subsystems and components*

Development of standardized products, subsystems and components in the infrastructure sector should take advantage of the recent development in product platforms, modularization and configuration strategies in the construction industry (Hvam 2007, Jensen et al., 2012, Segerstedt and Olofsson, 2010).

The same parts are seen as suitable both for standardization and prefabrication indicating that these structures are the most difficult to construct with traditional on-site construction. This contradicts the results from Questionnaire survey 2 which show that simple components are seen as more suitable for standardization and prefabrication. Superstructures are in need of complicated formwork and reinforcement activities on-site. Hence, a clear driver for standardization of parts is complex and time consuming on-site construction (Blismas et al., 2006). Product standardization is one of two strategies for decreasing complexity proposed by Bertelsen (2004). According to Gann (1996), flexibility is important and the superstructure is probably the structure least affected by unpredictable geotechnical conditions; hence, it is the most suitable component to be standardized.

Conclusions

This study contributes to the literature on industrialized construction by investigating this topic in a previously neglected context: the infrastructure sector. Our findings show that the knowledge of Swedish practitioners within the infrastructure sector regarding the concept of industrialized construction varies widely. This study aimed to identify core elements of industrialization and also barriers for implementation of this concept. A majority of respondents agree that industrialization is a part of the future of construction of infrastructure. However, since there is a lack of knowledge about the concept and its core elements, both among practitioners and researchers, it is difficult to be able to implement suitable strategies. Practitioners in general view prefabrication as the single most important element of industrialization, while practitioners who have more knowledge and experience of industrialized infrastructure construction have a wider view of the concept.

An important contribution to the literature on industrialized construction is the five identified core elements of industrialized infrastructure construction. Three are related to the process (Planning for efficient production, Integrated design & production, Continuous improvement) while only one (Prefabrication & automation) is directly related to the product. The fifth core element is Standardization, which is related to both the product and the process.

It is interesting that, out of the five largest barriers, three could be traced back to the client role. As such, the clients (i.e. STA in Sweden) must address these barriers in order to enhance increased industrialization. Launch of the long-term research and innovation program by STA, which promotes increased industrialization throughout the value chain and standardization of products, is a first step toward breaking down barriers and giving the potential for increased productivity.

The standardization of products is shown to be a possible way of decreasing the complexity related to on-site construction but will not become more common as long as the chances for large-scale production and repetitiveness are small. Future research should be encouraged to focus on the processes, both because of the identified knowledge gap, but also because of the importance of shifting focus from product to process in an industrialized infrastructure context. Since the empirical results are based on data collected only from Swedish practitioners, international generalizations should be made with caution. Future research in other countries would be relevant in order to investigate the differences and similarities of barriers to industrialized infrastructure construction.

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PAPER II

Advantages of Industrialized Methods Used in Small Bridge Construction

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ADVANTAGES OF INDUSTRIALIZED METHODS USED IN SMALL BRIDGE CONSTRUCTION

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ABSTRACT

Evaluating to what extent industrialized production methods used during the steel reinforcement, formwork and concrete casting of small bridges are beneficial to the construction industry. The study evaluates the economical value of the construction of small bridges in terms of design and constructability from a production point of view. Moreover, the health and safety issues of the production processes are considered.

The study method used is the internal documents study involved in the construction of the bridges. A comparison between data collected for previous studies on bridge construction projects and data collected from internal company documents will be performed. The study uses an economic analysis to evaluate alternative construction materials, assemblies, and bridge services with the objective to improve project planners or owners' decision making during the course of planning, designing and constructing a bridge. The use of bridge economic analysis to determine the most economically efficient choice among bridge design alternatives when it comes to steel reinforcement, formwork and concrete casting in regard to improved quality and working environment.

The study discusses and offers recommendations for a cost effective bridge construction process which reduces waste in the production process and keeps the project schedule.

KEY WORDS

Safety management, waste reduction, design and planning, construction process, quality, economic analysis

INTRODUCTION

This paper is the result of research work that has been done as a response to the increasing demand for more efficient and competitive ways of constructing bridges. The development in bridge construction has not been very progressive in Sweden over the last decades; new techniques and methods have seldom been presented. Traditionally, bridges are usually cast *in situ*, involving a massive use of manpower and techniques that may be characterized as more or less craftsman-like (Harryson, 2008). Industrialized construction methods and techniques such as self-compacting

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concrete (SCC) casting and the use of prefabricated reinforcement steel structures, for example, are not used very often.

Although the industrial construction sounds off as if it was something new. Already in ancient Greece instances occurred where famous structures were erected with prefabricated components of stone, as reported by Warszawski (1999). It is also reported that in ancient Israel, "the stones used in the construction of the temple were finished at the quarry, so there was no sound of hammer, ax, or any other iron at the building site" (1Kings 6:7, New Living Bible Translation, 2007).

During the industrial revolution Victorian engineers could not have managed to build structures such as The Britannia Bridge without prefabrication. Although the components were not constructed in factories originally they were made in safe places (Mason and Ghavami, 1994).

After the Second World War, the reconstruction of destroyed bridges during the war was an intense construction program which also became an ideal laboratory for evolution in the way bridges were built and thus construction systems such as the use of pre-stressed structures and prefabricated components were developed to increase the degree of constructability and to avoid the need for costly dense castles of scaffolding pipes (Iori and Poretti, 2009).

Today, off-site prefabrication and modern construction methods is some of many innovative ways used in the construction industry to developers seeking cheaper construction. With the continually increasing costs of building structures, there are at least two ways of getting on top of this problem in the construction industry. Firstly, the way the procurement of materials is done and secondly the use of available modern construction methods which possible leads less employees on the construction site.

METHODOLOGY

When the Swedish government decided to relocate the European road E4 around a major city, there were, apart from the actual road construction, 115 bridges to be constructed. The whole construction project was to be carried out during approximately a five year period. On this new road construction project, it was decided, during the early design stage, that there should be 110 different bridges; the question is, was that really necessary? No one seemed to be thinking in such terms as standardization, simplicity, and repetitive work, as Adams (1989) suggested, but solely on the architectural part of the road, and hence it was decided that 110 different bridges were to be constructed. The total contract sum for the road was estimated to roughly € 300 million. How much of that cost could have been saved if solely simplicity, standardization and repetitive work had been considered?

HYPOTHESIS

The hypothesis for the research study presented in this paper is that standardization and simplicity of structural design reduces costs related to building materials and manpower working hours.

CASE STUDY

The data presented in this paper were collected through a review of internal company documents as well as reviewing previous case studies on industrialized construction of bridges. The authors have had the opportunity to study most of the material concerning the construction of small bridges on a 70km long section of the E4 highway rerouting. Documents studied include designer drawings and information on the amount of time the designers spent on each project, contractor's perceptions on each project in terms of suggested construction methods and work time consumption for most of the work to be carried out and client's expectation in terms of early design drawings to name some of the documents. This research study has limited its scope on the construction of concrete rigid frame bridges within this project.

PREVIOUS STUDIES

Similar studies of the benefits in using standardization, simplicity and repetitive work has been carried out on smaller roads in Sweden by the authors. During one study, when constructing merely 10 different concrete bridges, the possibilities were to save roughly 20% of the construction time and approximately 5% of the construction costs, this when introducing alternative construction methods at a very late stage of the process. Had these different methods of construction been considered in the early design stage, the potential for improvement in production time and cost would have been significantly larger.

INDUSTRIALIZED PRODUCTION METHODS

The need to be competitive in the emerging global economy is very important topic in Sweden today. The use of industrialized production methods, such as the prefabrication of building components, is critical to competitiveness. Modern methods of construction have never been more relevant. Industrialized methods such as off-site manufacturing utilizing technically advanced prefabrication processes as well as using high performance building materials for the improvement of build quality and efficiency with rising importance to increase both the infrastructure objects built and the efficiency with which they are built.

