JÖNKÖPING UNIVERSITY
School of Engineering

Licentiate Thesis

Supporting the Design Phase of Industrialised House Building Using a Product Platform Approach

– A Case Study of a Timber based Post and Beam Building System

Shamnath Thajudeen

Jönköping University
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Shamnath Thajudeen

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Abstract

In recent years, industrialised house building has gained shares on the Swedish house building market. The market demands for industrialised house building are exceeding the available supply of housing and experiencing a substantial increase in the housing production costs. For industrialised house building, the design has been identified as a critical phase with the systematization of the design a necessary part of industrialisation. Therefore, companies strive towards the inclusion of standardization and controlled processes in the design phase. Product platforms have proved to be related to the standardization of processes and products. Introducing a product platform approach in the design phase of house building could be a way to improve the design and ensure value creation in entire processes. Thus, the aim of this research is to outline means to support and improve the design phase of industrialised house building by using a product platform approach.

A Swedish multi-storey house building company that uses glulam post and beam building system with a focus on platform development was used as the single case study in this research. The company intends to achieve increased efficiency by moving towards industrialized approaches. Empirical data were mainly gathered from interviews, observations, workshops, and document analysis. The findings present the existing challenges in the housing building industry and outlines twenty critical success factors that need to be considered in the design phase. Also, the result outlines support methods and tools that can be used for the improvement of the design phase when applying a product platform approach. Moreover, a flexible product platform can be developed with the support of parametric modelling and used to design building components having an engineer-to-order characteristic. Finally, the results show that a building system can be considered as part of a product platform in light of the necessity of an adequate support in the design process to maintain a sustainable platform. Thus, the contribution includes the addition of knowledge to platform theory in general and its application on the design phase of industrialised house building.

Keywords: Industrialised house building, Product platform, Design support, Building system, Post and beam, Glulam.

Sammanfattning

Under de senaste åren har det industriella husbyggandet tagit andelar på den svenska husbyggnadsmarknaden. Behovet av bostäder på marknaden överstiger tillgången och med ökning av bostadsproduktionskostnaderna som konsekvens. För det industriella husbyggandet har projekteringen identifierats som en avgörande fas och dess systematisering är en nödvändig för industrialiseringen. Som en följd strävar företag i segmentet efter att inkludera standardisering och kontrollerade processer i projekteringen. Produktplattformar har kunnat kopplas till standardisering av processer och produkter. Införandet av produktplattformar i projekteringen kan vara ett sätt att förbättra designen och säkra värdeskapandet igenom hela processen. Således är syftet i denna avhandling att ta fram medel för att stödja och förbättra projekteringen för industriellt husbyggande genom att tillämpa en ansats med produktplattformar.

Ett svenskt byggnadsföretag med flera våningar som använder limträ- och balksystem med fokus på plattformsutveckling användes som en enda fallstudie i denna forskning. En fallstudie har genomförts på ett företag som bygger flervåningshus med ett pelar-balksystem i limträ med fokus på plattformsutveckling. Företaget har ambitionen att nå högre effektivitet genom att röra sig mot ett mer industriellt tillvägagångssätt. Data samlades in från intervjuer, observationer, workshops och dokumentanalyser. Resultaten visar vilka de befintliga utmaningarna är för husbyggandet och presenterar tjugo kritiska framgångsfaktorer som ska beaktas i projekteringen. Studien har även tagit fram supportmetoder och verktyg som kan användas för att förbättra projekteringen vid tillämpning av produktplattformar. Vidare, en flexibel produktplattform kan utvecklas med stöd av parametrisk modellering och användas för att projektera byggnads-komponenter med engineer-to-orderegenskaper. Slutligen, resultaten pekar mot att ett byggsystem kan betraktas som en del av en produktplattform ur perspektivet att tillräckligt med stöd i projekteringen krävs för att underhålla en hållbar plattform. Således, arbetet har bidragit med kunskap till teori om plattformar i allmänhet och dess tillämpning på projekteringen för industriellt husbyggande.

Nyckelord: Industriellt husbyggande, Produktplattformar, Designstöd, Byggsystem, Pelar-balksystem, Limträ.

List of appended papers

The following papers constitute the foundation of this thesis

Paper I

Thajudeen, S., Lennartsson, M., & Elgh, F. (2018). *Impact on the Design phase of Industrial Housing When Applying a Product Platform Approach.* In 26th Annual Conference of the International Group for Lean Construction, 18-20 Jul 2018, Chennai, India (pp. 527-537).

Contribution: Thajudeen and Lennartsson conducted the interviews and wrote the paper. Elgh supported in setting the scope, synthesis, critically revising, structure the content and proofreading.

Paper II

Thajudeen, S., Lennartsson, M., & Elgh, F. (2019). *Challenges and Critical success factors for the Design phase in Swedish industrialised house building.* In 35th Annual ARCOM Conference, 2-4 September 2019, Leeds, UK (pp. 34-43). Association of Researchers in Construction Management (ARCOM).

Contribution: Thajudeen conducted the interviews and wrote paper. Lennartsson and Elgh supported in conducting the analysis, synthesis of the theory, critically revising, structure the content and proofreading.

This paper has been invited to be extended into a journal article.

Paper III

Thajudeen, S., Lennartsson, M., & Elgh, F. (2020). *Expanding the building system into a product platform for improved design and manufacture - A case study in Industrialised house building.*

Accepted to 9th Swedish Production Symposium, SPS 2020.

Contribution: Thajudeen wrote the paper, conducted the interviews and workshop at the case company. Lennartsson and Elgh supported in the conception of the work, synthesis of the theory, critically revising, structure the content and proofreading.

Paper IV

Thajudeen, S., Lennartsson, M., Elgh, F & Persson. P-J (2020). *Parametric modelling of steel connectors in a glulam-based post and beam building system- Towards a flexible product platform approach.*

Accepted to 27th International Conference on Transdisciplinary Engineering (TE2020).

Contribution: Thajudeen wrote the paper, conducted the interviews, workshop at the case company. Thajudeen and Persson set the scope and developed the computer supported tool. Lennartsson and Elgh supported in the conception of the work, critically revising and proofreading.

Additional paper

Popovic, D., Thajudeen, S., & Vestin, A. (2019). *Smart manufacturing support to product platforms in industrialized house building*. Modular and Offsite Construction (MOC) Summit Proceedings, (pp. 284-292).

Contribution: Popovic, Thajudeen & Vestin equally contributed to planning the study, data collection, analysis of data, synthesis of the theory, structuring and writing the paper.

Abbreviations

BIM - Building Information Modelling
BPI - Building Price Index
BS - Building System
B2B - Business-to-Business
B2C - Business to Customer

CODP - Customer Order Decoupling Point
CPI - Consumer Price Index
CSF - Critical Success Factors
CTO - Configure-to-Order

DFMA - Design for Manufacturing and Assembly
DS - Descriptive Study

ETO - Engineer-to-Order

GLT - Glued Laminated Timber

IHB - Industrialised House Building

LVL - Laminated Veneer Lumber

MTO - Modify-to-Order

PLM - Product Lifecycle Management
PDM - Product Data Management
PVM - Product Variant Master
PS - Prescriptive Study

SV - Select Variant

Contents

1. Introduction

The Introduction Chapter explains the background of Industrialised house building industry and problem areas to provide the readers with an overall idea of the research project. The purpose and research questions in support of the study are presented in this section.

1.1 Background

The Swedish house building industry is facing pressure due to the emerging needs of new housing solutions with lower project cost and shorter lead time. According to the National Board of Housing, Building and Planning (Boverket, 2016), an estimated 710,000 houses need to be built before 2025 with an estimated average annual rate of 70,000 units over the next five years. The housing construction attained a peak in 2016 and 2017 (Palmgren, 2019). However, the construction pace has declined in 2018, by 19% and according to the forecast by Swedish housing agency, in 2020, the pace will be about half of the level in 2017 (ibid). Thus, the increase in market demands has been observed to be more than the housing supply (Brege et al., 2017). Correspondingly, the necessity for Industrialised house-buildings (IHB) is witnessing an increased focus in Sweden. With the growth in demand, the market has been experiencing a substantial increase in housing costs (Lindblad, 2019). Reportedly, the general price level in Sweden is still relatively high compared to several other European countries (Eurostat, 2020). Over the past couple of decades, the price of housing in Sweden has accelerated at a faster rate compared to the average household income (Welin and Bildsten, 2017) and shows more than 130% increase since the mid-1990 (SCB, 2020).

Several factors in combination play a key role in influencing the rise of the general price level of housing in the market. According to Welin and Bildsten (2017), these factors could comprise increased disposable incomes, financial deregulation, low loan rates, negligible housing constructions over time, and unsociable location and types of housing. However, the increasing production costs of housing construction have been reported as a major barrier for the

Swedish housing market (Boverket, 2014; Larsson et al., 2014). Figure 1 shows the evolution of the Building Price Index (BPI) and Consumer Price Index (CPI) from 1992 to 2018 (SCB, 2020), which exhibits a steep increase in housing cost after the mid-1990s (Sørensen, 2013; Lindblad, 2019). The development of BPI projects twice as fast as the development of the CPI not only for the recent future, but also beyond. In addition, the graph illustrates the factors that impact the production cost of house building and shows an acceleration of these factors. Production cost refers to the total cost of a project after all stages of the construction process are included.

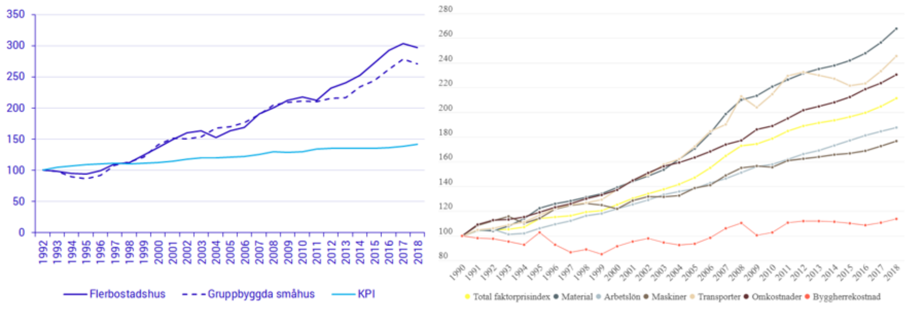

Figure 1: Building Price Index and Consumer Price Index (SCB, 2020).

