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Integrated design and construction for bridges: key aspects and benefits

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ABSTRACT

The rate of productivity and innovation capacity within the Swedish construction industry of today is perceived to lead to a poor return of investment within infrastructures. Bridges, are commonly designed for a long service-life, and all stages after realization is greatly dependent on and constrained by decisions made during design and construction of the structure. To design for ease of construction is something that is always demanded by contractors and a challenge for the designers. It is widely known that the ability to influence a structure and its future properties is at its greatest in early stages, i.e. the project preparation phase followed by the design phase. Even though there is an obvious need for knowledge of construction in design work, there is a lack of a consistent and structured transmission of experience between the construction and the designing engineers.

Different approaches that are used today to generate productivity improvements in the construction industry are presented, evaluated and compared. The results sheds light to the common features of the approaches and that they necessarily don't exclude each other. Life-cycle considerations, established team approach and identify critical design variables are common denominators. The outcome of a construction project is therefore in most cases dependent on the individual skills to collaborate and communicate.

A framework was established to identify areas of improvement to reach effectiveness within Swedish bridge design teams. The construction sectors are assessed and generates a common view regarding the collaboration and communication in the prevailing way of work. This the gives an indication of where to address the main efforts. Overall, the greatest potential for improvement were found at the project team level.

The contribution from this thesis provides with further knowledge to develop the contemporary approach in design and construction of bridges.

Keywords: Integration in construction, integrated design, concurrent engineering, industrialized construction, ICT, BIM, Lean Construction

Preface

This thesis is the result of the work carried out from March 2014 until April 2017 at the Chalmers University of Technology, Departement of Civil and Environmental Engineering, Division of Structural Engineering, Concrete Structures. The work is part of the ongoing collaboration between WSP, Swedish Transportation Administration and Chalmers in order to enhance the prevailing work in desing and construction of bridges.

I would like to thank my supervisor and examiner, Associate Professor Mario Plos, for his guidance and support in my ongoing journey towards being a Ph.D. A special thanks is also directed toward my assistant supervisor, Assistant Professor Rasmus Rempling: Besides his endless patience, also for all the guiding and supporting discussions over the years. Furthermore, I would like to thank WSP, and especially, my manager Roland Olsson for supporting me in this opportunity. A special thanks also to Peter Simonsson, Trafikverket for being very supporting and deeply engaged in the project.

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A final thanks to all my present and former colleagues at both WSP and Chalmers!

Göteborg, April 2017

Daniel Ekström

LIST OF PUBLICATIONS

This thesis is based on the work presented in the following papers:

I. Ekström, D., Rempling, R., Plos, M. (2017): Principles for effective bridge design – It's time to walk the talk. Submitted to *Construction Management and Economics, Special Issue: Bridging the gap – Building new bridges.*

II. Ekström, D., Rempling, R., Simonsson, P., Plos, M. (2016): Integrated project team in early design stages – Key variables influencing cost effectiveness in bridge building. Published in *Proceedings 19th IABSE Congress Stockholm, Challenges in Design and Construction of an Innovative and Sustainable Built Environment,* September 21-23 2016.

ADDITIONAL PUBLICATIONS BY THE AUTHOR

1. Ekström, D., Rempling, R., Plos, M. (2014): Industrial bridge building- An effective bridge construction process through an integrated design and construction process. Published in *Proceedings of the XXII Nordic Concrete Research Symposium*, (0800-6377). Vol. 2014 (2014), 2, p. 79–82.

2. Ekström, D., Rempling, R., Plos, M. et. al. (2014): Samarbetsprojekt för effektivare brobyggande. Published in Bygg & Teknik (0281-658X). Vol. 2014 (2014), 7, p. 58–61.

3. Ekström, D., Rempling, R., Plos, M. (2015): Industrial bridge construction: Need for a more effective bridge construction process. Published in *Proceedings of the Eighth International Structural Engineering and Construction Conference, Sydney, Australia*, November 23-28, 2015 p. 1115-1120.

4. Ekström, D., Al-Ayish, N., Rempling, R., Simonsson, P., Plos, M. (2017): Climate impact optimization in concrete bridges – towards sustainable construction. To be published in *Proceedings 39th IABSE Symposium Vancouver, Engineering the future*, September 19-23 2017.

Contents

1 Introduction

1.1 Background

The rate of productivity and innovation capacity within the Swedish construction industry of today is perceived to lead to a poor return of investment within infrastructures. As a result, several investigations and reports during the last two decades have clearly indicated that there are issues that needs to be attended (SOU 2002; SOU. 2012). This is not isolated to Sweden and research show the same trend in for example the rest of Europe and the US. A frequently recurrent reason in literature, is the fragmented approach commonly used in the construction industry.

Measures indicates that for the Swedish construction industry the cost increase is double compare to other industries over the last two decades (Trafikanalys 2012). Normally when judged, the construction industry is compared with the manufacturing industry. This may not be a fair comparison, but nevertheless, the increase in efficiency have up to date been lacking. Low productivity development and innovation capacity in construction leads to increased costs but not necessarily higher quality. This trend needs to be stopped, and the first step is to adopt a design and construction process that utilize the industries full potential.