FORMWORK

Formwork is a structure that keeps the concrete in the accurate place until it gains sufficient strength to support itself (American Association of State Highway and Transportation Officials, 1995). Current formwork often consists of temporary wood structures manufactured at construction site, with low initial material cost but the amount of labour hours needed during the construction is very high. In the studied E4-project, the total formwork material cost for slab frame bridges only stands for 6% of the total building cost, while the labour cost for the formwork was as high as 17% of the total building cost. Problems associated with this kind of formwork are e.g. leakage, with bad surfaces and increased life-cycle as a result, and also health and safety issues.

Left formwork is an interesting formwork which today is mostly used in house building but should, because of its benefits, be a natural structure in industrialized bridge building. Left formwork can consist of e.g. prefabricated shell walls, as formwork for the support walls and the wing walls, or prefabricated concrete plates, which together with prefabricated edge girder, could provide the formwork for the superstructure. Pre-stressed elements, e.g. hollow core or massive slabs, can be used to make the deck thinner without making it weaker, which leads to less filling of the bank (Betongvaruindustin, 2009).

Benefits of using left formwork are that you shorten the building time, less traffic disruption, fewer labor hours could be used, concrete surfaces has a better chance of satisfying the costumer and of course the health and safety at the site would be better. The down side of using left formwork is the increasing material cost and the logistic challenges it brings because of elements being large they have to arrive to the site location just-in-time to be assembled.

CONCRETE

Traditional vibrated concrete is still used for most of today's castings for both housing and civil structures. Approximately ten years ago the anticipation for Self Compacting Concrete, SCC, a concrete that level it self by the force of nature, was, that it would now encompass at least 50% of the market share, but that is not the case. Roughly 5% of all civil engineering concrete used in Sweden is SCC, and the number for housing project is slightly larger. The benefits with using SCC are that the casting goes faster, it requires less personnel, a decrease of 67% of working hours can be foreseen (Simonsson and Emborg, 2007), and the working environment becomes much better. The work environment is improved by a factor of 3 as documented by Rwamamara & Simonsson (2007). There have been problems with SCC before, such as variation in quality, separation of the concrete. However, most of these problems have been dealt with and can be considered eliminated; now the problem is education of contractors in the advantages and how to handle the concrete and catch 22. With the latter part means that since no one is demanding it the suppliers will not get much confidence in manufacturing it and, hence, the previous problems can come back. Still, most companies prepare for traditional casting of concrete.

REINFORCEMENT

Reinforcement is used to strengthen concrete for tension forces in structures. Reinforcement bars are often delivered cut and bended in right amounts, however it still needs to be fixed piece by piece into its final location. This work is very heavy to do and is often done in awkward working positions. It is also somewhat weather dependant and the productivity of the work force can vary depending on different circumstances, such as the weather and geometry of the structure.

Prefabrication of reinforcement cages however, ensures a continuous supply of reinforcement regardless of weather since these cages are manufactured in a controlled quality assured environment. Prefabrication of components allows a reduction in on-site steel fixing work time and in the number of workers needed for that particular work on site (Rwamamara and Simonsson, 2009). Furthermore, it minimises the amount of storage space required on what is usually considered to be a very congested construction site. The offsite fabrication of steel reinforcement offers a number of advantages such as difficult construction tolerances, improved transport and handling as well as contributing to speed of construction.

HEALTH AND SAFETY IN PRODUCTION PROCESS

Sweden's construction industry employs 286 thousand people of which 180 thousand people work with building and civil engineering work, making it one of the country biggest industries (Samuelsson et al., 2009). It is also one of the most dangerous. In last 30 years, over 336 have died from injuries they received as a result of building and civil engineering work. Many more have been injured or made ill.

Some construction occupational injuries are much higher than others. For instance, work-related musculoskeletal injuries are more common than other occupational illnesses among construction workers. Work-related musculoskeletal disorders (WMSD) are injuries of the muscles, tendons, joints, and nerves caused or aggravated by work. The physically demanding nature of construction work helps explain why strains and sprains are the most common type of injury resulting in days away from work in construction. In 2008, about 65% of all nonfatal injuries and illnesses in the construction industry resulting in days away from work were due to sprains and strains (Samuelsson, 2009). Cross-sectional studies also have reported a high prevalence of WMSDs among construction workers (Engholm and Holmström, 2005).

Occupational injuries such as Work-related Musculoskeletal Disorders (WMSDs) are unquestionably wasteful and non-value adding events in construction production systems. These events contribute to unreliable workflow, which in turn creates havoc on any construction project. As stated by Howell and Ballard (1994), achieving reliable workflow is possible when sources of variability are controlled. It follows then that safeguarding construction workers from occupational hazards is an integral part of the lean construction ideal of maintaining reliable workflow (Abdelhamid et al., 2003). Human-oriented work structuring will better the occupational health and safety of the construction workforce while simultaneously reducing workflow unreliability and enabling lean conversion efforts (Abdelhamid and Everett, 2002).

Industrialization process through industrialized methods used in the construction production has been given credit for reducing health and safety problems such as WMSDs among construction workers (Rwamamara, 2005). Industrialization describes and encompasses all three aspects of offsite construction work namely, modularization, prefabrication, and preassembly. Further, this industrialization process can be defined as an investment in equipment, facilities, and technology with the intent of increasing output, decreasing manual labour, and improving quality (Warszawski 1990). It uses the concepts of manufacturing and applies them to construction.

IMPORTANCE OF DESIGN IN BRIDGE CONSTRUCTION

DESIGN FOR EASE OF CONSTRUCTION

The terms constructability and buildability are often used when considering ease of construction during the production phase. The two concepts have similarities and differences; constructability refers to the total concept of production entailing everything from design to planning and purchasing to make a project as uncomplicated to build as possible whereas buildability refers to how the design process can accomplish simple construction.

According to Wong et al. (2006) there are two major definitions accepted on the term constructability. The definitions were stated by; CII (1986) “the optimum use of construction knowledge and experience in planning, design, procurement and field operations to achieve overall project objectives” and by CII Australia (1996), “the integration of construction knowledge in the project delivery process and balancing the various project and environmental constraints to achieve project goals and building performance at an optimal level".

The definition of buildability by Adams (1989) is well recognized and is stated as "the extent to which the design of a building facilitates ease of construction". Also according to Adams (1989) there are three key concepts within buildability namely; simplicity, standardization and clear communication.

Womack and Jones (2003) suggests that there are five key concepts in Lean, they are; define customer value, identify the value stream, make value flow through production, use a pull system for production and strive for perfection. When constructing bridges in Sweden, the customer, e.g. the government, has a clear set of rules for the construction which need to be followed, consequently one can interpret these rules as a part of the stated customer value. However, to identify the value stream at a construction site, to make the value flow through production and to strive for perfection the design stage is important; hence a focus on buildability and constructability can be advantageous.

During the design stage many obstacles arising within the construction stage can be foreseen and prevented. Thus, if buildability is considered and design is taken seriously, with enough effort and time, it will increase the flow of production. Considering also the implementation of constructability, consequently the experience in planning, procurement and field operations, the concepts of pull and perfection can be utilized and hence the production can be optimized.

DESIGN FOR HEALTH AND SAFETY

The traditional separation between design and construct functions in construction has been a barrier to the improvement of health and safety of construction workers. The Commission of European Communities claims that over 60 percent of all fatal construction accidents can be contributed to decisions made before construction work on the site (Commission of European Communities, 1993). According to Lingard and Rowlinson, 2005), this suggests that decisions made early in a project's life, particularly during design stages, may impact upon the health and safety of workers who must then construct the facility in accordance with design and specifications provided by the architect or design consultant. To strengthen this position further, 50 percent of the 71 contractors responding to a survey of the construction community in South Africa identified design as a factor that negatively affects health and safety (Smallwood, 1996).