Recently, the Swedish housing industry is witnessing a new trend with consumer demand and interest in sustainable and environmentally friendly buildings (Brege et al., 2017). This interest has largely been restricted to the industrialised buildings with entailing timber construction (Toppinen et al., 2018). A sustainable approach is important for future buildings and timber has several good qualities, for instance, it is light and strong concerning its weight (Stehn, 2009). Moreover, a positive interest is evident in the onsite assembly for multi-family houses (Schauerte, 2010, Toppinen et al., 2018) and the companies operating within this segment highlight wood as a suitable material for building (Stehn, 2009). An industrial apartment building has 40% lower CO2 emissions compared to a concrete house (Brege et al., 2017). However, the market development of multi-family houses shows that the solutions based on timber only constitute of 8.7 percent of total domestic housing (Lindblad, 2019). According to Brege et al. (2017), this share shows a future growth potential of 50% by 2025 and it is essential to meet the growing market demands.

Several initiatives and benchmarking activities have been adopted in the construction industry from other industries as an opportunity to reduce the inefficiencies and improve the productivity through a gradual, continuous improvement of the industrialised process (Pan et al., 2012; Mahdjoubi et al., 2015; Söderholm, 2010). Therefore, researchers and practitioners argue that the construction industry could improve the productivity by implementing techniques applied in manufacturing industries, to increase the industrialization of design and production processes (Larsson et al., 2014). However, the challenge, when compared with other technology areas is that the house building sector is characterized by short series and high complexity in the number of product variants and models (Jonsson, 2017).

The low production volume in the house building industry, when compared to the manufacturing industry such as the automotive industry, could attribute to this complexity leading to a relevantly lesser degree of standardisation. For the development of industry, economies of scale project significant value (Lindblad, 2019). The advantages of the manufacturing industry include higher production volume and a high economy of scale to test and implement different improvement tools and methods. These advantages are absent in the house building industry as every project is unique with respect to the level of customization requirement. By definition, customization refers to the abilities and strategies that aid designing and manufacturing customized products for an individual customer. In order to meet the customization, the house building companies can adopt different production strategies according to the degree of pre-engineering and the customer order decoupling point (CODP) (Hvam et al., 2008). According to Hansen (2003), the four production strategies are Engineer-to-Order (ETO), Modify-to-Order (MTO), Configure-to-Order (CTO) and Select Variant (SV). The house building sector has been categorized as one of the largest ETO sector (Gosling and Naim, 2009). The ETO design processes generates technical solutions which are not easily reused in successive projects (Jensen, 2014). The fluctuating requirements of customers create complexities in the design phase, adding time and cost to the process. Therefore, the design phase must be more efficient in such a way that informed decisions at the beginning of the project can result in increased internal (production) as well as external (customer) efficiency. Thus, projecting a need for IHB sector to address the question of how the building process can be supported for improved design and manufacture.

1.2 Problem area

History has shown that house building requires much lead time, are over-budgeted, and suffer from poor workmanship and materials problems (Karim Jallow et al., 2014). The industrialization of construction processes has emerged as a capable approach for improving the house building productivity (Höök, 2008; Lessing, 2006) and competitiveness from a holistic view (Unger, 2006). However, from a process perspective, several other areas also need to be organized and developed in the house building sector (Ekholm and Wikberg, 2008) and design is a critical phase (Haller et al., 2015). The IHB sector is striving for improvement and inclusion of standardised processes in the design phase (Viklund, 2017) as it has been identified as a decisive stage (Haller et al., 2015). According to Söderholm (2010), the design phase is a crucial juncture for establishing the manufacturing prerequisites and assembly of building components. This phase, as such, consumes more time compared to production and assembly phases (Bonev et al., 2015). Moreover, customization or unique needs from the customer have been identified as a common challenge in the IHB industry (Jansson et al., 2014). The level of customization requirement and uniqueness varies significantly between projects, thereby limiting the reuse of previous projects experiences and yielding higher lead time and overall cost for building construction. Thus, the design phase requires proper solutions to deal with highly customized requirements and support methods and tools to reduce the design lead time and thereby reduce the cost incurred.

Platform-based product development has been considered as a success factor in many other industries and markets, such as automotive, electronics, software, and domestic appliances, etc. (Simpson et al., 2006). Several companies within these industries leverage the component-based product platform approach to stay ahead of the competition in the market. A product platform, *as a method of sharing components and processes, allows the companies to develop differentiated products efficiently through a flexible and responsive process* (Robertson and Ulrich, 1998; Meyer, 1997). It has been acknowledged as a capable approach in terms of standardisation of product and process resulting in reduced cost and lead time (Jiao et al., 2007; Halman et al., 2003). This optimization is achieved by adopting a combined product platform approach with different concepts, such as mass customization, modularization, and product configuration. These combined approaches enable the companies to develop opportunities in expediting their business model developments (Bonev et al., 2015; Kudsk et al., 2013; Styhre and Gluch, 2010). The house building sector necessitates efficient and innovative platform development for the expansion of a sustainable society (Jansson, 2013). Therefore, the introduction of a product platform approach in house building could be a way forward in value creation for the entire process (Bonev et al., 2015; Veenstra et al., 2006). Jansson (2013) outlined in his doctoral thesis that the practice of a platform-based product development approach in house building could lead to optimized design activities. Product platforms can enable the companies to achieve high levels of product variety, reduced time-to-market, better operational efficiency, and responsiveness to market needs (Lessing, 2015). In order to meet these benefits, house builders should strive for structured and modulated design processes (Johnsson, 2013).

The systematization of the design phase in house building becomes an integrator when shifting from the traditional construction to industrialised practice with the ability to support the entire supply chain (Johnsson, 2013). The building system (BS) is considered a strategic asset (Johnsson, 2011) and the foundation of continuous improvement in the IHB processes (Söderholm, 2010). Currently, the lack of proper modelling and documentation of the BS makes the system difficult to adapt to variable customer requirements (Andersson and Lessing, 2017). The BS is closely related to the design phases (Söderholm, 2010) and plays a crucial role in supporting the decision-making in different design stages (Malmgren, 2014). Correspondingly, working with building systems implies transferring the gained experiences and knowledge from individuals to the building systems (Andersson and Lessing, 2017). The building systems based on ETO products can be regarded as complex as the customer order penetrates the product design phase (Gosling and Naim, 2009). Thus, adequate support is needed for the BS to fulfill customer needs, adapt to technology changes and increase productivity, as the project undergoes several design stages with varying degrees of details (Lessing and Brege, 2015). Johnsson (2013) suggests that platform-oriented thought processes could offer a solution to achieve early implementation of such ideas in house building. Moreover, customization can be supported by creative as well as systematic design work in projects (Jansson, 2013). However, the current scenario demonstrates a lack of knowledge regarding how platform-based product development can be adopted in ETO based IHB (Jensen, 2014). To enable support development in the design phase, it is crucial to understand the current state of practice, existing challenge, and key success factors in the process. According to Wuni and Shen (2019), gaining a deeper understanding of the critical success factors is an effective method to improve the productivity of the industrialised building. Consequently, it is important to investigate the problem inherent in the design phase of house building industry and improve it by developing systematic support and means for improved efficiency from a product platform perspective.

1.3 Research focus

Several studies have been conducted as part of the product platform development in the IHB sector, including modularization (Kudsk et al., 2013), configurators (Jensen, 2010; Hvam et al., 2008; Malmgren et al., 2010), product families (Bonev et al., 2015) that significantly support the establishment of a component-based platform approach. This refers to a product platform for predefined variants or configurable modules (André, 2019) suitable to meet standard product requirements. However, in IHB, extensive engineering activities are required for certain components during development as customization yields a high level of complexities in design. As discussed earlier, it is necessary to explore the evident lack of a platform approach that can be used to support the design of a customized and evolving product (André, 2019, Raudberget et al., 2019). This necessitates dedicated support for products with ETO nature and to design it more efficiently and ensure producibility. Therefore, the research focuses on the introduction and use of a product platform approach in an IHB context within systems or components with ETO characteristics.

1.4 Aim and research questions

This research aims to *outline means to support and improve the design phase of industrialised house building by using a product platform approach*.

The study aim has been addressed using the following three supportive research questions (RQs):

RQ1: *What are the state of the art and current practices in the design phase of the Industrialised house building industry when using a product platform approach?*

The first research question (RQ1) aims to answer, how the product platform approach has been defined in the design phase of the Industrialised house building at present as a part of the research gap analysis. Also, explore and analyse the current practices and trends in the housing industry. This includes the mapping of the design process to identify how the design activities have been developed from a product platform perspective and evaluate with existing literature.

RQ2: *What are the challenges and critical success factors that should be considered in the design phase of the Industrialised house building?*

The second research question (RQ2) allows the study to identify the challenges and outline critical success factors in the design phase that have been adopted by the house building industry from literature as well as industrial viewpoint. Moreover, this question helps to explore the common challenges in the house building industry.

RQ3: *What means can be used to support the design phase of industrialised house building when introducing a product platform approach?*

Research question three (RQ3) mainly addresses what type of means can be used to support and further improve the design phase to reduce the lead time and general production cost of house building.

1.5 Scope of the research

The research presented in this thesis focuses on the timber based IHB companies in Sweden and the scope of the whole research is further limited to the design phase of the house building. Here, the design phase refers to the start of project inquiries by the customer to the completion of production drawings including the conceptual phase, system-level phase, and the detailed design phase. For the case studies, a higher focus was accorded to a post and beam type building system while other types were also included in answering

RQ 2. The design process of a post and beam type building system named *“Trä 8”* developed by Moelven Töreboda AB has been studied and constitutes the main unit of this research. The studies were carried out in close collaboration with the case company through analysing the design development and use of a product platform approach. In terms of academic scope, the research presented in this thesis contributes to the knowledge of product platform development in the IHB industry.

1.6 Introduction to the main case company

The case company is one of the leading manufacturers of Glulam (Glued laminated wood) in Europe and is located in the mid-south part of Sweden. The company is a standalone unit within the Moelven group and was established in the year 1919. The company has an annual production capacity of 55,000 m^3 with a turnover of €30 million and 115 employees. They offer to construct and produce wooden load-bearing structures for all construction purposes in Sweden and Norway.