In this project, a collaboration between WSP, Swedish Transport Administration and Chalmers, the main purpose is to develop and increase the efficiency in bridge construction. A more efficient construction of bridges generates the possibility to enhanced customer value and to get the most out of construction. Besides cost, an efficient construction industry relies on solutions chosen with a sustainable approach, yet with a focus on productivity and innovation. Such a solution may vary from process development to structural detailing.

Productivity and innovations are clearly related. New and developed methods, processes, and products is a constant need for the construction industry to be competitive (Winch 1998). This need will never reach a final state, and instead a continuous improvement and development of the building market is needed. A development that should incorporate the advancements of other areas such as materials science and technology, design and analysis methods, production techniques, as well as the rapid development in ICT (Olofsson et al. 2010). The main client within Swedish infrastructure is the Swedish Transport Administration (STA), which thereby has a unique position to influences the productivity and innovation capacity of the construction industry (Harryson 2008). STA has taken several initiatives to turn the current trend. The productivity program can be divided into seven focus areas where several measures are identified to improve the productivity within each area. This project is closely connected to at least three of these areas; *Industrialized production*, *Innovation and new production methods* and *Measuring and monitoring*.

Other areas such as the manufacturing industry, and more specifically the automotive industry, have been acting as a role model in discussions regarding methods to adopt to increase the rate of productivity within the construction industry. Toyota, as an example, and their Toyota Production System, TPS, has ever since the start been an inspiration to companies all over the world on how to monitor, control and continuously improve the process of manufacturing. Based upon Toyotas philosophies, Lean production was born Womack and Jones (1990) which also later was developed by yet another set of researchers into Lean Construction (LCI, 2010). By adopting philosophies from Lean, and with high ambitions to introduce industrial processes, the construction industry has been expected to increase the rate of productivity.

1.2 Purpose

The general purpose of this research was to contribute to the ambitious task of generating a systematic and holistic design approach which can foster many kinds of project-settings and pre-requisites. Through the adoption of a production oriented design approach it is more likely to establish the progress that the construction industry needs

In an overall perspective and by the conducted research, there is an ambition to contribute to the development from the contemporary approach in design and construction of bridges. The research intends to contribute to the push towards a change in both attitudes and way of working in the bridge construction process. A change towards a more enhanced use of industrialized thinking in the design and construction of bridges and an improved productivity and value added in investments.

1.3 Aim and objectives

The performed work in this research was divided into two subsequent steps with the aim to establish a foundation and framework for a systematic and holistic design approach. **Step I**: The objective of the comprehensive literature review was to identify the common foundation for the suggested improvements of design and construction. Due to the variety and diversity in the identified approaches there is a need for clarification in the field to be able to adopt changes. From the identified concepts, it is possible to provide a framework for the progression to the use of industrialized processes in construction.

This thesis presents different approaches used to generate productivity improvements in the construction industry are presented, evaluated and compared. The reasoning in the paper sheds light to the common features of the approaches and that they necessarily don't exclude each other.

To concretise an objective for this first step, a research questions was stated**:**

RQ 1: What is the research foundation of integrated design and construction in the context of bridge design and construction?

To do so, the following sub-questions are addressed in Step I.

- What does the integration mean for construction?
- What does the integration mean for design?
- What does the integration mean in the bridge construction process?
- Who is responsible for generating that integration?

Step II: The objective of the second step was to identify a framework and areas of improvement in terms of generating effectiveness within Swedish bridge design teams.

Assessing the construction sector and generating a general view regarding collaboration and communication in the prevailing way of work, and giving an indication of where to address the main efforts.

The following research question was stated for the second step:

RQ 2: What is the framework and which are the areas of improvement of integrated design and construction in Sweden?

To do so, the following sub-questions are addressed in Step II.

- What are the organizational hindrances and facilitators for the support of Integrated Project Team (IPT) within project-settings?
- Which aspects of collaboration on project-team level enables IPT?
- How are the personal traits and values important for the individual support of the IPT?

1.4 Limitations

Highlighted by many authors and reports, the pre-construction stages are vital for how to undertake construction and in many cases for the entire service life for a structure. The interest for integration is by that put to the pre-construction stage and during early design stages. A very comprehensive and exploratory approach have been adopted to this project, leaving the author with much freedom when choosing the direction. Despite that, a natural limitation is the adapted perspective from a structural engineer and how structural engineering and design issues are both effected and effect the integration of design and construction process. Even though, a large amount of international literature is studied, the perspective of the study is primarily focused on the current and future situation in Sweden. By the fact that the major part of the developed countries is facing the same issues or problems, this work is applicable with the international perspective as well.

1.5 Outline

The thesis is based upon two appended papers and an introductory part. The introductory part starts with a general overview of the theory that the foundation and framework have been built upon. The presentation of the established foundation and framework finishes with discussing the contribution of the two studies to the overall purpose. Finally, the general conclusions are presented by answering the main research questions.