Designer decisions made during the schematic and design development phases of a project directly impact the health and safety of the construction workers construction workplace. Many decisions also impact the safety of end users, maintenance and repair workers, and construction crews during renovation or deconstruction cycles. A safety analysis conducted during design phases is an effective means of identifying unnecessary hazards in the project design, many of which may be "designed out" through the use of alternative components, systems, or construction methods (Haas, 1999).

RESULTS

Distribution of total costs for the constructed bridges can be seen in Figure 1. It can be seen that the costs for material and labor for formwork, reinforcement and concrete is approximately 23 % each of the total costs. It can also be seen in Figure 2 that the labor cost for formwork and reinforcement stands for approximately 85% of all labor cost associated with the project. However, the work labeled remaining work (e.g. pile driving, railing, asphalting) is done by subcontractors and, hence, the main contractor has no labor costs for these activities.

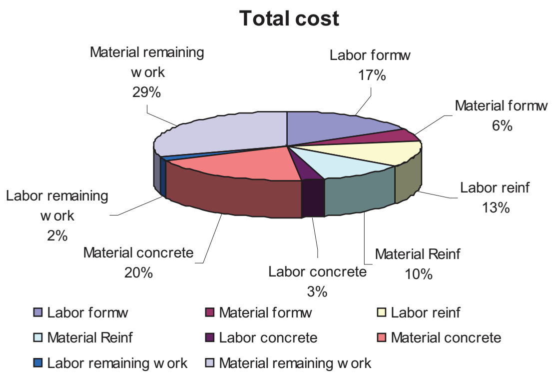

Figure 1: Distribution of total costs for the constructed bridges in the studied project.

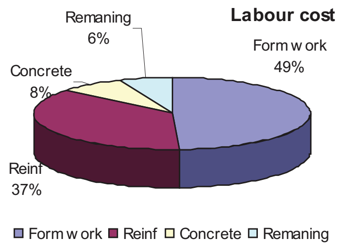

Figure 2: Distribution of labor costs for the different activities in the studied project.

STANDARDIZATION AND SIMPLICITY

It is possible to group the foundations of the studied bridges into different geometries and load capacities and consequently standardize them. Instead of constructing for instance 64 different reinforcement cages for the foundations required for the 32 studied bridges, it would have been possible to group the reinforcement cages for the foundations into 6 different groups. Hence, a standardization of one component for the bridges can be foreseen to have an impact on the construction schedule time and cost of the project. If a grouping of the foundations had been done there would have been a possibility to save more than 22 worker weeks at site and approximately 50 % of the anticipated labor costs for reinforcing the foundations, Table 1.

Table 1: Manufacturing time and labor costs for the three different solutions of the standardized foundations.

	Traditional	Subcontractor	Field factory
Manufacturing h	1728	643,2	960
Manufacturing cost €	60480	22512	33600
Mounting of rebar basket at site	0	16	16
Mounting cost €	0	3200	3200
Total work time at site	1728	16	976
Total cost for cages in form	**60480**	**25712**	**36800**

It would also have been possible to use a site factory for manufacturing of these foundations; the result would have been a reduction of approximately 50% of labor work time, Table 1. This work could have been used as buffer of work, as suggested by Ballard (2000) in the Last Planner of Production Control, to level out the demand of the work in production.

Table 2: Difference between using traditional concrete and SCC

Traditional	**Volume m3**	**Casting time h**	**No. Workers**	**Worked h**	**Cost €**
Foundation	2351	118	4	470	16457
Superstr.	7429	371	8	2971	104001
Linkplate	1470	74	4	294	10291
Sum	**11250**	**562**		**3736**	**130749**
SCC	**Volume m3**	**Casting time h**	**No. Workers**	**Worked h**	**Cost €**
Foundation	2351	78	1	78	2743
Superstr.	7429	248	5	1238	43334
Linkplate	1470	49	1	49	1715
Sum	**11250**	**375**		**1365**	**47792**

If traditional concrete had been replaced by SCC, the potential for saving in production time at site would have been considerable. Approximately 60 worker weeks could have been used more productively in total for all concrete casting activities and only for the foundations some 10 weeks could have been saved in production time at site, Table 2. This work time could have been used to e.g. reinforce the next part of the bridge and, hence, reducing the total production time. The link plate mentioned in Table 2 is used to even out any possible settlement of the filling material close to the bridge.

Formwork, as shown in figure 2 stands for approximately half of the labor hours used in the studied project. If left formwork have been used instead, there would have been a possibility to save more that 630 worker weeks at site and approximately 80 % of the estimated labor costs of the needed labor hours for formwork, see Table 3. As for the reinforcement, a site factory could have been used which means that this also could be used as buffer work. Using a site factory would also make the logistic issues easier to handle, which otherwise could be a problem due to large sizes of prefabricated elements.

Table 3: Needed labour hours for formwork during the construction of slab frame bridges in the E4-project.

Formwork	**Labour hours**	**Cost €**
Traditional	29578	990863
Left	4369	146362

DISCUSSION AND CONCLUSION

The size of the studied project makes it eminent for using industrialized production methods and for standardization of components to the bridges. The focus in the design phase in the early stage of the project should have been on standardization, simplicity and communication and consequently on constructability and buildability of the bridges. The potential, if the designing and the planning of the bridges had been done appropriately, would have been vast and this has been demonstrated by studying the results from the bridges foundations.

It can be concluded that when projects of this magnitude, which is fairly rare in Sweden, are to be constructed, they need to be treated differently than an ordinary project with a much less number of bridges. Consequently, the reduction of accidents will decrease and the health and safety at our work sites will increase if these parameters are considered during design.

The largest factor hindering the introduction of industrialized working methods is the late involvement of the contractor in the project process. According to answers of several contractors during interviews, "there is simply not enough time for site management to rethink production". It seems as if the organizational culture is not geared to implement changes at that time during a project. There is a sort of tradition of conservatism in the trade, and consequently there is a need for a paradigm shift in organizational culture with in companies and the in building trade for industrialization to succeed.

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PAPER III

Barriers and Drivers for Increased Use of Off-site Bridge Manufacturing in Sweden

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BARRIERS AND DRIVERS FOR INCREASED USE OF OFF-SITE BRIDGE CONSTRUCTION IN SWEDEN

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There is great pressure to change the civil engineering industry in Sweden, which is said not to follow efficiency growth other manufacturing sectors are achieving. This increases a demand for innovative construction methods and a growing industrialised thinking for sustainable construction. By implementing off-site manufacturing (OSM) into bridge construction, client satisfaction can increase, bridges can be constructed faster using less resource, and more bridges for the same invested capital can be realised. A questionnaire survey and a workshop have been undertaken partly to identify benefits and drawbacks for OSM in bridge construction and partly to study if OSM satisfies the client better than on-site construction. The outcome shows that drivers of OSM meet client needs better than on-site construction alternatives. Time, cost and working environment are large drivers, correlating well with previous surveys undertaken. However, quality, as in other surveys tend to stand out as a driver, is a barrier in comparison with on-site construction. This opinion may be due to both the generally negative views for OSM bridges in Sweden and also due to previous bad experiences. Despite these negative views, results show that the hypothesis of OSM being a better alternative for satisfying the client is true. To increase its market share, barriers like reduced quality and not aesthetically pleasing must be overcome. OSM bridges are to date a rare feature in Sweden, but by display the drivers, it could become a common construction method in Sweden.

Keywords: off-site manufacturing (OSM), bridge construction, client needs, barriers, drivers.