The company has several common aspects with the IHB conceptualization and is moving towards the direction of increased IHB. They own a post and beam building system in the multi-storey house building market named *Trä 8 building system*. From a structural perspective, the post and beam are the main load-bearing structure and the loads from the floor element are transferred through different connectors to this structure. Currently, the company operates as a business-to-business (B2B) approach and acts as a system supplier of a host of components except for the wall elements. However, the ambition of the company is to expand its product portfolio and add the missing components to move forward and deliver a complete offering to clients. The company is a part of the Swedish housing industry and intends to adopt an industrialised approach to achieve higher efficiency. The building system comprises standardised technical solutions and demonstrates the ability to adapt to diverse project needs and the potential to add more components. Moreover, the company owns a fixed-production factory that is equipped with required machinery, standardised work routines and human resources, which are essential of IHB. Additionally, they are involved in the design process of house building, which is a common part of an IHB company.

1.6.1 The Trä 8 building system

The Trä 8 building system was launched in the year 2009 and can be categorized in the timber post and beam based-industrialised building system. The system was developed based on the prefabricated technique and materials used are glulam and laminated veneer lumber (LVL). As the name implies, the system can be used for up to 8-meter of a free span that enables flexibility for architectural designs. The fundamental part of the system is the idea of "Big Size Pre-Cut", wherein, a high level of prefabrication of large building elements and sets of material is gained through efficient production methods. The main components of the building system include post, beams, trusses for stabilization made of glued wood, floor elements and roof elements made of Kerto LVL material and steel connectors. The components of the Trä 8 building system are presented in Figure 2.

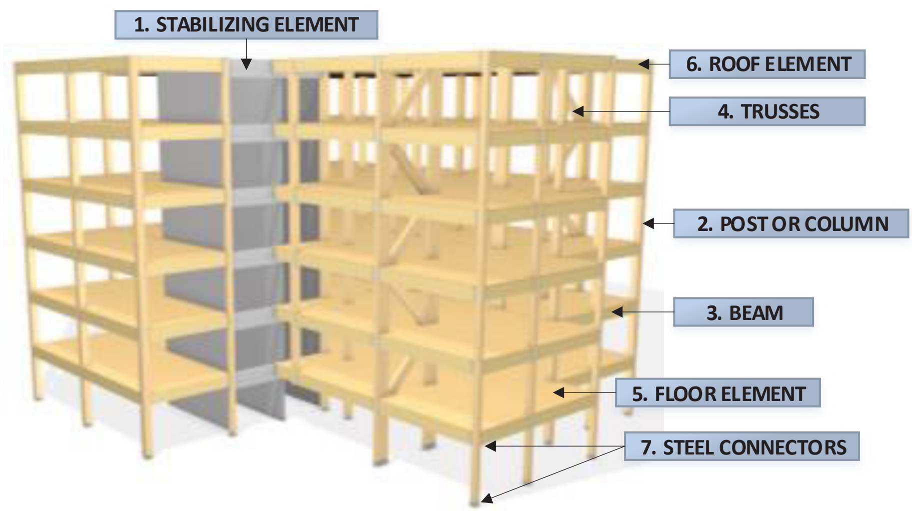

Figure 2: Components of Trä 8 building system.

1. Horizontal stabilizing element- The main horizontal stabilization element is constructed with stair-case and elevator shaft or trusses. The trusses are made out of glulam and the staircases are normally made of concrete. The purpose is to stabilize the entire post beam that allows 8 meters span.

2. Post- They are made by glueing together the small lamellas and are used to handle the vertical load imposed on the building which is anchored to concrete foundation. It may be subjected to both compressive and bending forces and is designed to carry the imposed loads such as snow, wind, live and dead loads.

3. Beam- The beam primarily function as the vertical load-carrying element from the floor element of the building and is connected horizontally to the posts with the help of steel brackets.

4. Trusses- Trusses are the diagonal structure which is used as a stabilizing member to balance the fluctuating wind load. The truss elements are connected to a post with steel fin plates and dowels to provide stiff connections between the members. The dimension of trusses depends on the varying load due to wind and vibrations from the building.

5. Floor element- They are built with a top board of LVL and beam frame of glulam. The cavities are insulated with mineral wool for sound insulation. The elements are light and very stiff and good features in terms of soundproofing, especially at low frequencies.

6. Roof element- The roof structure is most conveniently designed with LVL board having surface insulation with a layer of insulation material on top.

7. Steel brackets- Steel connectors are precisely engineered components used to transfer loads from the floors to the vertical posts. They function as a stabilizing element for the building by transferring horizontal loads to the wooden trusses. There are four main types of steel connectors used in the Trä 8 building system (see Figure 3).

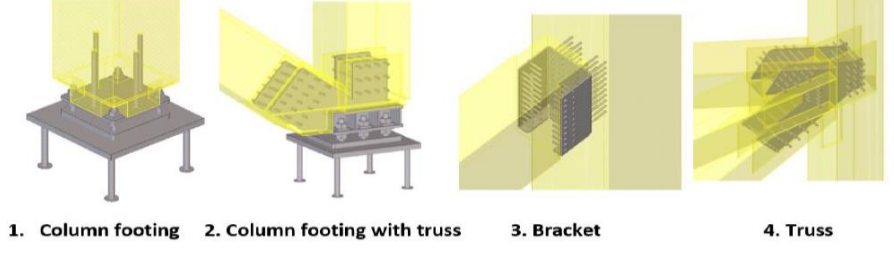

Figure 3: Different types of steel connectors used in Trä8 building system.

The height and width of the connectors depend on the dimension of the beam and the required load capacity.

1.7 Thesis outline

This thesis consists of six chapters and four appended papers. A brief description of each chapter is presented below:

Chapter 1 introduces the *Research Study* presented in this thesis with the background and problem area. Following this, the chapter showcases the research focus, purpose and research questions and lastly the description of the scope of the research and introduction to the main case company.

Chapter 2 describes the *Research Methodology* employed to answer the proposed research questions and data collection methods used in the study. The chapter ends by discussing the research quality and the framework that has been used for the overall research and association between individual papers.

Chapter 3 presents the *Frame of Reference* that is used to support the research subject, state of the art, challenges and fundamental theories. The chapter ends with a summary of the review and research opportunities with this thesis.

Chapter 4 outlines the *Summary and Empirical* findings of the four appended papers and how they progress in different papers.

Chapter 5 presents the *Discussion of the Findings* presented in the previous chapter and focuses on the results obtained highlighting how these inferences address the research questions. Then, it presents the discussion of the research approach and the study quality. This chapter concludes by presenting scientific and industrial contributions along with the study limitations.

Chapter 6 briefly summarizes the *Concluding Remarks* along with suggestions of *Future Research* work.

2. Research methodology

This chapter presents the research methodology adopted for this research project. Firstly, the general description of the research design, the data collection methods and its analysis are presented. Then, the chapter concludes with a presentation of quality aspects of research including validity and reliability.

2.1 Research design

This research aims to outline means to efficiently support and improve the design phase of industrialised house building by using a product platform approach. This research work adopted the Design Research Methodology (DRM) defined by Blessing and Chakrabarti (2009). DRM is used as a support tool for conducting research in the design field and developing innovative solutions to solve practical problems and allow a theoretical contribution. DRM is a four-stage iterative process used as a framework for the whole research project. Figure 4 shows the framework of DRM methodology mainly consisting of four stages named as Research clarification, Descriptive study I, Prescriptive Study, and finally Descriptive study II.

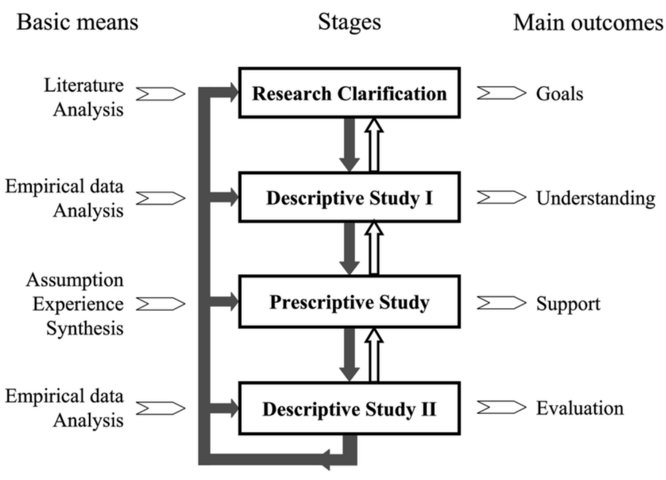

Figure 4: Design research Methodology (DRM) framework according to Blessing and Chakrabarti (2009).

1. Research clarification (RC): In this initial research stage the researcher attempts to identify support or evidence to formulate the research goals. Furthermore, it is imperative to understand and visualize the existing condition to analyse and develop a tool for improving the current situation. As shown in Figure 4, the literature review and analysis can be conducted to learn the initial description and current practices in the study field. The main outcome of this process is a set of defined goals.

2. Descriptive study (DS-1): In this stage, the researcher develops a clear idea about the research problem, based on the literature review and by understanding the industrial concerns without the necessary evidence. Empirical data collection and analysis can be conducted in order to gain deeper knowledge and determine the key factors by observation or interviewing the stakeholders accessing the current state. The main outcome of this stage is improved research understanding.

3. Prescriptive Study (PS): The prescriptive study is the third research stage, wherein, the researcher can begin with the systematic development of new methods and tools to support the improvement of an existing problem leveraging the two previous stages. The main outcome of this stage is support development.

4. Descriptive study II (DS-II): The researcher can now proceed to the Descriptive Study II stage in order to investigate the impact of the support method and its ability to realize the desired situation. The method is thus tested and validated with the final evaluation for all the criteria considered to develop the support method. This iterative process is shown in Figure 4. According to Blessing and Chakrabarti (2009), the iterations necessarily result in improving the research understanding.

2.2 Data collection and analysis

The data collection and analysis are a significant part of conducting research. The selection of various data collection methods, such as qualitative and quantitative data depends on the nature of the study.