2 Research design

For this project, the approach was chosen to gain a broad and general understanding of both the field of research and industry practice. The initial aim was mainly to establish a clear focus and to understand in what direction the project should be conducted. To use a qualitative method is then a good start, since qualitative research is not based on a unified theoretical and methodological concept. Subjective viewpoints are a first starting point (Flick 2009). At this initial stage the purpose of the qualitative method approach was primarily to generate that distinct understanding of the area to be studied. By adopting an explorative approach towards existing literature, and interpret it based on many years of experience from the bridge sector a deeper knowledge of underlying root causes for the prevailing problems the construction industry is experiencing was obtained. Also, a clear picture of common approaches adapted to enhance and/or improve the industry could also be created. From the results of the qualitative analysis, a subsequent study with qualitative methods were used to investigate and quantify findings. The progression of the research is schematically displayed in Figure 1.

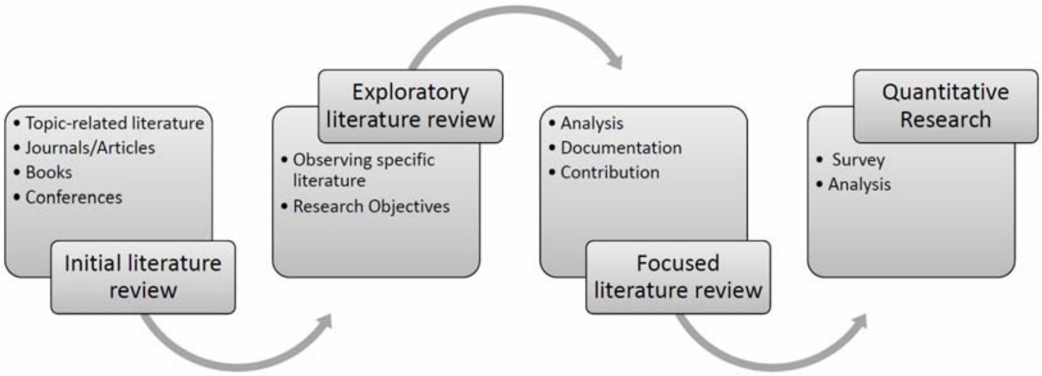

Figure 1: The subsequent stages of the conducted research

So, both qualitative and quantitative methods were used in this work. This is supported in (Flick 2009), where it is stated that a study may include both qualitative and quantitative approaches in different phases of the research process. The suggestion is to use qualitative research for developing hypotheses, which afterwards will be tested with quantitative approaches. "Qualitative and quantitative methods should be viewed as complementary rather than rival camps". There are some basic differences between the methods; quantitative methods transform information into numbers, diagrams and tables while in qualitative methods the researcher's own interpretations of the information are in focus, but cannot be transformed into numbers. The choice between the different methods must be based upon the purpose of the study and the most suitable method for achieving the goal.

The conducted review in Paper I was of an exploratory character. Based on the initial review, a sense that all the efforts made to generate necessary change within the construction industry were very similar yet, claimed to be different. To increase the utilization of industrial processes in construction and to adopt an integrated design approach has, in some way, been the predetermined direction from both academia and governmental reports (SOU 2002; SOU. 2012; Larsson et al. 2014). Even though a roadmap has been established by many years of research in the field, how to walk it is still somewhat vague. Many clients and organizations have adopted new approaches at a strategical level, but what this means and how this effects the everyday activities on an operational level are still unclear in the industry. The aim of the qualitative approach in paper I is to broaden the perspective when finding the direction.

For Paper II, a quantitative approach was used. In quantitative research, you rely on the existing literature about the issue of your study, derive hypotheses from it, and then test these hypotheses. The work in paper I generated that existing literature, and from the results, research questions to the following study could be derived. By assuring that the two studies were aligned a combination of both approaches could be established (Flick 2009), by linking the results of qualitative and quantitative research in the same project. This link is basically established based on two different aims and with three possible outcomes:

- To obtain knowledge about the issue of the study which is broader than the single approach provided; or
- To mutually validate the findings of both approaches.

Three kinds of outcome of this combination may result:

- Qualitative and quantitative results converge, mutually converge, and support the same conclusions
- Both results focus on different aspects of an issue, but are complementary to each other and lead to a fuller picture
- Qualitative and quantitative results are divergent or contradictory

3 Integrated design and construction for bridges

3.1 The design and construction process

The construction industry is by tradition exposed to extreme fragmentation within its stages and a relational short-term perspective (Anumba et al. 2002). The process of construction can be viewed as an arena for collaboration between numerous of suppliers all from early design stages up until completion of construction. This is a process not owned by anyone, and progress is achieved by involved participants by continuous negotiations: These negotiations are predominantly done with each individual product at focus, not project success. The process itself looks more incidental, but none the less, this is the process which determine the key outcome (Oakland & Marosszeky 2006).

Construction is a project-based industry and due to its fragmentation, there exists several sources of waste and values loss. During construction value is generated by producing construction works, either in terms of new structures or by improving the already built environment (Anumba et al. 2007). Construction is also an industry often described to contain several special features which underlies many of the perceived "problems" (Koskela 2003). In construction, a single focus on transformation and a lack of focus on flow and value is usually apprehended. Koskela (2003) stress, if neglecting flow and value the elimination of special features of construction leaves construction in the same place as manufacturing was before addressing waste explicitly. Before concepts like lean production and quality management a large amount of waste existed also within manufacturing.