INTRODUCTION

Today there is a lot of talk about the demand of change within the Swedish civil engineering to become more industrialised. Like in many countries (Egan 1998, Blismas & Wakefield 2007), Swedish construction industry has been linked with inefficiency and not meeting client needs. To be able to implement new methods and techniques, a whole new approach involving all actors have to be implemented (Simonsson 2011). Off-site manufacturing (OSM) and standardisation are seen as large parts of industrialisation in Sweden. According to Eriksson et al. (2011) and Olander et al. (2011) the benefits for industrialisation is increased productivity, leading to time and cost reduction. Barriers include conservatism, strict codes and unsuitable contracts. Several productivity studies, e.g. (Horman and Kenley 2005, Mossman 2009) identify that wasteful activities stands for between 50-65% of available construction time. OSM is seen as a method to reduce waste and complexity related to on-site construction (Tam et al. 2006, Ballard and Arbulu 2004).

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Much has been written on drivers and barriers of OSM in general; nevertheless little emphasis of this construction method within bridge construction exists. OSM bridges can be seen as Non-volumetric preassembly products that are produced in a factory and then only installed into their final position at the construction site (Gibb & Isack 2003). These OSM bridge units can consist of beams and slabs but also prefabricated reinforcement cages and left formwork. Bridges in Sweden are to date most often on-site constructed, while OSM bridges are a common feature in other countries e.g. the Netherlands, Denmark, Poland and the United States, to name but a few. By highlighting the drivers and barriers with this construction method, the use of OSM within Swedish bridge construction could become more common as in other countries.

In this research, benefits and drawbacks are product related and only become drivers and barriers if these factors are important for the client. Hence, drivers and barriers are important factors to satisfy client needs.

To investigate if OSM is satisfying client needs better than on-site construction and also to highlight barriers and drivers for OSM a comprehensive survey has been completed. To complement important results from the survey a workshop has been undertaken. In spring 2010, a new Swedish authority (Swedish Transport Administration) was formed with the task to develop an effective and sustainable transport system. The authority has, from the government, been given the task of creating conditions for increased productivity within the industry. This should be done through conveying a larger responsibility to the actors on the market e.g. contractors and designers. STA is responsible for the construction, operation and maintenance of public roads and railways including bridges. Because of this transformation, the opportunity to change Swedish bridge construction is today larger than ever. It is easier to define client satisfaction within bridge construction compared to e.g. house construction, because only one major client exists operating under strict codes (Eurocodes).

Consequently, this paper aims to answer the following research question: Is client satisfaction increased by implementing more OSM into Swedish bridge construction?

OSM RESEARCH

General

OSM has in general been recognised as a vital element for improving construction in terms of efficiency and productivity (Blismas & Wakefield 2007). Drivers often associated with OSM are time, quality, cost and health and safety (H&S) related (Blismas et al. 2006, Gibb & Isack 2003). Perceived drivers and barriers of OSM are well documented (Blismas et al. 2006, Gibb & Isack 2003, Nadim & Goulding 2011). OSM and its' benefits are poorly understood by many involved, consequently a reluctance of using it is widely spread (Pasquire & Gibb 2002, CIRIA 2000).

Barriers for increased use of OSM are mostly process, value, conservatism and knowledge related (Blismas et al. 2005). A major drawback is that design of the structure has to be established early in the projects lifecycle because of the long supply-chain associated with OSM. A more complete understanding of the process and cooperation throughout the whole supply-chain are two major issues needed to be understood regarding OSM (Pan and Sidwell 2011 and Gann 1996). According to Nadim and Goulding (2009), both academia and practitioners agree that communication skills, teamwork and problem solving plays major part in increasing the uptake of OSM. Construction industry is more focused on initial construction cost rather than value, hindering OSM to be equitably evaluated (Blismas et al. 2006, Pasquire & Gibb 2002). Previous OSM research regarding drivers and barriers is summarised in Table 1.

Table 1: Research summary of drivers and barriers for off-site manufacturing

General OSM	**Research method**	Quality	Predictalility/Consistency	Fewer defects	Cost	Initial cost	Life-cycle cost	Value for money	Profitability	Time	Minimize on-site operations	Minimize construction delays	Traffic disruption	Process	Reduce waste	Cooperation	Codes	Lead-time	Design fixed early	Present process and management	Health & Safety	Environment	Productivity	Constructability	Fewer people involved	Need of skilled workers	Suitable evaluation tools	Negativism/Conservatism	Lack of knowledge	Few available suppliers
Blismas et al. (2005)	S									D				B				B		B							B		B	B
Blismas et al. (2006)	C																										B			
Blismas & Wakef. (2007)	W, C, I		D		D	B				D				D	D		B	B	B	B	D	D				D		B	B	
Gibb & Isack (2003)	I	D			D					D	D			D				B	B				D		D		B			
Goodier & Gibb (2001)	L, S, W	D				B				D																	B	B		
Pasquire & Gibb (2002)	I	D	D	D	D			D	D	D											D	D	D				B			
Tam et al. (2006)	I														D															
Pan & Sidwell (2011)	C				D					D						B														
Olander et al. (2011)	L, C				D											D	B			B			D					B		
Eriksson et al. (2011)	I				D					D													D				B	B		
OSM bridge																														
Russell et al. (2005)	C	D					D						D								D	D		D						
Freeby (2005)	C	D					D						D								D	D		D						
Fed High. Adm. (2006)	C					D				D																				
NCHRP (2003)	L	D			D	B				D		D	D								D									
Summary		6D	2D	1D	7D	1D 3B	2D	1D	1D	9D	1D	1D	3D	2D 1B	2D	1D 1B	2B	3B	2B	3B	5D	4D	4D	2D	1D	1D	6B	4B	2B	1B

D=driver, B=barrier, S=survey, C=case study, I=interview, W=workshop, L=literature review

OSM bridge

Research within off-site bridge construction often involves case studies of a specific project or concept, not surveys and interviews which often are included in general OSM research. Concerns associated with bridge construction is often the same as for general construction, but one specific area for bridges is traffic disruption which often has to be considered (NCHRP 2003). Case studies are often performed on prefabricated bridge concepts and reducing traffic disruption is often highlighted as the major driver (Freeby 2005, Russell et al. 2005). OSM are often evaluated on the assumption that they reduce traffic disruption in comparison to on-site construction.

Other documented drivers for prefabricated bridges are; improved H&S, improved constructability, increased quality, reduced environmental impact and lower life-cycle costs. These are correlating well with drivers for OSM in general (Gibb and Isack 2003). OSM bridge research seldom discusses drawbacks, but only highlights the benefits that are available (Freeby 2005, Federal Highway Administration 2006, Russell et al. 2005). Insufficient attention has to date been devoted to explore what barriers and drawbacks that exist for OSM bridge construction and how this construction method satisfies client needs, see Table 1.

QUESTIONNAIRE SURVEY AND WORKSHOP

A comprehensive questionnaire survey has been undertaken to form the foundation for this research. The respondents include contractors, consultants/designers, OSM suppliers and clients. For a complete summary of respondents and their experiences of on-site and OSM, see Table 2. Questionnaire forms where sent to the respondents by email and completed surveys where sent back by return email, making it possible to reach numerous respondents at the same time. 159 questionnaire forms where sent out, with 66 answering respondents which makes the respondent rate approximately 42%. The number of respondents is not sufficient for the results to be statistically significant. The survey and workshop contains qualitative elements which support the quantitative results, making it possible to draw conclusions.