2.2.1 Data collection methods

An essential part of any research is to review the existing literature in the field of interest and body of knowledge (Karlsson, 2010). It plays a central role in helping to narrow down the research scope. The interview is one of the several qualitative data collection methods and correspondingly, interviews preferably are used to gain more knowledge about a topic because they permit collecting individual experiences working in the innovation process (Williamson, 2002). There are three different types of interviews: structured, semi-structured and unstructured interviews. In addition, the workshop methodology is structured as the introduction, review, and development of shared vision (ibid). In some scenarios, the best way to collect data is through observation, which can be done with the subject (directly or indirectly) knowing or unaware that they are under observation. According to Yin (2014), the main advantage of direct observation is the option to study and analyse important processes, behaviour, and environmental conditions in real-time. Document analysis enables insightful and better knowledge about the project activities and accord more understanding about the challenges from the practical viewpoint (Williamson, 2002).

2.3.4 Data analysis

The analysis of data collected from different sources is a key research step to accomplish the research aims. Data analysis is aimed at describing, explaining, and then interpreting the studied subject to enable the researcher to optimally answer the research questions (Denscombe, 2014) and it should be well-structured and systematic (Karlsson, 2010). According to Williamson (2002), data analysis is the process of bringing order, structure, and meaning to the mass of collected data. Qualitative data analysis is predominantly concerned with the analysis of talk and text (Denscombe, 2014).

There are mainly three parts for qualitative data analysis according to Miles et al. (2014): data reduction, data display, and conclusion drawing/ verification. Data reduction is at the core of the task of analysing the qualitative data and begins by data reduction with reduction of research control data and classification for reduction of contextual data e.g. transcribe recorded interviews and workshops into text. According to Miles et al. (2014), data reduction refers to "the process of selecting, focusing, simplifying, and transforming the data that appears in written-up field notes or transcription". This is followed by data presentation for an organized assembly of the information enabling informed derivation of conclusions. The categorization of data can be performed according to data contents and themes. The final step of the process is to draw conclusions and verification to derive meaning from data and build a logical chain of evidence. According to Denscombe (2014), the empirical data can be analysed alongside the collection, which is a common practice within qualitative research. Analysis can be both within and across cases depend on the nature of the planned method. Content analysis can also be employed to examine the body of literature.

2.3 Research quality

The quality of research often refers to the validity and reliability of the data and result obtained from the study. The validity mainly refers to the extent to which a research instrument measures what it is designed to measure (Williamson, 2002). Using different data collection strategies and sources may enhances the construct validity by viewing the phenomenon from different angles (Voss, 2010). Construct validity implies that the operational methods used to measure the constructs actually measure the concepts they are intended to measure (Karlsson, 2010). Triangulation is often utilized to check the consistency of findings. There are three types of triangulation: method triangulation, data triangulation, and investigator triangulation (ibid). Internal validity is about the establishment of causal relationships between the variables and the results (Voss, 2010). Triangulation is often utilized to check the consistency of findings. There are three types of triangulation: method triangulation, data triangulation, and investigator triangulation (ibid). Internal validity refers to the establishment of causal relationships between the variables and the results (Voss, 2010). Triangulation or the application of multiple data collection techniques is often used to ensure internal validity (Karlsson, 2010). External validity also means in a related way that the results are valid in similar settings external to the studied objects (Voss, 2010). In case study based research, an analytical generalisation refers to generalisation from the empirical observation to theory (Yin, 2014).

According to Williamson (2002), reliability mainly refers to the consistency of results produced by a measuring instrument when it is applied more than once in a similar situation. Reliability refers to the replicability of findings (Yin, 2014). In other words, reliability examines the possibility of achieving the same kind of result and conclusions with the repeated studies of the research by another researcher in the same settings. Moreover, the key principles in research ethics proposed by Bell et al. (2018) are informed consent, principles of no harm of participants, and respect for privacy.

2.4 Application of research methodology

The research presented in this thesis has been executed using DRM, proposed by Blessing and Chakrabarti (2009). The research works for licentiate thesis were performed between September 2017 and February 2020. Three research questions have been formulated to fulfill the aim, by including four studies supported by four papers. The research questions addressed were exploratory and followed the DRM framework. As mentioned earlier, there are four iterative stages for the DRM framework. The proposed research questions can be related to the different stages of DRM adopted in this study. Figure 5 shows the chronological order of work and connection between the research questions, research methodology and research strategies used for individual studies that resulted in intended papers.

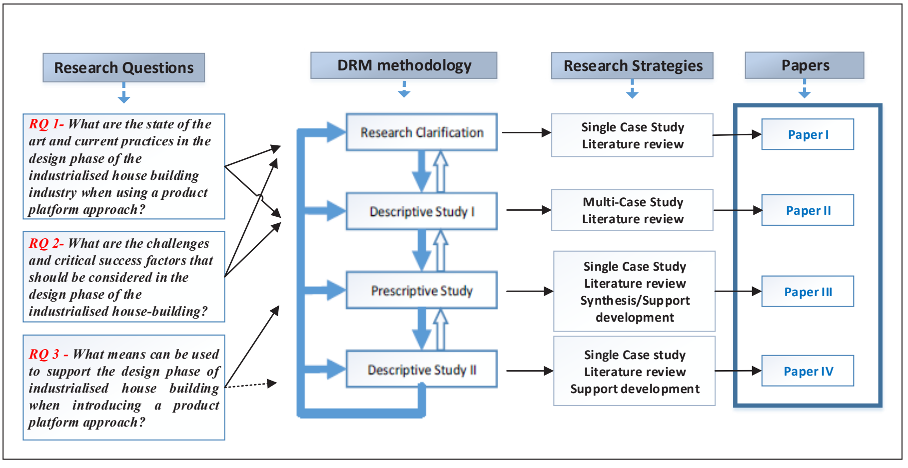

Figure 5: Linking the research questions, research methodology, research strategies and papers.

This research adopted a qualitative data collection approach with tools, such as interviews, workshops, observations, and document analysis.

The RC stage focused on the formulation of the research goal. The first study consisted of a single case study and a literature review (Yin, 2014). The literature review was performed to understand the platform approach conceptualization and current application in the IHB industry. Multiple sources of data were analysed for this study with semi-structured interviews and document analyses. For the empirical data, semi-structured interviews with open-ended questions (Williamson, 2002) were conducted with five respondents from the case company, that is, Managing Director, Design Manager, Structural Engineer, Design Engineer, and Project manager. The document analysis of previously completed projects was also conducted as part of the data collection. It includes structural calculations, 2D drawings, 3D models of buildings, MS Excel spreadsheets, and activity plans for different projects, etc. The study used qualitative data analysis with three steps mentioned by Miles et al. (2014) for all analysis purposes.

The study contributed to answering RQ1 mainly and RQ2 partially and resulted in Paper I. This paper presents the state-of-the-art and current practices in the design phase of glulam post and beam-based building system with an analysis of design assets from a platform perspective. Moreover, it helped to identify the general design process perspective and analyse problem areas with specific support and evidence to formulate the research goals (Blessing and Chakrabarti, 2009). This study also outlined the research gap and presents the research opportunity in the IHB sector having different production strategies.

The DS-I stage was carried out to identify the challenges and critical success factors for understanding industrial concerns. The work was based on a multiple case study performed at three Swedish timber-based house building companies in combination with a literature review. The data collection was based on semi-structured in-depth interviews. An interview guide was developed before the interviews to aid the assessment of challenges and CSF. This stage helped to gain deeper knowledge about the existing challenges and determine the key success factors in the design phase of IHB. Thus, RQ 1 and RQ 2 were answered. The unit of analysis was the design phase of Swedish

IHB and qualitative data analysis was performed based on the three steps defined by (Miles et al., 2014).

The study contributed mainly to answering the RQ 2 and partially to RQ 1, thereby yielding Research Paper II. This paper helped to identify the existing challenges in the design process and outlined the critical success factors in the different stages of design from a practitioner's perspective. Additionally, Paper III has also provided an understanding of the current building system support as part of the descriptive study and answer RQ2.

In the PS stage, the systematic means and support were developed for the design phase to mitigate the challenges identified from the DS-I stage. Two studies were conducted as part of the prescriptive study and together they contributed to answering RQ3 and resulted in Paper III and Paper IV.

Paper III aimed to explore the current state of the IHB system as well as outline design support solutions. A qualitative study was conducted with a combination of a literature review and a single case study at one of the Swedish multi-storey house builders. The empirical data was gathered using semi-structured interviews (five persons) and two workshop sections (seven persons) conducted with the design and management team. In addition, the study conducted a synthesis and conceptualization of idea formation. The data analysis for this study was conducted in accordance with the steps defined by Miles et al. (2014) for analysing qualitative data. In this study, methodological support was developed to address the key factors identified from the DS-I stage. The result outlined various methods and tools for supporting and improving the design process with examples. Some of the results obtained from this study have already been implemented at the case company. The study reported in Paper III mainly contributed to answering RQ 3, with additional support in answering partially the RQ2 in the descriptive stage.

Pape IV aimed to conduct a detailed development of support to improve the design process and further substantiate the answer to RQ3. The study reported the ongoing platform development at the case company. Empirical data were collected through a workshop, semi-structured interviews, and document analysis. Additionally, unstructured interviews were conducted with the key designer frequently. A workshop was conducted initially to brainstorm the needs, current challenges and understand the company's business vision. As an outcome from the workshop, a project team was formed aiming different improvement activities as part of platform development. The interviews provided an opportunity to dig deeper into questions that had emerged during the workshop. The observation method was used in this stage to understand different tasks involved in the different phases of connector design. Besides the interview and observation, a document analysis of previously completed projects was conducted as part of the data collection. The documents included the structural calculations, 2D drawings, 3D models of buildings, excel spreadsheets and activity plans for different projects. Computer-based support has been developed with the help of a design engineer and investigate the impact of the support method and its ability to realize the desired situation.

In the DS-II stage, the focus was on the evaluation of the support developed in the previous stage. Some solutions developed in the prescriptive stage have already been implemented at the case company in the design process, e.g. Architect guide (Paper III), parametric modelling (Paper IV) etc. At this stage, this research is at the initial phase of the implementation of support solutions as part of platform development. Therefore, a primary evaluation was only conducted with the designer who actively participated. The evaluation for the parametric modelling approach in the design process was conducted. However, a systematic evaluation will be considered for future studies to complete the fourth stage (DS-II) of DRM framework.

3. Frame of reference

This chapter presents the theoretical foundation of the research underlying this thesis. The chapter includes research pertaining to the IHB, design process, BIM and product platform concepts. Figure 6 shows the main concepts used in this thesis, including area of contribution, essential, useful and considered research fields. The chapter ends with a summary of the research opportunities derived from the survey.