Over the years it has become evident that the design and construction process needs to be understood in another way if to facilitate all the elements essential in delivering a project. In construction, sources to waste are mainly identified to occur in the interaction between different trades. This is also in general related to the self-interest of different parties which makes them put themselves first (Forbes & Ahmed 2011). The integration of different trades in the construction industry has been in focus within research for several years in order to generate a more effective process (Oakland & Marosszeky 2006; Larsson et al. 2014) and also a prioritised area within a productivity program launched by the Swedish Transportation Administration (STA).

There are several ways to define and divide the stages of a construction project. Here, to explain the design and construction process, it is in large divided into three different stages; pre-construction, construction and post construction. Applying a time perspective, there are distinct separations in three different stages, such as pre-construction, construction and post-construction. The main objective of any construction project is to finalize and deliver construction works, so from a customer perspective, this distinction of different stages is of course rational and logical in that sense, Figure 2. How the design task is undertaken during the pre-construction stages, and how this best can facilitate the activities in the construction stage is the main interest in this project.

Figure 2: The construction project process can be divided into three main stages.

A brief review of the different stages is stated in the following sections.

3.1.1 Pre-construction stage

During the pre-construction stage, the client's needs are developed into a final and appropriate design solution. This stage includes several different stages, or levels, of design and are usually divided into three phases, namely conceptual design, preliminary design and detailed design, e.g. (Mora et al. 2006). Detailed design can be divided into general design (or basic design) and final design (or execution design), although this division is traditionally not often used in Sweden (Harryson 2008). When entering construction, all the necessary elements of a project that will enable its performance should be in place (Anumba et al. 2007).

The prevailing pre-construction stage consist of a fragmented approach between different design phases and different trades. It is during these phases which literature frequently suggests more collaboration and integration to enhance the outcome of construction (Owen et al. 2010; Larsson 2009; Anumba et al. 2002). To do so, this normally requires overlap of domains, for example meaning that a contractor takes part during design development and in the conceptual discussions or even to compete with different bridge concepts or the structural engineer gets involved in upstream activities to support in the architectural design (Uihlein 2015).

3.1.2 Construction stage

During the construction stage, the only concern should be the production of the final structural solution. If the full benefits of coordination and communication have been addressed in the pre-construction stage, it is here the gain will be fully realised (Anumba et al. 2007). At this stage, usually any changes in client's requirements or interference with production comes with a high cost. Discussions regarding productivity are basically aimed towards this stage, and at construction productivity, see e.g.(Simonsson 2011). At this stage, all the benefits from, for example pre-fabrication, pre-assembly, off-site manufacturing etc. are finally reaped. Although, extended use of industrialized methods also increases the demands on earlier stages (Koskela 2003).

Studies have shown that too much time and effort are spent on the construction site trying to make designs work in practice. Research indicates that, on average, 1/3 the defect cost originates pre-construction activities, i.e. can be referred to the design phase (Love & Sing 2012; Josephson & Saukkoriipi 2005). For defects and rework related to design, those originating from missing co-ordination between disciplines are the largest category (Josephson & Hammarlund 1999). Engineering design as such, is very important but also needs to be considered as one part in a larger process (Löfgren 2002).

3.1.3 Post-construction stage

This is the stage where traditional projects terminate and client taking ownership of the built structure. Even though the designing engineer/team usually are since long disconnected from the project, the effects of the choices during design will be present.

The effects of design during the service life will be related to of structural strength, durability and operability. Considering the long service-life for bridges, a successful design will generate a structure with a well-balanced cost between structural performance, repair and maintenance, and operability.

3.2 Integration in construction

3.2.1 Industrialization in construction

In the last decade or two, industrial production has shifted its focus from being generally connected with mass production and more related to customer value through adopting the philosophies of Lean Production. Mass production is a concept that never been suited to bridges and this shift in focus has enabled many industrial concepts to be adopted for industrial bridge construction.

Frequently mentioned techniques and methods that characterize industrial construction are standardisation, modularisation, prefabrication or off-site fabrication, as well as on-site fabrication, pre-assembly, mechanisation, automation and the use of different building systems. Many of these techniques and methods, if not all, can be applied in bridge construction. The goal of industrialization is to generate products at low cost, to produce higher quality products at the same cost and to reduce the overall construction time. This, while maintaining all the quality and environmental requirements.

Swedish literature, indicates that the perception of the term industrialized construction varies between different authors. Industrialization has been mentioned as the solution to the lack of productivity in the construction industry, but still it may not be clear to the industry what the terms of industrialization and industrialized construction represents.