Table 2: Experience of the respondents from the questionnaire survey

Roll (Resp. num.)	Contractor (27)			Client (21)			Designer (13)			OSM suppl. (5)		
Experience (Years)	<1	1-5	>5	<1	1-5	>5	<1	1-5	>5	<1	1-5	>5
Construction	0%	7%	93%	0%	0%	100%	0%	0%	100%	0%	20%	80%
On-site	4%	11%	85%	10%	10%	80%	0%	0%	100%	20%	40%	40%
Off-site	41%	22%	47%	29%	23%	48%	24%	38%	38%	0%	40%	60%

The survey was kept as short as possible containing a total of 25 questions, hence a too comprehensive survey increases the risk of losing respondents and the answers tend to contain less thoughtful answers (Holme & Solvang 1991). The questionnaire were discussed and debated with several persons, both practitioners and academics, before distribution, in order to minimize misunderstandings and leading questions. Leading questions and loaded formulations could otherwise greatly influence the answers (Andersson 1985). The research is inductive meaning that the survey was undertaken before theory around the topic where studied.

The survey formulated most questions with structured responses through a five-point scale making it easy to answer and to compile the material. Most questions allow respondents to provide comments in addition to the structured response options, making the answers more rich (Bergman & Wärneryd 1982). Topics for the survey were selected to give an overview of the industry today and what is expected of the future including questions about; different contract forms, early involvement from different actors, development of the industry in Sweden, OSM, standardization, on-site construction, industrialised thinking and important factors for bridge construction.

To complement results from the survey, a workshop involving contractors, clients and OSM suppliers has been undertaken. Participants were selected based on experience and influence opportunity for the development of the industry, making it possible for the outcome to be passed out to the rest of the industry. Four groups were formed to discuss five specific questions during the workshop; industrialisation, client/customer satisfaction, cooperation, uniqueness of the construction industry and reluctance to change. The topics were chosen based on problems for sustainable development identified in the undertaken questionnaire survey.

RESULT AND ANALYSIS

According to the survey, all participants are convinced that bridge construction in Sweden has to become more efficient and effective in the future. Involved actors tend to blame low productivity and lack of development on thoughts that the industry in some way is unique and therefore, impossible to change. Other causes for lack of development are according to the survey; strict rules and norms, wide spread conservatism and lack of competition with few contractors.

Respondents are disagreeing on the question if bridge construction has become more industrialised the last years. Many respondents are only associating industrialisation with OSM and not with other factors, e.g. processes and standardisation.

Benefits and drawbacks for off-site manufacturing

An overview of the ranked benefits and drawbacks for OSM bridge construction in Sweden, according to the outcome of the survey, shows that time and health and safety (H&S) are the largest benefits. Aesthetic aspects are according to the undertaken questionnaire survey a major drawback, see Figure 1.

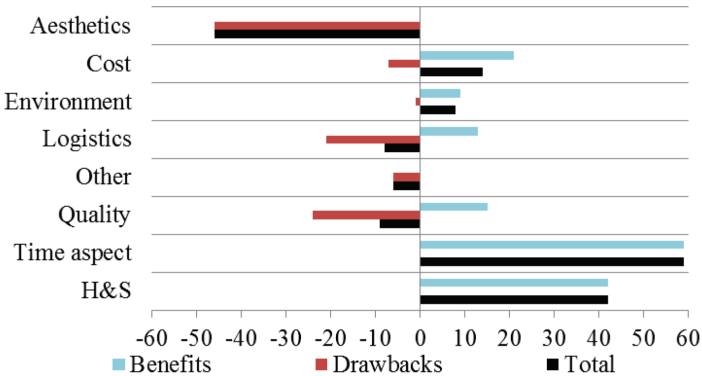

Figure 1: Benefits and drawbacks for OSM. Scores were derived from survey results where respondents could choose up to three factors

Respondents often use words like "ugly" and that all prefabricated bridges look the same. Quality, which often is stated in previous research as a benefit for OSM, is in this survey seen as a negative factor for OSM bridges. Studying this question even deeper, reveals that OSM suppliers are seeing quality as a major benefit but especially clients and designers see quality as a drawback.

Benefits and drawbacks for on-site construction

Two major benefits for on-site construction are aesthetics and quality according to the survey, see Figure 2. Quality which is seen as a minor drawback for OSM bridges is seen as the largest driver for on-site construction. This result does not correspond well with previous undertaken research (Freeby 2005, Blismas & Wakefield 2007, Gibb & Isack 2003).

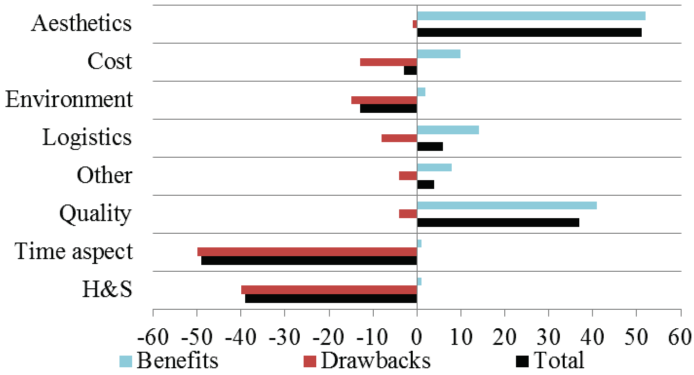

Figure 2: Benefits and drawbacks for on-site construction. Scores were derived from survey results where respondents could choose up to three factors

Client satisfaction

Factors with the greatest importance when constructing a bridge in Sweden, is according to the questionnaire survey quality and cost, see Figure 3. Time is less important for contractors and consultants, but instead these actors seem to think aesthetic aspects are very important. The total score is correlating well with what clients seem to think are important factors. Quality, cost, time and H&S are the four most important factors for satisfying client needs when constructing a bridge. This result correlates well with previous survey undertaken about OSM in general. Hence, these four could be seen as drivers or barriers for the different construction methods.

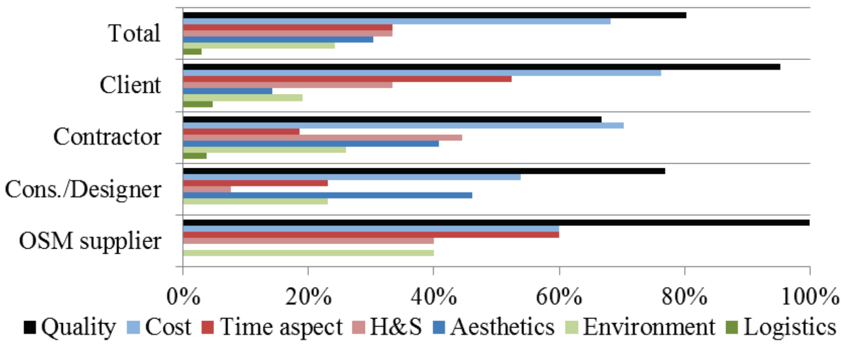

Figure 3: Most important factors for bridge construction. Scores were derived from survey results where respondents could choose up to three factors

By taking the benefit scores for the four most important factors out of Figure 1 and Figure 2, and multiplying these with the total importance for each factor, Figure 3, the drivers and barriers for the construction methods are revealed, see Figure 4. By making a radar diagram of the scores obtained shows that OSM is satisfying client needs better than traditional on-site construction, see Figure 4. The sum for OSM drivers are 60 while the same number for on-site construction is 40. Quality is, according to the radar diagram, the largest barrier for OSM, while time, cost and H&S are drivers for increased use of OSM within bridge construction in Sweden.

	Quality	Cost	Time	H&S
Benefits for OSM	15	21	59	42
Benefits for On-site	41	10	1	1
Importance of factor	0,80	0,7	0,3	0,33
Drivers for OSM	12	14	20	14
Drivers for On-site	33	7	0	0

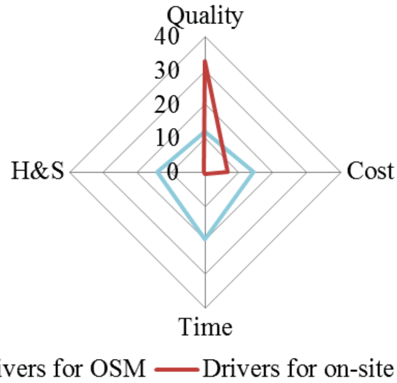

Figure 4: Construction methods most suitable for satisfying the client needs

Structures suitable for OSM and standardisation

Bridges in Sweden will, according to the questionnaire survey, in the future consist of a combination of on-site construction and OSM, see Figure 5. Clients and OSM suppliers are more positive to OSM than contractors and consultants. According to the survey, differences between the two construction methods are mostly time, quality and aesthetics related, but also flexibility and process are frequently mentioned. Design has to be set earlier in an OSM project, hence OSM is less flexible and changes are more difficult to deal with at the construction site.