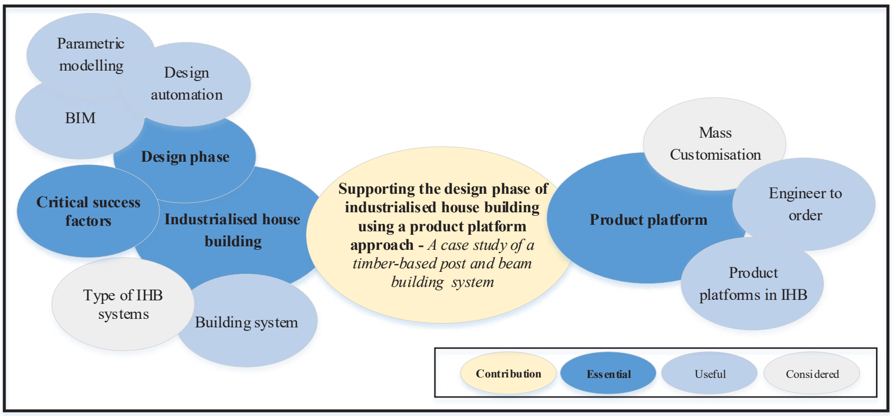

Figure 6: ACR diagram (Inspired by Blessing and Chakrabarti (2009)).

3.1 Industrialised house building

The Industrialised house building mainly focuses on the components production in a closed factory environment where only assembly is performed at the construction site, with one evident process owner and a clear product goal of repetition in housing design and production" (Höök and Stehn, 2008). The definition of IHB, according to Lessing (2006) "*a thoroughly developed building process with a well-suited organization for efficient management, preparation and control of included activities, flows, resources and results for which highly developed components are used in order to create maximum customer value"*. Clearly, the process, organization and technical aspects connected to the house building must be well developed in order to leverage the advantages of industrialization. One of the most essential advantages of industrial housing is the short duration of the project from start to delivery, slashing costs for the builder by yielding expedited revenues (Lennartsson, 2009). Moreover, IHB reduces the influence of project orientation and creates a high degree of stability in production and coordination with the stakeholders ensuring reliability and faster delivery times (Brege et al., 2013). An important part of IHB is the prefabrication and efficient use of technical systems and components with different levels of standardization, that combined form unique end products (Lessing, 2015). Jansson et al. (2014) proposed that product platforms are fundamental elements in the IHB development. Lessing (2006) developed a process model named Industrial house building process Model (IHP Model) that can be used as a tool for assessing the industrialization level from a process-oriented approach. Figure 7 shows the framework containing the eight characteristic areas, covering the technical, process and organizational matters that need to be integrated and reinforced by continuous improvements to establish IHB.

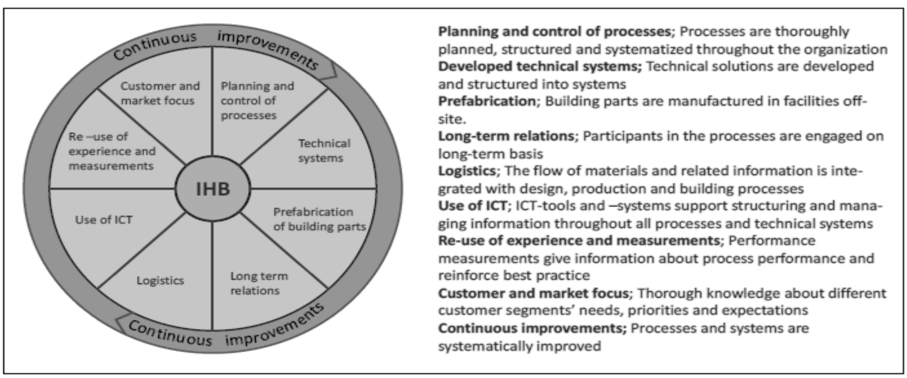

Figure 7: A framework for Industrialised house building (Lessing, 2006).

3.1.1 Building system

Building system for IHB is defined as "*the collected experience and knowledge in how to realize a construction project* (Söderholm, 2010). In IHB, the building system constitutes the core of the construction design process as it underscores all projects' implementation (ibid). The type of building system that a company determines to develop is typically aimed at ensuring a balance between efficiency in design and production and flexibility of adapting to customer requirements (Olofsson et al., 2010). One way to control the inherent uncertainty levels (due to the factors involved) in the design process of IHB is to determine the degree of flexibility of the building system. The building system includes both a technical and process platform (Lessing, 2006). Normally, the documentation of the building systems contains standard solutions (components) and detailed specifications (joints). The building system is a potential bearer of information necessitating extensive documentation (Söderholm, 2010). Building systems can also be categorized according to the product specification process (Johnsson, 2013).

3.1.2 Types of industrialised building system

In IHB, the classification of different building systems is based on the degree of prefabrication as discussed below:

Element prefabrication comprises the production of different elements manufactured in the factory environment with controlled manufacturing processes (Sardén, 2005). These prefabricated elements are subsequently transported to the construction sites where these elements are assembled with other sub-assemblies, elements or components according to a specific design (Höök, 2005) (see Figure 8).

Figure 8: Element prefabrication production process (Höök, 2005).

Volume elements prefabrication is the production of various building elements, and assembly of building elements to three-dimensional volume elements (Höök, 2005). Before the modules are ready for delivery to the construction site, they are finished with installations, facades, interior surfaces and other interior finishing, such as wardrobes, kitchen utilities, sinks, cabinets and toilets within the in-house production floor. These modules are then transport to the construction site for assembly assembly (see Figure 9).

Figure 9: Volume prefabrication production process (Höök, 2005).

Element and volume prefabrication refer to the innovative effort in Swedish house building market where the combination of both element prefabrication and volume element is used to construct the houses.

Post and Beam system use buildings that need larger free spaces and the system consist of prefabricated beams and posts load-carrying frames with intermediate floor, wall and roof elements. e.g., commercial buildings, school facilities, sports arenas (Tlustochowicz et al., 2010). The important factor within the timber post and beam system is that almost all the preparations, such as cuts and drills of building components are done at the factory prior to transport to site for improved efficiency from an industrialisation perspective.

3.1.3 Critical success factors

Critical success factors can be defined as those relatively small numbers of truly important matters, which mark the difference between success and failure (Rockart, 1980). CSFs are a limited number of key variables or conditions that impact the successful and efficient accomplishment of a project's mission by an organization (Wuni and Shen, 2019). The CSFs are more beneficial in decision-making support and should include issues important to the current operations and future success (ibid). Clearly, the study of CSF is important for improved project effectiveness in the project (Chan and Chan, 2004).

The criteria, such as time, cost and quality were widely adopted as performance indicators and have been addressed by several researchers (Yong and Mustaffa, 2017) and constitute the traditional measures to assess the success of projects. However, it is essential to consider several other factors IHB design. Halttula et al. (2017) highlighted these factors as flexibility, environmental aspects, manufacturing and assembly in construction projects. Alkahlan (2016) discussed the importance of manufacturing, assembly, transportation and producibility factors in the design of modular house building. In addition, the importance of factors such as legal regulations, design for manufacturing and assembly aspects in industrial building projects was highlighted by Yuan et al. (2018). A study on success factors from a German housing platform was conducted by Thuesen and Hvam (2011) and highlighted the importance of continuous learning, repetition, and standardisation through long-term incremental and systematic innovation with a clear separation between the continuous development of platform-based production.

3.2 Design phase of house building

The design process is a challenging and multidisciplinary task in all the product development projects (Söderholm, 2010). Normally, the design process starts with conceptual designing by the architects and continues through design development including systems design, and detailed design (Mukkavaara, 2018). The decisions concerning several significant aspects of the final building are taken during the early stage of design process. The detailed design of a house building should provide adequate information about the customer requirement starting from the concept design which expands to component drawings and details explaining the correct dimensions and describing the main components of whole building and how they fit together. Many participants are involved in the process by iterating and incorporating their design results to align with the customer requirements. The activities involved in the different phases of IHB design are summarized in Figure 10.

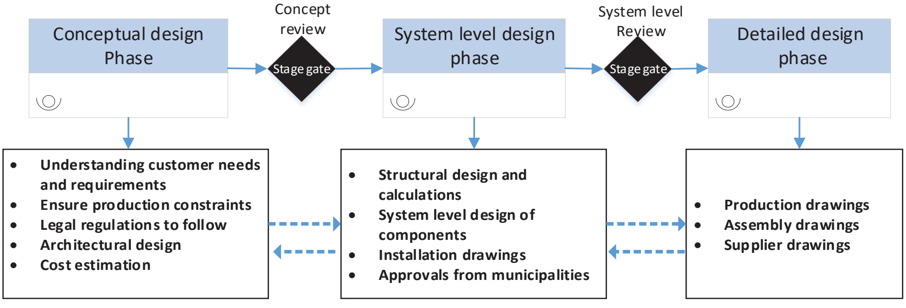

Figure 10: Design process of IHB.

In IHB, systems to reduce costs and increase production flow is essential to manage the process and related flows in design work (Johnsson, 2013). The standardization of work is imperative during the design phase of house building projects as the process is complex and necessitates multiple iterations with a high level of flexibility in customer requirements that change from time to time (Jansson, 2013). Thus, highlighting the significance of standardized processes for repetitive work in order to better utilize resources as well as ensure that knowledge of the product and the building system is captured within the system itself, is not only workforce dependent (Jansson et al., 2008). The decomposition of house building processes into activities in a breakdown structure facilitates control over the progress deliveries from the design work (Ekholm and Wikberg, 2008).

3.3 Parametric modelling

Parametric modelling feature permits regeneration of geometry based on geometrical constraints (Sacks et al., 2004). Parametric Design is the "*process based on algorithmic thinking that enables the expression of parameters and rules that, together, define, encode and clarify the relationship between design intent and design response*" (Jabi, 2013). It allows to integrate domain specific knowledge using explicit mathematical expressions (Lee et al., 2006). According to Singh et al. (2011), the modelling and technical flaws can be decreased by predefining the set of rules for building modelling using parameters in BIM. Monizza et al. (2018) conducted a study on implementing parametric and generative design techniques in Glued Laminated Timber (GLT) and observed that it could improve the overall efficiency of the entire value chain system. Parametric and generative design techniques can be considered an effective tool for improving capabilities of design and engineering processes as well as for increasing the efficiency of manufacturing processes in the building industry (Monizza et al., 2016). Parametric constraint-based design within BIM platforms offers an automatic design validation, wherein, the entire model is automatically updated to adapt changes (Khalili-Araghi and Kolarevic, 2020).