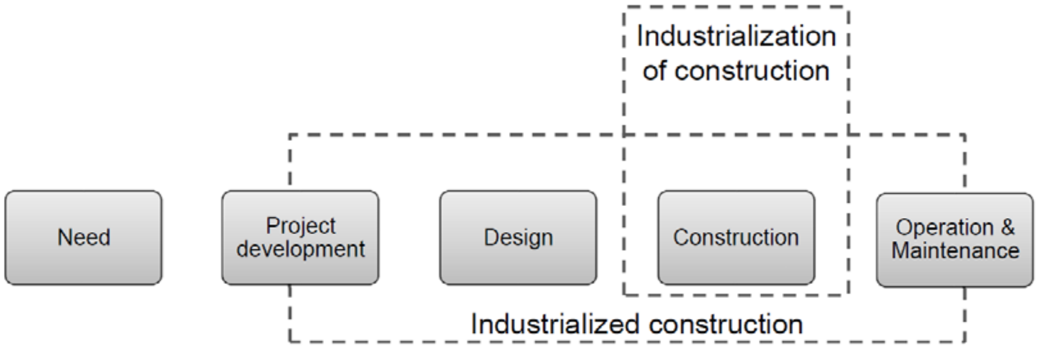

Figure 3: Different perspectives on how to adopt industrial processes in construction, modified from (Lidelöw et al. 2015).

Some research argues that industrial development is reached mainly through modernising of traditional construction methods (industrialization) while other argues that it is reached by developing new methods or materials from scratch (industrial construction approach). Of course, there are also those who mean that it is more a question of the distinction between pre-fabrication and construction on-site and its degree of industrialisation, and states that there is no difference between the two mentioned approaches.

Despite the differing in views, there are also some agreement within the industry. One is that there are many different acting stakeholders, components and parties involved and that industrialized construction clearly are multi-disciplinary. In such a multi-disciplinary environment, information- and communication technology (ICT) plays a key-role to generate the possibility to work efficiently within and in between all the involved disciplines.

Based on the TFV-concept presented by Koskela (2000), which is a comprehensive theory of production, Harryson (2002) presented three cornerstones of industrial bridge construction which was identified as process development, productivity development and product development, the three P's. Serving as the natural link and generating a continuous circle of development between the three P's is ICT. The rapid progress of development and increased knowledge about the use and strategies about how to implement the use of ICT/BIM into industrial construction, this might be the single most important factor for developing new and successful industrial concepts.

Resent research at Luleå University of Technology presents two strategies that normally are undertaken to minimize the complexity of construction; standardization of products and standardization of processes (Larsson et al. 2014). It is also stated that it has been proved difficult to achieve standardization in both areas since the experiences and innovative ideas from contractors are not utilised in early stages of design. Some core elements to support standardization and increase the industrialization of infrastructure construction are identified in the article, and some barriers and its actors which has the power to eliminate them. Many of the core elements identified are related to long term actions, such as processes, rather than short term actions, such as projects. Here, integration between design and production is identified as one of the five largest core elements. Notably, and very interestingly, three out of the five largest perceived barriers can be eliminated by the client's role. Hence, lack of repetition in construction, prevailing procurement approaches, norms and regulations.

3.2.2 Knowledge management – Create learning organizations

A fundamental prerequisite when introducing and managing industrial methods in the construction industry is to have systems to handle experience feedback. Adopting an approach for standardization and continuous improvements establish the foundation for a learning organization (Lessing 2006; Simonsson 2011; Lidelöw et al. 2015). In design firms, while being a knowledge enterprise, stored knowledge usually is available in reference documents from completed projects, or in the form of knowledge at the individual level. With inadequate management of information along with staff turnover there is a high risk of losing valuable knowledge if this is not handled properly. Johansson (2012) refers to (Polanyi 1983) by a citation "we know more than we can tell". This indicates that when knowledge is stored on an individual level, an organizations level of knowledge may very well exceed what it explicitly can express. This clearly gives an indication that it is necessary to find a systematic way to carefully nurture the knowledge gained within a team or organization by creating a learning environment. (Sumner et al. 1999) states that "Integrating working and learning is not a desirable luxury – it is a fundamental requirement for businesses to remain competitive."

Simplicity in design and ease of construction is something valued by contractors and a challenge for the designing engineers. The possibility to influence the future properties of a structure is at its largest during the different pre-construction stages. This is well known to the industry. The design and conduct of a construction are closely attached and highly dependent to each other and consequently, the choice of construction method dictates the rules of the design. Due to the sequential design process, a construction method often needs to be assumed in design without necessarily considering all its requirements (Fischer & Tatum 1997). Even though there is an obvious need for construction knowledge in design work, there is a lack of a consistent and structured transmission of experience between the contractors and the designing engineers

(Olofsson et al. 2010). There is a historical aspect to this dividing line between design and construction. This has been a matter of concern ever since the design and construction functions once were separated from each other and becoming two professions with divergent goals (Puddicombe 1997). This separation and divergent goals have led to decreased will to co-operations leading to time, cost and quality becoming areas of disagreement.

3.2.3 ICT/BIM as an integrator

Ever since the introduction of BIM in the early 21st century the construction industry has been waiting and anticipating how this will radically change the way construction is undertaken. The expected benefits are related to how things are built, to minimize the deficiencies and errors, and to create higher productivity and profitability for all involved parties. This implementation has unfortunately never materialized to the fullest potential, and many existing advantages and benefits that BIM can provide are left unused (Linderoth 2013). Until just a few years ago, there were no clear commitment to implementation from the client, so the development were mainly technology-driven. Consequently, this led to a scenario where the product developers supplied the market with the software, and then tried to convince users and clients of all its benefits.