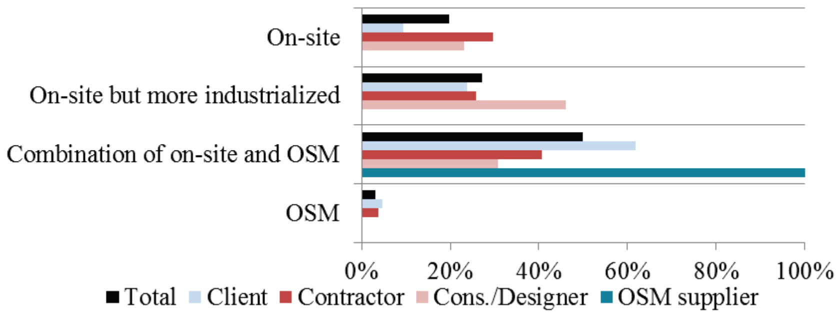

Figure 5: Future construction methods for bridges in Sweden

94% of all respondents think that it is possible to standardise bridges or at least parts of bridge structures. Almost 50% of all respondents think that the superstructure of bridges benefits most of OSM and standardisation. Hence, OSM superstructures have been tested in Sweden and abroad with satisfying results. 33% of all respondents believe that the superstructure is the bridge structure that demands most working hours on-site, probably contributing to the positive approach for OSM.

Workshop discussion

To complement the survey results, a workshop has been undertaken. A summary of the three most important questions for this research from the workshop can be seen in Table 2. The first question is about industrialised thinking and what elements that are involved in it. One aim with industrialised thinking is to increase the customer satisfaction. Hence, second question is about what elements that are associated with customer satisfaction, in this case the customer is the user of the bridges. The industry is said to be change reluctant and that involved actors often are conservative. Third question deals with components that could facilitate for possible changes.

Table 2: Summary of the three most important questions from the workshop

Elements associated with industrialised thinking	
Processes	OSM
Standardisation	Traceability
Elements associated with customer satisfaction	
Satisfying a need	Shortened construction time
Information about disruption	Minimise traffic disruption during construction
Elements that facilitate for changes	
Must be able to see profit of changes	Focusing on value when peforming the procurement
Understanding of the process	More available time in the beginning of the project
Positive and involved clients	Increased understanding and respect for people

OSM is a major part of an industrialisation of construction in general, but also for bridge construction. A standardised product is in need of a standardised process to be as efficient and effective as possible to construct. Standardised work and standardised products are of great importance to be able to gain advantages associated with repeatability. For that to be possible, similarities between projects have to be recognised and utilised. Working with continuous improvements and seeing the whole value chain is, according to all group discussions, an important part of an industrialised thinking. Cooperation between involved actors and creating clear communication channels are necessary to increase the client satisfaction. By letting involved actors fully understand what the changes is all about and that it takes to time to change a whole industry is of great importance to be able to get everyone on-board.

It is important to conduct long-term thinking regarding changes within this or any industry to recognise the value of changes. In bridge construction it is important not only to focus on initial construction cost but also on, e.g. improved working environment, decreased life-cycle costs and improved quality. Increased understanding of the complete construction process, and not only for the own companies process, is of great importance for the project to be planed correctly and successfully executed.

DISCUSSION & CONCLUSIONS

The presented result from the survey shows that client needs are better fulfilled by using OSM for bridge construction in Sweden. It also provides opinion of how different actors within civil engineering think about OSM and the utilisation of this construction method. Despite that OSM is a rare feature in Sweden, 70% of all questionnaire respondents answer that they holds more than one year of OSM experience. The conclusions are based on one questionnaire survey including 66 respondents. Hence, some limitations in the conclusions can be foreseen. A workshop has been performed to verify some important results from the survey.

Major drivers for OSM within bridge construction in Sweden are time, H&S and cost. Largest drawback for OSM bridges is the aesthetics. Prefabricated bridges are most often associated with unattractive appearance and that they all look the same.

Quality is seen as a major driver for on-site bridges even though this construction method often is linked with unpredictable construction conditions, e.g. weather. By constructing the bridge in a factory, as for OSM, and only assemble it at the construction site, circumstances for obtaining high quality products should increase. This rather unexpected result, for the quality factor, is probably based on past experience and also due to the general resistance and negative view that exists for OSM in Sweden.

If considering the four most important factors for bridge construction according to the questionnaire survey; quality, time, cost and H&S, from a client perspective, these fits better into OSM than traditional on-site construction according to the survey. For OSM to be more common, both client and contractor have to understand the benefits of using it.

Future research will focus on process platforms for bridge construction containing elements like experience feedback loop, this to be able to work with continuous improvements. By having a standardised process, it will be possible to measure how changes are affecting the end product.

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PAPER IV

Decreased Complexity of Bridge Construction through Prefabrication: A Case Study

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DECREASED COMPLEXITY OF BRIDGE CONSTRUCTION THROUGH PREFABRICATION: A CASE STUDY

Johan Larsson[1] and Peter Simonsson[2]

ABSTRACT

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

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

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

KEY WORDS

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

INTRODUCTION

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

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concept is quicker and easier to construct but some concerns like less flexibility and importance of correct dimensions are recognized. Prefabrication is seen as a method to reduce traffic disturbance, costs and to improve on-site work safety (Freeby 2005).

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

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

COMPLEXITY IN CONSTRUCTION

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

The project team should reduce the degree of uncertainty by planning the process as well as possible. Focusing not only on reducing; on-site activities, variation and engaged participants but also on putting more effort into design will achieve a more predicted construction process (Sardén and Stehn, 2006). Reducing the complexity at a construction site can be divided into two different strategies emerged from Lean Construction. By either developing on-site construction processes as proposed by Koskela et al. (2003), or to develop prefabrication and standardized processes as proposed by Ballard and Arbulu (2004). Höök and Stehn (2005) called the latter a prefabrication strategy. The idea is to simplify and minimize work at site and by doing that involving every phase in the delivery process. Prefabrication as part of an industrialized construction process is a way to control unpredictable events (Björnfot and Stehn 2005). Standardization and pre-assembly is not always the answer. Conflict between standardization and flexibility has not yet been resolved (Gibb 2001).