3.3.1 Design automation

The field of design automation has seen enormous growth over the past several decades (Rigger et al., 2018). Design automation refers to "*Engineering IT-support by implementation of information and knowledge in solutions, tools, or systems that are pre-planned for reuse and support the progress of the design process*"(Cederfeldt and Elgh, 2005). The benefits of the automation level include significantly reduced design effort and time-to-market and definitely, design automation can serve as a means for enhanced production (Elgh, 2007). The design automation strategies for prefabrication dramatically increase productivity in the construction industry (Jensen et al., 2012).

Moreover, design automation can be easily applied in parametric tools and product configurators typically used by the mechanical industry (Olofsson et al., 2010). Also, knowledge-based models that support automation seem to be closely connected to building systems and constrained-based programming using parameterization (Sandberg et al., 2008). The development of building systems together with design automation changes the roles of architects and engineers in the construction industry (Jensen et al., 2012). The customization of a modularized product family is normally supported by configurator tools (Hvam et al., 2008). Approaches to automating BIM-based workflows in the design process includes the application of parametric modelling, optimization, and multidisciplinary (Mukkavaara, 2018).

3.3.2 Building information modelling (BIM)

Building information modeling has generated growing interest in the construction industry (Ozturk, 2020) and the term BIM has been increasingly used, rather than product modeling to describe the processes of generating and managing data during the entire life cycle of a building (Lee et al., 2006). BIM refers not only to computer applications' support of the 3D object modelling of buildings but it also allows both the automatic parametric generation of designs that respond to various criteria and the prospect of computer-interpretable models and automated checking of generated designs (Eastman et al., 2011). According to Succar (2009), the use of digital representation for the management of essential building design and project data constitutes the core of BIM. The knowledge representation during the design phase is certainly becoming an important issue in the area of design automation (Medjdoub and Bi, 2018). The transfer of the data from one system to another has emerged as an important issue in BIM implementation. The challenges of interoperability and information exchange have also received a lot of attention in BIM research (Mukkavaara, 2018). Interoperability refers to "*the ability of diverse software and hardware systems to work together smoothly, which enables integrated project delivery via BIM model*" (Ozturk, 2020).

3.4 Mass customization and specification processes

The ability to design and manufacture tailored products for individual customers refers to customization. According to Pine (1993), the purpose of mass customization “is to develop, produce, marketing, and deliver affordable goods and services with enough variety and customization that nearly everyone finds exactly what they want” The ability to adopt mass customization is based on three fundamental capabilities (Salvador et al., 2009): (1) S*olution space development*, which aligns the variety of product attributes with the variety of customer desires; (2) *Robust process design*, which structures the organizational and value-chain resources to fulfill customer wishes; and (3) *Choice navigation*, which supports decisions of customers when defining their solution while reducing choice complexity. There are two main enablers for mass customization (Hvam et al. (2008): (1) product development should be module-based, and (2) configuration systems should be used to support related tasks involved in custom-oriented business for specifications of customized products.

Winch (2003) argues that the house building industry can gain the most from the manufacturing industry. Thus, to explore the potential for platforms, manufacturing companies are classified according to the CODP. The definition of CODP, according to Rudberg and Wikner (2004) is “the point in the value-adding material flow that separates decisions made under uncertainty from decisions made under certainty concerning customer demand”. Companies have been observed to employ several production specification strategies to satisfy varying customer demands (Winch, 2003, Hvam et al., 2008). According to Winch (2003) model, CODP entails four strategies: concept-to-order, design-to-order, make-to-order, and make-to-stock. Wikner and Rudberg (2004) have added three more strategies to the chart: concept-to-stock, design-to-stock, and assemble-to-order. Likewise, several authors and studies have attempted to define production strategies. For all research purposes, the current thesis has used the specification process presented by Hansen (2003) in this study. There are four types of production strategies according to Hansen to meet the client's needs and these include ETO, MTO, CTO, and SV (see Figure 11).

Engineer-to-order (ETO): - The ETO based companies offer highly customized products where the product specification process is based exclusively on norms and standards.

Modify-to-order (MTO): - The MTO companies produce a customized product based on technical platforms (Jensen, 2010) and according to

Hvam et al. (2008), the MTO or ETO processes are appropriate when the product is complex or requires more creativity in design.

Configure-to-order (CTO): - The CTO products are produced based on modules and the standard parts are evaluated according to a set of predefined rules.

Select variant (SV): - Select variant is a type in which a standard product is chosen to fulfil the customer's needs.

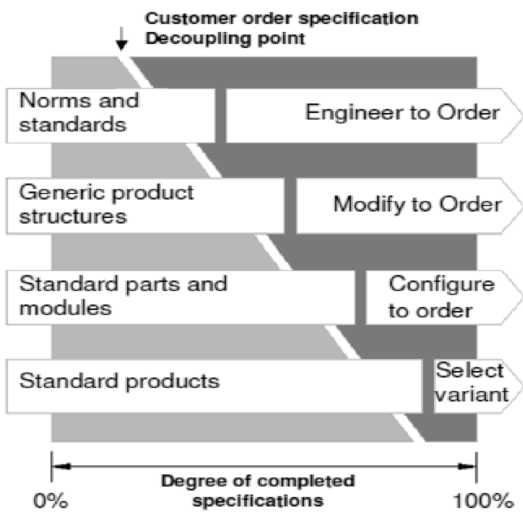

Figure 11: Product specification process, adapted from (Hansen, 2003).

The house building companies can also use different production strategies to meet the demand of customer fitting to the degree of pre-definition. House building platforms allow companies to move from pure customization towards mass customization (Johnsson, 2013). In order to achieve the benefits from the use of platforms, the company must postpone the CODP. A central aspect for understanding the IHB process is to categorize the production process by its level of predefinition (Jansson, 2013). The difference in project progression between a traditional ETO specification process and MTO, CTO or STO-type processes affects the scope for customization in a given project as well as the organization of platform architecture (Jensen, 2014).

3.5 Product Platform

Platform planning is a cross-functional activity involving the product planning, marketing, design, and manufacturing functions of the firm (Robertson and Ulrich, 1998). Literature and several industrial cases report multiple platform approaches. Many researchers have defined the concept of the product platform and some of the definitions are presented below:

"The collection of assets [i.e., components, processes, knowledge, people and relationships] that are shared by a set of products"(Robertson and Ulrich, 1998).

"A set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced" (Meyer, 1997).

"A product platform is a collection element particularly the underlying technology elements, implemented across a range of products"(McGrath, 1995).

"The product platform provides the basis for the product family, which is derived through the addition, subtraction or exclusion of one or more modules from the platform or by scaling the platform in one or more dimensions" (Jiao et al., 2007).

"A group of related products that is derived from a product platform to satisfy a variety of market niches"(Simpson et al., 2006).

The definitions indicate a variation in the product platform concept perspective based on different contexts. A common derivation from this set of definitions is that the components and processes are more important in the platform. However, a widely used definition of product platform presented by Robertson and Ulrich (1998) ideally fits this research context and has been used primarily for the studies. They define the fundamentals of the platform which consists of four parts: components, processes, knowledge, and relationships. Components *are the building blocks used when designing a product and designing component-specific tools for manufacturing*. The processes include *the tasks involved in the different phases such as design, production process and assembly*. Knowledge is described by *the technical and design knowledge, knowledge transfer between projects, production and* *assembly knowledge including testing*. Relationships concern *interactions internally between team members, and externally with organizations, networks with suppliers and the broader supply chain*. These assets are critical in the development of platform approach for any business settings.

According to Simpson et al. (2014), a product platform approach can be of two kinds: (1) The module-based (discrete) approach which is characterized by sets of components clustered into interchangeable modules that together form the product. (2) The scalable platform supporting adaptation by stretching or shrinking the product instances following variations in design variables. Both approaches, support the generation of product families, which is a group of different products generated from a common set of components (modules) with several common characteristics. Hvam et al. (2008) introduced a tool for product platform focusing on implementing product configurator with a mention of the modularization concept. According to Maxwell and Aitchison (2017), the platform approach to creating value projects a clear and profound impact on the consideration of design-value issues for construction as it connects end-users and production through a design-focused platform. The successful product platform development enables a continuous stream of incremental innovations by using cross-functional teams and multidisciplinary information in design and development (Ohvanainen and Hietikko, 2012). According to Suh et al. (2007), a successful product platform must be flexible to adapt changes. The author used a combination of quantitative analysis and engineering knowledge to design a flexible platform. Li et al. (2013) presents a flexible platform method by integrating the flow analysis, DSM multidimensional scaling and fuzzy clustering to obtain modular identifications.

3.5.1 Product platforms in industrialised hose building

For house-building, the main purpose of the platform is to share, visualize, and control projects in a decentralized organization where collective experience disappears or is brought forward to the next project (Styhre and Gluch, 2010). Jansson (2013) developed a framework for the continuous development and use of platforms in house building (see Figure 12). This ETO platform framework shows the combination of knowledge within the context of creativity in design work (project development) and a systematized process in a product supply chain (ibid).

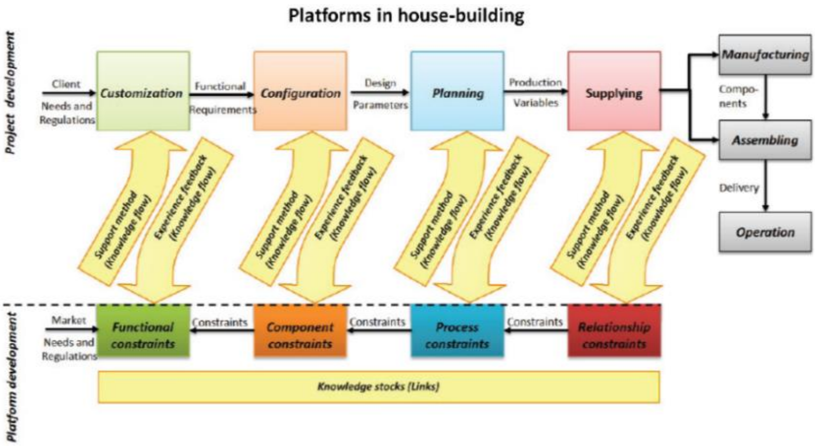

Figure 12: Use of platforms in house building (Jansson, 2013).