For a long time, this also limited the industry's ability to achieve only what is possible with the products, and perhaps above all, to what product developers wanted to deliver. Today, the industry has the knowledge and understanding of the systems required to turn the relationship around. Instead, demands on what the software and products needs to perform can be addressed. To find the most optimal ratio, and to create the conditions for long-term development, it requires strong initiatives from both sides to generate both the "technology push" and "market pull" (Harryson 2002).

Another reason for the slow implementation may very well be related to the differential views to BIM amongst the industry. In general, the scientific community has understood BIM as a process tool whilst practitioners usually refer to this as common digital model with the ability to store and share additional information between different professional groups (Ogbeide 2010). The distance between the extremes has severely decreased, and the trend is towards a more unified view of BIM. STA and several industry practitioners have now clear objectives and strategies for the use and the implementation of BIM. There are also ongoing partnerships within industry organizations between many of these parties. As part of the implementation of BIM, STA initiated some pilot projects operated as "BIM-projects", all from procurement to management. The design and construction of Röforsbron is one such example, where BIM was used in all stages (Malmquist 2012).

In (Linderoth 2013), it is highlighted that if BIM is to be seen as a mean to develop and change the way construction is undertaken, the implementation needs to be view upon as an ICT-supported process of change. By that, Linderoth (2013) continuous, there are four main challenges to address: technical, legal, organizational and leadership. Still, organizational and leadership issues have been overlooked in favor of technical and legal issues.

3.3 Integration in design

Integrated design and construction as an expression may constitute a limitation due to its vague statement and understanding. In this work the meaning of an integrated design and construction process is an approach to undertake the work by a collaborative, integrated and multi-disciplinary approach. Many of the concepts and methods proposed in literature are by nature multidisciplinary and multifaceted. This also involves a situation where the proposed changes might mean different things to the different participants within a project. Integration of design and construction often generates opportunities for the client to generate greater efficiency in construction, resulting in lower cost, reduced construction time, and/or improved quality. To the engineer, the understanding of the methods and constraints of the actual construction required to execute the design. For the contractor, it is a combination of effort required to implement the design most efficiently and the opportunity to minimize the resource effort and cost. The integration of design and construction here is not intended by merging different stages. The integration refers to the flow and use of information and how knowledge is used to transform the needs and requirements from the client into the final product.

3.3.1 Integration and teamwork

Many project-based industries have recognized that multi-function teams reduce the probability of costly changes and production difficulties. This is enabled by addressing design and production decisions earlier in the process (Anumba et al. 2002; Crowley 1998).

In an American study, Uihlein (2015) studied the integration between architects and engineers and what aspects were the underlying drivers regarding the structural integration. From the results, the time when structural engineers were introduced to the projects was considered a very important factor. The importance was found at several layers or organisational levels. If introduced in conceptual stages the structural engineers could not only be involved in the development of structural ideas in line with the aesthetics, the engineer can also attend to avoid structural inefficiencies. On the more individual level, the feeling of being valued as an asset to the end-product was significant to the engineers. From an individual perspective, it is natural to desire to influence as far upstream as possible and to gain control and dictate your own conditions. By this, of course, the traditional domains between participants starts to overlap. This overlap offers the opportunities for collaborative work and ultimately a shared understanding between all the stakeholders already in earlier stages of the project. At this stage, an engineer can not only offer suggestions and develop structural ideas in keeping with the architectural concept, but the engineer can prevent structural inefficiencies from being added to the scheme. Additionally, this early inclusion signified to engineers that their input was valued as they were being given the opportunity to invest in the big ideas—structural and architectural—of the project. If adding the knowledge from contractor or construction engineer (Tatum & Luth 2012) this is of course value added to this process. This integrated and concurrent engineering process is a way to achieve an efficient design process adapted to facilitate construction to be performed effectively.

This is view also supported by (Moum 2006). In a study of the interaction between the architect and engineer a framework is presented consisting of three hierarchical project levels: macro-, meso- and micro-level to represent different social constructions in construction. The intention of the framework is to study the level of integration, the impact of information and communication technology (ICT) within project settings, as well as highlighting the non-technical parameters influencing the integration.

Anumba et al. (2002) identified that there are eight basic elements of CE divided into two aspects as follows in Table 1.

Table 1 Basic elements in CE according to (Anumba et al. 2002).

Managerial and human aspects	Technical aspects
• Cross-functional, multidisciplinary teams to integrate design of products and their related processes • Adoption of a process-based organisational philosophy • Committed leadership and support for this philosophy • Empowered teams to execute the philosophy	• Computer aided design, manufacturing and simulation methods to support design integration • Methods to optimise products design and its manufacturing and support process • Information sharing, communication and co-ordination systems • Development and/or adoption of common protocol, standards, and terms within the supply chain

The two aspects were categorized as *Managerial and human aspects; and Technological aspects.* This division in technical and non-technical aspects are also recognized by researchers in concepts such as industrialized construction (Lessing 2006), constructability (Francis & Sidwell 1996)

3.3.2 Teams in construction

When discussing integrated projects, it is generally the contract or the way of procurement that is at the primary focus, e.g. Partnering or Integrated Project Delivery (Kadefors 2002; The American Institute of Architects (AIA) 2007; Mosey 2009) but this is usually not enough. While contracts act as a stabilizer and formalizing the patterns between client and its suppliers, findings in (Forgues & Koskela 2008) indicates that there also is a need to change the relational patterns in order to move from fragmented to integrated design. Problems with project performance of integrated design teams are in general related to the context and not the process itself, i.e. they are not technical but socio-cognitive (Forgues & Koskela 2008; Moore & Dainty 1999; Baiden et al. 2003).