MAPPING CONSTRUCTION PROCESS

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

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

USING VSM TO IDENTIFY COMPLEXITY

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

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

OMITTED ACTIVITIES

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

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

STUDIED BRIDGE CONCEPTS

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

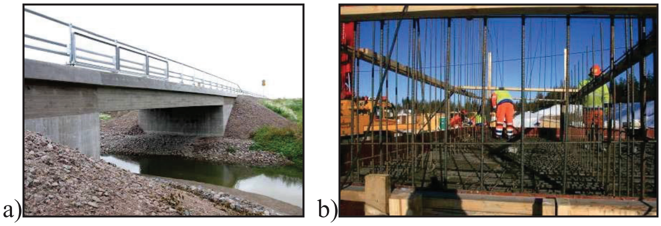

Figure 1: a) Complete bridge at construction site. b) Traditional on-site construction

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

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

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

RESULT

CURRENT STATE

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

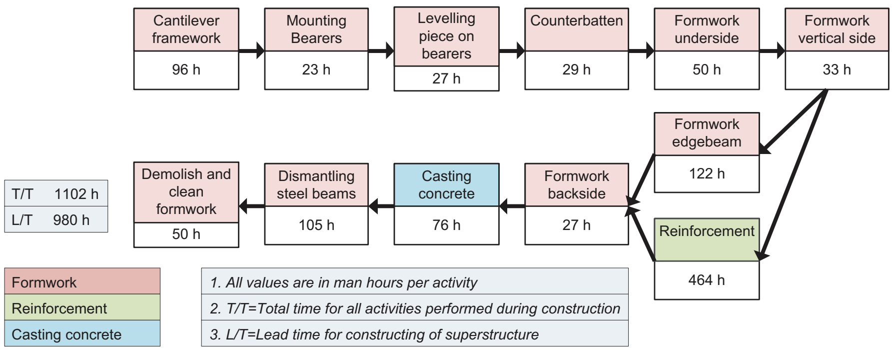

Figure 3: VSM for current state of construction

FUTURE STATE

Only six activities are performed during construction of future state and only one parallel, figure 4. Total lead time for future state is 249 working hours. Three out of six activities are performed by the prefabrication supplier, the rest are performed by the contractor. This prefabrication supplier is working with Just-In-Time (JIT), meaning that beams and slabs arrived at construction site JIT to be mounted onto the plate structures making the handling minimal. A specialized assembly team from the supplier performed the mounting. This make the process efficient (Gibb 2001).

According to the summary calculation, the total amount of hours for the semi-prefabricated concept is about 720 including all activities.

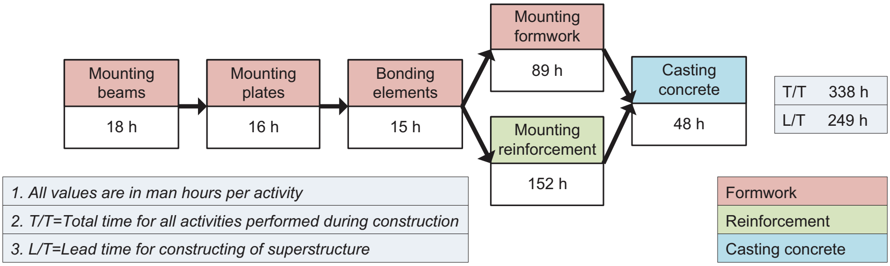

Figure 4: VSM for future state of construction

Shortcomings of future state

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

a) b) c)

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

ANALYSIS & DISCUSSION

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

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

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

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

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

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

Table 2: Causes to problems

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

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

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

IDEAL STATE

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

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

CONCLUSIONS & FUTURE RESEARCH

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

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

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

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

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Appendices 1-2

Appendix 1: Questionnaire survey – Questions

Appendix 2: Workshop – Questions and summary of results

I denna enkätundersökning kommer ni som respondenter att svara på frågor som berör brobyggandet i Sverige. Enkäten kommer enbart att användas i forskningssyfte och alla respondenter har möjlighet att svara anonymt. Då ni svarat på enkäten samt sparat era svar sänder ni tillbaka enkäten till samma e-post (johan.ojanen@ltu.se) som ni fick den ifrån. Tack för din medverkan och bidrag till en utveckling mot en hälsosammare och effektivare bro bransch.

Namn (frivilligt)	
Företag (frivilligt)	
Kön (frivilligt)	Kvinna
Jobbtitel/arbetsuppgift	
Antal år i byggbranschen	>10 år
Erfarenhet av platsbyggt	>10 år
Erfarenhet av prefab	>10 år

1. När blir ni delaktiga i ett broprojekt?
   Förstudie

2. Kan du i din yrkesroll påverka och förändra utformningen av ett broprojekt (koncept, konstruktion, tidsaspekt m.m.)?
   Instämmer helt

3. Skulle du vilja kunna påverka mer i utformningen av ett broprojekt, om ja så motivera ditt svar?

   Ja

4. Hur bör en projektering vara utformad för en gynnsam utveckling mot en mer effektiv anläggningsbransch?

5. Vilken har störst ansvar för en snabbare utveckling av brobyggarbranschen, motivera?

   Trafikverket

6. Vilken entreprenadform är vanligast vid ett broprojekt?

   Funktionsentreprenad

7. Har situationen förändrats något under de senaste åren med avseende på entreprenadformen, motivera?

   Instämmer helt

8. Vilken entreprenadform anser du vara mest gynnsam för utvecklingen av anläggningsbranschen, motivera?
   Funktionsentreprenad

9. Vilka brodelar utgör största svårigheterna vid konstruktion av en bro?
   ☐ Ingen uppfattning

10. Vilka brodelar kräver mest arbetsresurser vid byggandet av en bro?
   ☐ Ingen uppfattning

11. Hur tror du att framtidens bro kommer att se ut?
   Platsbyggd

12. Finns det någon/några speciella delar av en bro som du tror passar bättre att prefabricera än andra, motivera?

13. Vilka är de största fördelarna med platsbyggda broar, välj högst tre alternativ?

- ☐ Arbetsmiljö
- ☐ Estetik
- ☐ Kostnad
- ☐ Kvalitet
- ☐ Annat, i så fall vad
- ☐ Logistik
- ☐ Miljöpåver
- ☐ Tidsaspekt

14. Vilka är de största fördelarna med prefabricerade broar, välj högst tre alternativ?

- ☐ Arbetsmiljö
- ☐ Estetik
- ☐ Kostnad
- ☐ Kvalitet
- ☐ Annat, i så fall vad
- ☐ Logistik
- ☐ Miljöpåver
- ☐ Tidsaspekt

15. Vilka är de största nackdelarna med platsbyggda broar, välj högst tre alternativ?

- ☐ Arbetsmiljö
- ☐ Estetik
- ☐ Kostnad
- ☐ Kvalitet
- ☐ Annat, i så fall vad
- ☐ Logistik
- ☐ Miljöpåver
- ☐ Tidsaspekt

16. Vilka är de största nackdelarna med prefabricerade broar, välj högst tre alternativ?

- ☐ Arbetsmiljö
- ☐ Estetik
- ☐ Kostnad
- ☐ Kvalitet
- ☐ Annat, i så fall vad
- ☐ Logistik
- ☐ Miljöpåver
- ☐ Tidsaspekt

17. Vad är de största skillnaderna mellan prefabricerat och platsbyggt?

18. Tror du det är möjligt att standardisera broar eller i alla fall vissa delar, i så fall vilka?

Ja

19. Har anläggningsbranschen förändrats mot ett mer industriellt byggande under de senaste åren, motivera?

Instämmer helt

20. Tror du att anläggningsbranschen kommer att bli mer industrialiserad i framtiden, motivera?
    Instämmer helt

21. Vad anser du är de viktigaste faktorerna vid brobyggande, välj högst tre alternativ samt motivera?
    - ☐ Arbetsmiljö
    - ☐ Estetik
    - ☐ Kostnad
    - ☐ Kvalitet
    - ☐ Logistik
    - ☐ Miljöpåverkan
    - ☐ Tidsaspekt

22. Tycker du att brobyggandet behöver bli mer effektivt?
    Instämmer helt

23. Hur mycket diskuteras filosofier som Lean, Lean Construction, slöseritänkande, ständiga förbättringar inom denna bransch?
    Väldigt mycket

24. Man pratar mycket om att anläggningsbranschen inte har följt effektiviseringen som ägt rum i andra industrier, vad tror du är de största anledningarna till det?

25. Vad behöver förändras för att denna bransch ska bli mer effektiv?

1) Vilka komponenter ingår i industriellt tänkande?