The product platforms have originated from the industries employing a make-to-order production approach, e.g. the automotive industry. The practice of reusing processes and technical solutions leads to the formation of product platforms in house building (Jansson et al., 2014). IHB comprises technical and process platform which is basically the technological and process related aspects to be considered during the platform development. The definition of both technical and process platform has been considered as an important step in product platform implementation. Lessing (2006) argues that a technical and process platform developed in close collaboration can emerge as a powerful and potential way to collect solutions, methods, and tools in a context where they are designed to fit together and collaborate in a system. Therefore, it is important to understand the details of technical and process platform.

Technical Platform consists of technical and modularized solutions of the building parts of various kinds e.g. structural elements, walls, roof solutions, installations, bathrooms, equipment with interfaces that allow interchangeability and parts that can be combined to create a variety of end-products. It also contains technology, such as machinery and production tools including the support of ICT tools for development.

Process Platform can be developed mainly to support the technical platform by providing an adequate definition of the main process in the company and subsequently different process modules can be developed to establish concrete process tools. The instructions, guidelines related to the production process are defined in the process platform.

3.6 Summary and research opportunity

The frame of reference provides an understanding of the IHB, the design process and the product platform approach in general. It is based on an initial selection of references to outline the area of contribution and initial identification of the research opportunity. This will establish the scope for the literature reviews as part of the underlying reference study to be done and reported in upcoming publications. From the frame of reference, it can be inferred that the existing platform theories pay limited attention to the application and use of platform-based product development in the IHB industry. The benefit and use of component-based platforms and related tools are well documented. However, the existing body of theory on how to integrate the platform approach in the design phase of an IHB process that deals with high a high level of customization is unclear. Moreover, the theory explaining how the product platform approach can be applied in the design phase of housing building using different production strategies is not well-defined. The literature review suggests an opportunity for developing a comprehensive methodology that defines the support methods and tools to manage the IHB design phase. However, to be able to implement a platform approach, the existing challenges and critical success factors should be first identified (Wuni and Shen, 2019) with an overview of existing support in the design process from a building system perspective. Therefore, this thesis aims to outline the means to support and further improve the design phase of IHB by using a product platform approach.

4. Summary and contribution of appended papers

This chapter presents a summary of empirical and theoretical findings from the four appended papers to answer the research questions. This section presents the study aim, followed by an overview of the empirical findings and results of each paper. The chapter concludes with a discussion on how the appended papers contribute to the research questions presented in this thesis.

4.1 Paper I

The objective of the work was to map the state-of-practice in the design phase for a glulam building system from a platform theory perspective and outline a path forward for a sustainable platform development where a component-based product platform does not suffice. The paper was based on interviews conducted at a Swedish multistory house building company based on glulam post and beam building system and literature review. The current state of practice and impact on the future state of the design phase has been analyzed and discussed to realize the potential of the product platform approach.

This paper corresponds and analyses the theory of platform assets presented by Robertson and Ulrich (1998) with the design process to identify the problems and understand the current state of platform definition at the case company. The results show that the current platform is not structured enough to support the stakeholders, as well as it lacks a proper definition of components and boundaries. As such, the process and knowledge assets are weak and not supported by tools leading to misalignment between the platform definition and the theory. The analysis of the state of practice shows the projects at the case company are customer-driven and thus, the company cannot develop a fully predefined and one platform system for all the offers. The interviews showed that the view and understanding of platform-based product development among the respondents appear far from the theory as they were not familiar with the term and concept of a product platform approach. The component analysis indicated that the company is limited from adopting a specific, comprehensive and same overarching production strategy as only a few components of the building system can be standardized. In fact, while some demonstrated a modular approach, others were found to either have a configured approach or some components were yet to be in ETO for customization. Therefore, an immediate application of a uniform product platform approach seems to be challenging. Though the case company has the potential to achieve high levels of product variety, better operational efficiency and faster response rates to the market need with the support of product platforms. However, this necessitates the development of additional tools and methods in the design process.

The literature review also indicates a lack of well-defined theory concerning the application of the platform approach in the IHB sector. Moreover, the existing platform theory does not fit the IHB context due to adoption challenges for companies working with a combination of production strategies. Thus, the study reveals a lack of theoretical knowledge on the suitability and robustness of the combination of different production strategies, as well as their alignment with the companies operating in the same sector as the case company. This outlines the research gap and opens a need for further studies. The results suggest that the combination of production strategies (Hansen, 2003) is better aligned with the business needs of such companies in the construction sector where some subcomponents from the building system are configure-to-order, few parts fit in modify-to-order process and rest fulfil the unique customer needs. The gap identified between the theoretical review and practice was evident in terms of design support methods of platform development.

4.1.1 Applying a conceptual product platform support

The case company is operating both with the ETO and MTO approach where customized buildings are developed. Thus, it is significant to develop their business model based on the principles of product specification process shown by Hansen (2003). Moreover, a conceptual product platform support is recommended to meet the increasing and evolving market demands of the building system (see Figure 13). The support methods, such as design planning, collaborative design, design optimization, and requirement iterations should be developed and in alignment with different design assets can significantly impact the design process (Jansson et al.,2014). Paper I concluded the requirement of more studies to improve the theoretical knowledge that defines proper strategies and methods for product platform approach and support of the design process in IHB companies.

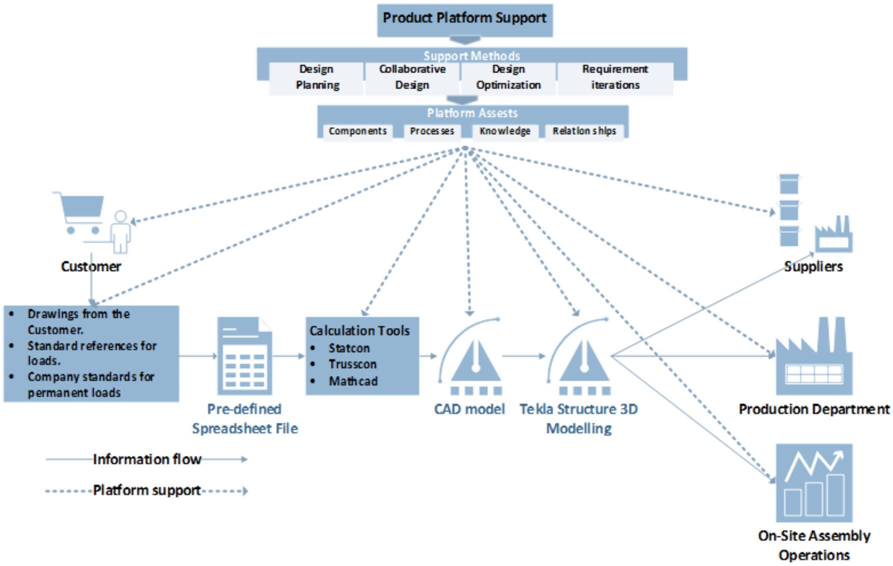

Figure 13: Platform support in the design phase.

4.2 Paper II

The purpose of this study was twofold: first to identify challenges, and second to outline the critical success factors in the design phase of IHB. In order to fulfill the aim, empirical data from three Swedish timber-based house building companies were analysed with the existing literature. This paper sought to create a greater understanding of the common challenges faced by the industry and critical success factors in the different phases of the IHB design process. A broader list of critical factors was developed by shortlisting the existing factors from literature and factors imperative during the execution of the design process from a practitioner's perspective (empirical data).

4.2.1 Challenges in the design phase of IHB

The first objective of this paper was to explore the challenges in the design phase of IHB. Several challenges in the different phases of the design process such as conceptual, system-level and detailed design were identified. The literature review shows that research provides discussions pertaining to challenges from both traditional and IHB, in general. The existing challenges in different stages of the design phase from the three case companies are presented in Table 1.

Table 1: Main challenges in the design phase articulated by the respondents from multiple case studies.

No.	Company A	Company B	Company C
1	Uniqueness in technical and functional needs from the architect and customers which lies outside the company`s BS	Customer needs for open spaces and more windows conflict with struct. design. Architect does not follow BS	Customization and develop solutions from existing the components. Fulfil demands and keep internal efficiency.
2	Late changes in design from customers results in reworks and generate wastes in process	Changes in legal regulations for energy requirement of the buildings, transportation etc.	Changes in legal regulations and late approvals, Varying market demands etc..
3	Lack of tools and checklists to plan and monitor projects.	Planning issues in managing multiple projects	Sales offers solutions outside the building system
4	Design knowledge not captured and reuse it properly	CAD and ERP systems not connected	Employee turnover and documentation of knowledge
5	Poor information flow among stakeholders and issues with communication.	Rework & issues related to information exchange/loss while updating several times	Poor information flow among stakeholders, e.g., between sales & design
6	Clash issues among installation drawings in CAD model.	Clash issues due to consultant's CAD software not working	Clash issues due to consultant's CAD software not working
7	Tools for final evaluation of drawings and details missing	Additional drawings requirements from customers	Long lead time for some components e.g. Windows
8	No formal system to collect and analyse the customer feedback	As-built drawings not updated due to poor feedback from site.	Inflexible due to fixed production and clash issues during installation works
9	No checkpoint to validate and confirm late customer changes	Cultural resistance to move towards digital way of working.	Cultural resistance to move towards digital way of working.

The empirical results confirm that the customization and distinctiveness in the product remain to be still recognized as a common challenge for all case companies. Companies generally receive unique needs from customers which in fact fall outside of the norms of the building system, leading to a trade-off in managing customization and utilizing production efficiently. The lack of geometrical standards also emerged as a common issue resulting in loss of data clarity while transferring information between systems. The case companies also lack a reinforcement of tacit knowledge (Malmgren et al., 2010) and it has been acknowledged as a common barrier. However, the studied building systems have the necessary capabilities to manage most of the challenges identified in this study with adequate support in the design process.

4.2.2 Critical Success Factors in the design phase of IHB

The second objective of this paper was to outline the critical success factors to be considered in the design phase of the industrialised house building. The factors that are crucial to consider during the design were examined from both literature and practitioner's perspective to achieve the aim of the research. An aggregation of several success factors has been listed in Table 2 and shown the possible connection between the CSF and challenges identified. The sources of data collected are also presented to give a clear picture for readers.