Activities on a construction site are performed by individuals with different skills belonging to different companies in temporary organisations. These actors need to share information and knowledge for optimum decisions. Management of these activities performed by individuals and groups of individuals within the organisation are coordinated to ensure a value flow, and therefore an organised flow in the work schedule. Baiden (2006) asserts that teamwork is not an option but a prerequisite for a successful delivery of a construction project. Efficiency for effectiveness within the team in a construction project is consequently necessary and needs to always improve. Project teams in construction usually works are put together for the development of a single project. Consequently, a complete project team rarely works together on more than one project (Anumba et al. 2007). Successful teams in manufacturing are teams which have multiple project experience, and have developed a shared culture and organization of work and design processes. Therefore, due to the short-term perspective, there is always a significant risk that design coalitions in construction will not perform well, or might even be dysfunctional (Forgues & Koskela 2008; Sumner et al. 1999) if not well managed.

3.3.3 Process development

Since the construction industry started to adopt Lean philosophies, several methods have emerged to undertake and facilitate construction projects. Some of the methods used in construction are ICE (Integrated Concurrent Engineering), VP (Visual Planning), VSM (Value Stream Mapping) and LP (Last Planner). The basic idea and foundation of these concepts is to visualize the working processes. During reoccurring meetings with involved project members, visualization is used to highlight and/or prevent issues or conflict in the project. The meetings and visualization enables the project members to establish a better understanding for both their role and contribution in relation to their own organizational values as well as the customer needs (Tjell & Bosch-Sijtsema 2015).

3.4 The ambiguity of productivity

Productivity as a concept is out of the scope of this thesis, yet it is important in terms of understanding where the driving forces originates from. Without that understanding many of the existing loaded terms such as "more value for money", "zero defects", "minimum waste and environmental impact" are relatively vague. Customers are commonly stating the interest in value for money, although few can explain what that means (Gibb 2001).

Productivity is obviously and closely related to innovation, constructability and buildability and several other aspects which are connected to industrialized construction (Winch 2003; Simonsson 2011). In the same manner as industrialized construction, productivity is also a clearly multifaceted concept and there is no consensus or one generally accepted definition of the term as such (Tangen 2005). This is related to the fact that productivity is dependent on the context that it is measured within. Without knowing the context, or even the background and in which profession, there is a large risk of interpreting the outcome incorrectly. The construction industry has for long been conceived to be haunted by low productivity. Even though there are tonnes of reports to the statements there are several authors and reports that question this from the standpoint that the measurements used today are too simplistic (Harty et al. 2007; Song & Lind 2012; Bröchner 2010). Simplistic in the meaning that the measures don't measure what's expected. In an investigation, Statskontoret (2010) stressed that "every productivity study should be critically evaluated and with a high degree of scepticism". Unfortunately, there are no specific statistics regarding efficiency in the construction industry today. Available statistics, are far too general to be used without manual work. As an example, in the available statistics for repair and maintenance is categorized together with construction. Bröchner (2010) suggested several measures to control development in construction, and one of the six task groups worked specifically with bridges and highlighted the lack of resource data which makes measurements of effectiveness difficult.

One clear concern with the idea of productivity is, though it acts as one of the most important measures to evaluate an organizational success, that there is no consensus in interpreting it (Polesie 2011). In research there has been many efforts made to create a scheme over the different relationships related to the term and to define it (Tangen 2005; Polesie 2011). As an example, the common customer of infrastructure is a public transportation organization. Working on an annual budget, this leaves productivity equated to lower costs and/or improved quality. Lower costs end up in more infrastructure for the same amount of money. Other effects are quality improvements which generates into durability and improved operations

One strong benefit for the use of industrialized methods in construction is the shortened time on-site. Shorter construction time leads to reduced interference and reduced public cost. However, BIM and off-site manufacturing are two ingredients expected to reduce the construction time, but cannot be connected to increased efficiency in the public statistics. According to (Bröchner 2010), the expected effect in the statistics during construction will be limited regardless how industrialized a contractor becomes. For this reason, besides cost comparison, no conclusions regarding the efficiency through use of industrialized methods can be made. This underlines the need for reliable measures to use in construction.

4 Discussion

The general purpose of the research presented in this thesis was to contribute to generating a systematic and holistic design approach. In addition, the work should provide a push towards a bridge design and construction process enhanced by an increased use of industrial thinking to provide productivity improvements and added value.

"Project success relies upon the right people having the right information at the right time " (Anumba et al. 2007). This statement origins from a view in favour for the integrated and collaborative environment which concurrent engineering is proposing. Even if a bit simplistic, this statement doesn't lack reason. Still "*the challenge is to ensure that the right information gets to the appropriate person at the right time*" (Baiden & Price 2011).