Grupp 1

- Upprepning
- Standardisering
- Process (tänka i dessa)
- Planering (effektiv)
- Prefabricering (alla former)
- Partnering
- Logistik
- Effektiva metoder (metodval)
- Ett sätt att tänka
- Tänka hela kedjan

Grupp 2

- Standardiserat arbetssätt
- Många standard arbetssätt ger standardprodukter
- Spårbarhet avseende på tid, plats och person
- Ständiga förbättringar bygger på spårbar
- Modularisering & prefabricering
- Standardisering
- Återanvändning av ex. form

Grupp 3

- Minimera icke värdeskapande arbetstid
- Minska antalet fel
- Minska slöseriet på arbetsplatsen
- Upprepning (projekt till projekt)
- Förbättra processen
- En process med ständiga förbättringar
- Effektivare inköpsprocess
- Produktivitetsutveckling
- Produktutveckling
- Prefabricera komponenter på annan plats

Sammanställning

- Processer är något som förknippas med industriellt tänkande. Att tänka hela kedjan och arbeta med ständiga förbättringar är viktiga aspekter.
- Standardisering av arbetssätt och produkter för att kunna ta del av upprepningseffekter och erfarenhetsåterkoppling är viktigt.
- Att förlägga delar av produktionen till annan plats och arbeta med prefabricering modularisering är även ett viktigt inslag.
- Att kuna spåra produkter för att kunna jobba med att minimera slöserier och fel
- Samarbeta för att uppnå dessa komponenter

2a) Vad är kundnöjdhet?

Grupp 1

- Infria förväntan
- Kommunikation (varför & vad)
- Rätt kvalitet
- Spara tid & stress för kunden
- Tillfredställa ett behov

Grupp 2

- Rätt kvalitet
- Rätt tid
- Rätt plats och pris
- Öppna väg tidigt
- Minimera störningar
- Information (för kunden)
- Tillgänglighet av väg (lite underhåll)
- Att minimera störningar

Grupp 3

- Att uppfylla kundens förväntningar
- Minska trafikstörningar under byggtiden
- Korta ner byggtiden
- Införa/öka projekt med ett grönt alt.
- Få ätor kan vara ett incitament på kundnöjdhet
- Funktionell funktion med liten störning

Sammanställning

- Att tillfredställa ett behov hos trafikanten i form av rätt kvalitet, tid, pris och produkt är att infria förväntningarna.
- Om trafikanten dessutom får tillträde till vägen tidigare (förkortad byggtid) och att information (varför & vad) angående störningar finns ökar kundnöjdheten.
- Minimering av störning under byggandet är viktigt för trafikanten.

2b) Hur ökar vi den?

Sammanställning

- Dialog (mot kund & mellan aktörer)
- Partnering
- Tydlig kravspecifikation
- Skiljer mellan kund & kund
- Känna kundens kund
- Information
- Samarbete mellan kund och utförare
- Ta med mjuka parametrar ex. trafikstörning vid byggandet i upphandlingen

3) Hur skapar vi samarbete tidigare i projekt?

Grupp 1

- Upphandla entreprenör tidigare
- Fler med tidigt men också senare
- Gemensam utveckling
- Alla parter måste få igång samarbete tidigt i projekten
- Prata med varandra
- Bättre geoteknisk utredning i förprojekteringen

Grupp 2

- Att inblandade aktörer lär sig varandras processer
- Sker genom ökad samverkan och tätare möten
- Utveckla moderna entreprenadformer
- Användning av moderna dataverktyg typ BIM, 3D
- Konsulter med längre i processen
- Tätare möten
- Intresserade & involverade parter

Grupp 3

- Vara tydlig i tidigt skede
- Vilken entreprenadform som väljs alternativt ingår i förutsättningarna
- Bra kompetens på båda sidor så att ett bra diskussionsklimat kan etableras
- Förståelse för att utförare och beställare har olika mål men skapa en win-win situation
- Införa "samverkans workshop" i ett tidigt skede i projektet samt uppföljningar kontinuerligt

Sammanställning

- Samarbete bygger på involvering och detta måste etableras tidigt i projektet men även att flera aktörer är med längre i projektet för att lära sig, ex. konsult med i byggskede.
- Möten och workshopar i början på stora projekt för ökad involvering samt uppföljningar kontinuerligt, ex. stage-gate process.
- Att välja en entreprenadform som ger möjlighet för detta är en förutsättning.
- Att förstå varandra och dess process och mål för att skapa en win-win situation.

4a) Vilka likheter finns mellan broprojekt och har potential att erfarenhetsåterföras och standardiseras?

Grupp 1

- Allt är jämförbart
- Vägdragning

Grupp 2

- Det mesta utom geoteknik
- Ökad standardisering avseende mått, lättare att använda prefabricering och att återanvända temporära material
- Process
- Servicematerial

Grupp 3

- Standardisera dimensionerna av komponenter i ett projekt med flera likartade broar
- Standardiserad basprocess som kan modifieras med enkla medel
- Brodelar

Sammanställning

- Allt är lika verkar vara ett svar som kan tolkas både på allvar och skoj. Att processen är lika mellan projekt verkar alla vara övertygade om iaf.
- Det som skiljer är mest geoteknik

4b) Åtgärder för att bättre kunna utnyttja likheterna

Grupp 1

- För mycket gestaltningskrav, måste tänka igenom krav innan
- Gestaltarna skapar unikhet då de är tidigt med i projekt
- Ta med byggare tidigt tillsammans med gestaltarna
- Tradition

Grupp 2

- Skapa effektivitetsmått så man kan jämföra varandra, utmanar kollegorna i branschen

Grupp 3

- I ett tidigt stadie "förprojektering" sträva efter att broarna blir mer lika
- Specialiserad kompetens för processen så att erfarenheten kan föras vidare i nya projekt

Sammanställning

- För att kunna dra nytta av alla likheter måste gestaltarna få mindre inflyttande och fler aktörer måste bli involverade tidigare.
- Som det är idag är det svårt att jämföra olika alternativ så att skapa ett effektivitetsmått där man väger in alla viktiga aspekter vore idé.
- Processkompetens för ökar erfarenhetsåterföring möjlighet.

5) Hur ökar vi förändringsbenägenheten i branschen?

Grupp 1

- Mer tillgänglig tid
- Handla upp på systemhandling
- Planering & samordning
- Tillåt sidoförslag och alt. lösningar
- Kontinuitet för att förstå vinsten
- Serieupphandlingar
- Värdera tid & förslag, inte bara huvudanbud i form av kostnad
- Involvering

Grupp 2

- Kunskap om varandras behov och förutsättningar
- Ökad nåbarhet
- Öppna upp för alternativa lösningar
- TrV sitta närmare projekten
- Det nya måste vara så mycket bättre
- Ska man ändra något i projektet tar det för lång tid (granskning)
- Är dålig på processen
- Standardiserad process inom organisationen vilket underlättar erfarenhetsåterkoppling
- Samarbetsvilja från TrV
- Ökad mängd totalentreprenader

Grupp 3

- En uthållighet och långsiktighet hos beställaren så satsning på utveckling hos entreprenörerna kan ge lönsamhet på sikt
- En högre grad total- & funktionsentreprenader
- Mer positiv inställning hos beställaren att värdera sidoanbud/förslag
- För liten marknad för utveckling
- Andra krav i form av tid & störning från beställare

Sammanställning

- Att förstå att detta inte går snabbt att förändra och att man ser vinning på långsikt är viktigt.
- Hur upphandling och entreprenadformerna är utformade verkar alla vara övertygade om är viktigt. Att inte bara ta priset i beaktning utan värdera ex. tid och störning mer.
- Att ha större förståelse för processen, inte bara sin egen utan hela kedjan. Att få mer tillgänglig tid tidigt för att kunna utforma den bästa lösningen medan låsningarna är få.
- En ökad förståelse och respekt för varandra samt att beställarna är positiva och involverade i projektet ökar dialogen och gör processen smidigare.

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