The studied concepts presented in Paper I have integration as a clear common denominator. The intent with the integration and to adopt a team approach is to overcome the linear and fragmented design which is normally undertaken in construction today. Construction projects are normally planned and executed in teams or groups, in one way or the other. The outcome of a construction project is therefore in most cases dependent on the individual skills to collaborate and communicate. Based on established communication in and between teams, both risks and uncertainties are commonly reduced. Communication is a central part for team performance, maybe especially in construction due to its multi-disciplinary nature.

For teams to be successful it is critical to be provided with the right people (Radtke & Jeffrey 1993; Paris et al. 2000; Forbes & Ahmed 2011). The teams should also, according to (Baiden 2006) consist of personnel from owner, design-engineering and contractor organizations, and these key members are recommended to be hand-picked and involved early in the projects as well as consistent through the different project stages. In design and construction, teamwork is usually not an option, but a prerequisite for a successful delivery of a project.

To increase and enhance the level of industrial thinking is clearly difficult based on the findings presented in Paper I. The implementation of industrial processes has clearly reached the farthest within housing, but in recent research Malmgren (2014) claims it has not propagated to any important change as a future method in the construction industry. Eriksson et al. (2014) reported findings from recent and international research indicating that the benefits behind the interest for implementing industrialized construction in infrastructure still are the same today, i.e. time savings, improved cost efficiency, improved safety and better quality. Yet, Eriksson et al., (2014) continues *"The rationale for the application of industrialized construction in the infrastructure sector is yet to be investigated.*" Does this give an indication that the question of industrialized construction of infrastructure is lost between market-pull and technology-push? Is it neither a customer- nor producer-driven concept?

For the study presented in Paper II, a framework was established, see Figure 4. The framework aided to examine the collaboration between different disciplines during the development of construction documents for new bridges in Sweden. The framework combines a vertical and a horizontal dimension to form a matrix-analysis and enables to identify nine different areas of measurements.

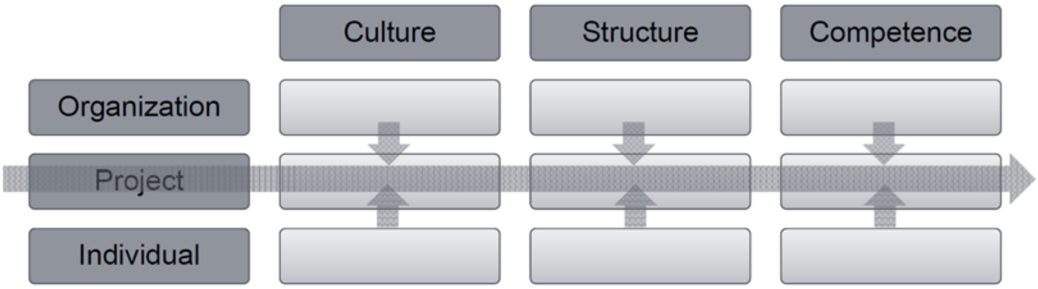

Figure 4: Survey evaluation matrix, in Paper II.

Supported by the matrix, the findings established some specific areas of improvement. Declared need of efforts was appointed to the following areas where the largest gaps existed between potential and realized benefits, see further explanation in Paper II:

- *Project culture*
- *Organisational structure*
- *Project competence*

Even though the greatest potential for improvement were found at the project team level, the individual contribution and the organisational support to the project team's performance cannot be overlooked or neglected. Reliable measurements are needed on all levels to sufficiently capture the true project performance and to fully benefit from the project team. The outcome and performance from the application of Integrated Project Team (IPT) in the Swedish construction industry are yet poorly evaluated. The lack of knowledge how to sufficiently collaborate in a project team setting, which is indicated by the score in *Project Culture,* are also supported by the results in previous research presented in Paper I.

5 Conclusions

RQ 1: What is the research foundation of integrated design and construction in the context of bridge design and construction?

There are several clear and common denominators linking the different studied concepts, but the three strongest was

- Holistic view to design
- Adopt a team approach
- Critical design variables

Construction projects are normally conducted in teams or groups, in one way or the other. The outcome of a construction project is therefore in most cases dependent on the individual skills to collaborate and communicate. Based on established communication in and between teams, both risks and uncertainties are commonly reduced. While communication is a central part for team performance, maybe especially in construction due to its multi-disciplinary nature.

RQ 2: What is the framework and which are the areas of improvement of integrated design and construction in Sweden?

Based on the findings in Paper II it is possible to evaluate the level of the integrated project team by a matrix analysis. The results show that the major areas for improvement in the Swedish construction industry are:

- Project culture
- Organisational structure
- Project competence

Overall, the greatest potential for improvement were found at the project team level, even though it stressed that both the individual contribution and the organisational support to the project team's performance cannot be overlooked or neglected. Reliable measurements are needed an all levels to sufficiently capture the true project performance and to fully benefit from the project team.

6 Future work

Based on the aim and purpose of the presented research and previous conclusion, the following points summarises the suggested future research:

- Reliable measurements are needed on all levels to sufficiently capture the true project performance and to fully benefit from the integrated project team.
- Establish an implementation strategy for integrated design and construction for bridges.
- Establish indicators to measure team performance in integrated design and construction for bridges.
- Increase the utilization of ICT and BIM in support to integration in design and construction for bridges.

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