The literature review shows a lack of focused attention on addressing the CSF explicitly in the IHB design phase. Traditionally, for project performance evaluation, the four most cited critical factors are time, cost, quality, and safety. In addition, this study acknowledges and accounts for more critical factors. The empirical results show that fixed production is crucial to identify success factors rather than a building system. CSF varies in terms of different production settings and commonly the BS structure or framework is based on these predefined settings. However, currently, companies are limited from benefitting fully from the building system due to its inherent inadequacy to deal with the variety of challenges in the absence of necessary support. A partial alignment between CSF and challenges has been identified and these components demonstrate an association (Table 2) indicating that the intensity of challenges can be reduced by developing support for these factors. The factors such as time, cost, manufacturability, and assembly emerged to be most critical for company A, whereas, manufacturability, assembly, cost and customer requirements for company B and manufacturability, assembly, customer requirement and legal regulations for company C were identified as critical. Thus, the analysis indicates the manufacturability and assembly factors as common for all companies and most critical for IHB. This study also emphasizes the *platform based DFMA approach* to be successful in the design process. From a practitioner's perspective, it is significant to prioritize the critical factors and develop support for those factors for improvement in design efficiency. This eventually helps to develop a robust building system with better process control to meet the transforming market demands.

Table 2: Critical success factors in the design and connected challenges.

Critical factors	Description	Phase	Challenge	Source
Lead time	Time associated with different process	O	All	L, A, B, C
Cost	Cost associated with different process	O	All	L, A, B, C
Quality	Quality associated with different process	O	All	L, A, B, C
Market demands	Consideration of changing demands from different markets during the design	C	C2, C3	B, C
Customer requirements	Fluctuating and exclusive requirements	C, S	A1, B1, C1	L, A, B, C
Legal regulations	Legislations and policies from local and central municipalities	C, S	B2, C3	L, B, C
Environmental aspects	Design parameters specific for different regions, sustainability focus etc.	C, S	B2, C2	L, B, C
Cost effective materials	Cost decisions to select material and fulfil internal & external needs	C, S	B2, C2	B, C
Structural aspects	Including robust structural design to fit building function	S, D	A1, B1, C5	L, A, B, C
Technical & Functional requirements	Fulfilling technical specification, detailing and functional requirement to meet customer demands	O	A1, B1, A5, C5, A9	L, A, B, C
Flexibility	Flexibility in design strategies to meet changes for building components	O	A2, C8	L
Re-usability	Include re-usable material in building components and structures design	C, S	A4, C4	L
Modularity	Plan for modular design of component to ease prefabrication process	S, D	A1, A7	L, A, B, C
Production infl. design	Channel to exchange knowledge between people from production to designers.	S, D	A5, B8, C8	B
Manufacturing	A design approach that utilise the capability of fixed production and its constraints	O	A1, B1, C1, C7, B7, C8	L, A, B, C
Producibility	Ensure the functional properties of building and efficient production of components	S, D	A1, B1, A5, B5, A6, B6	L, A
Transportation	Approach focusing on efficient transportation of building components	S, D	B2	L, A, B, C
Safety	Safe design plans reducing risk during production and on-site assembly	O		L, A, B, C
Assembly & Installation	A design approach that focuses on efficient assembly and Installation at the site	S, D	A6, B6, C6, B8, C8	L, A, B, C
Disassembly	Approach focusing on dismantling strategies of building components during early design	S, D	A4, C4	L, A

Phases: Overall (O), Conceptual (C), System level (S), Detailed (D); Challenge and source: Table 2 (1-9) & Literature (L), Company A-C (A, B, C).

4.3 Paper III

The objective of this work was to explore the current state of the IHB system and outline specific design support solutions from a product platform approach. The unit of analysis took into account the current way of working in the design process with a special focus on the use of the building system. The paper also assessed the existing support in the design phase and challenges in the design process with the purpose to identify critical gaps and potential improvement areas. This study focuses more on a single case and the empirical data were gathered from five semi-structured interviews and two workshop sections.

4.3.1 Analysis of building system support for design with platform assets

A comparative analysis of existing building system support in the design process were conducted with the platform assets defined by Robertson and Ulrich (1998). This was mainly conducted to understand the use of design assets at the case company and their familiarity or awareness of the product platform approach. The empirical data, existing support, and tools explicitly used by designers at different stages of the design development process were examined for all study analysis purposes (see Table 3). Following this, potential platform assets were identified in alignment with the BS of the case company.

Table 3: Framework of platform assets and building system support in the design phase.

Support tools and methods in design phase	Component	Process	Knowledge	Relationships
BIM tool		X		
Structural calculation tools		X	X	
Parametric CAD modelling		X	X	
Checklist		X		
Custom component library	X		X	
Cross functional team				X
External consultant support			X	X
ERP system			X	
Cost calculation tools		X		
Mock-up for testing			X	
Clash checking		X		

From a platform perspective, the building system mainly comprises component-based assets defined with technical details and functionality of products. According to the analysis, the case company projects a weak and unstructured predefinition of process, knowledge, and related assets. Moreover, it reveals a lack of support methods for the process and knowledge asset. The analysis of the state of practise shows that the design phase has been identified as a more challenging phase. A project-based approach can be seen in the overall development. The absence of common standards for an efficient information exchange creates frequent rework with multiple iterations for projects due to the involvement of several subcontractors in the process. Moreover, the documentation of knowledge appears to be limited, indicating that the building system cannot fully serve as a comprehensive carrier of information (Söderholm, 2010). The main finding is that none of the building components can be produced as off-the-shelf solutions because the company act as a supplier of major building components and every project is unique. Therefore, standardisation of the design process and building system emerged as an imperative that can be achieved by incorporating new methods and tools to support the design work and to ensure that solutions can be easily reproduced and assembled on site.

4.3.2 Principle support solutions for the improvement of building system

As part of the platform development at the case company, a fishbone analysis was conducted to identify the root causes of various challenges in the design process. Following this, a methodology with principle solutions was developed focusing more on the design process as part of the prescriptive study phase of research. Together with the support of the participants from the company, these solutions were ranked and categorized under three main areas that need improvement (see Figure 14). The focus was on the process standardisation, front end process control, and information and communication emerged as the bottleneck in the process and relationship assets. The solutions that lead to the same goal were summarized in one section. Also, these support methods and tools can be formalized and classified into different platform assets as shown in Figure 14.

This paper also presents the results of prioritized support solution development at the case company. The architect guide and process mapping were initially prioritized solution from the final workshop. This architecture guideline was created to guide and assist architects early-on in the design process while using the building system for designing various types of multi-storey buildings and to understand the product assortment. The process mapping helps the design team to realize and visualize the opportunities for improvement in the design process.

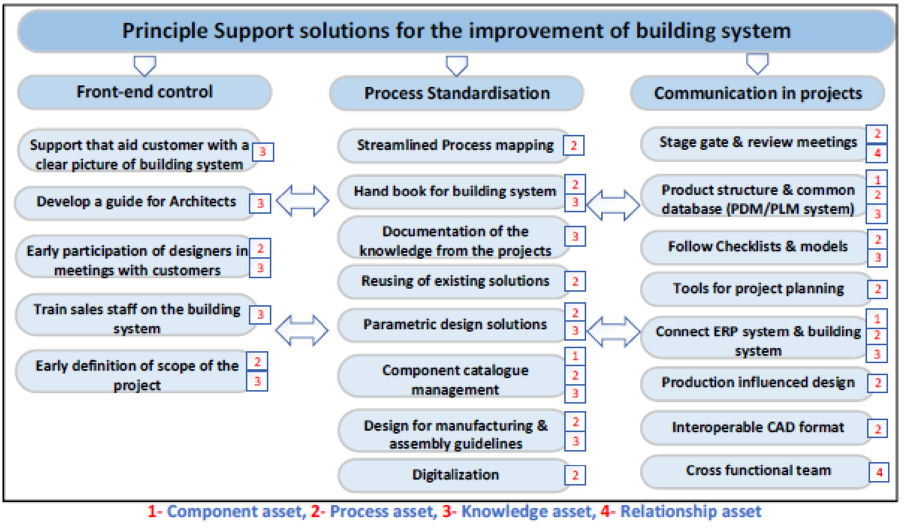

Figure 14: Methodology with principle support solutions for system improvement.

As a summary, the study verified the lack of important assets not completely described in the BS to operate as more like a product platform. The reason is the absence of several supports that are key to the design development. However, the result shows that a building system in many disciplines can be considered as a part of a product platform. The central part of the improvement solutions underscores the process aspects. The development of the building system in terms of different assets can be safely deemed to align with the platform development defined by Robertson and Ulrich (1998). Moreover, the findings reported in this article align with the three capabilities of mass customization presented by Salvador et al. (2009) such as solution space development, robust process design, and choice navigation. Correspondingly, two possible options are recommended to increase the efficiency of the IHB design process. Firstly, companies need to pre-define the main building components at a different level. Secondly, they must develop support methods and tools that can help generate solutions if the first option is not possible. Additionally, more support in the design would eventually increase the flexibility of the building system where it can effectively respond to uncertainties.

4.4 Paper IV

This paper continues to build on the support presented in Paper III with a detailed application and further development of solutions. Thus, the objective of this paper was to apply parametric modelling in the design process of steel connectors used in the building system as part of a flexible product platform development for increased design and production efficiency. A single case study has been carried out with a Swedish multi-storey house building company using glulam post and beam system. Connectors have ETO characteristics and currently, limited support is available to streamline the design and it is challenging to reuse variants within and across the projects. These constitute the challenging components of the existing platform and manual modelling is time-consuming and prone to errors. As such, the company needed efficient support to improve productivity in the design process.

4.4.1 Application of parametric modelling in the bracket connection

For the application of parametric modelling, bracket connection was chosen as the experimental object. The main goal was to enhance the current way of connectors' design and improve the ability to respond quickly (Jabi, 2013). This study adopted coding and testing of the algorithm for modelling as the two primary steps during the prescriptive stage of DRM. In the first phase, programming the parametric algorithm was performed for the brackets in a visual studio. The parameters were defined with rules, constraints, dependencies, and boundary conditions. The coding began with defining all the standard parameters and their respective dimensions as in the table shown in Figure 15. Following this, plates were added to different coordinates. The different holes and details of screws that should generate in the plate were specified. Finally, the cutting of the beam was defined to ensure that the beam was properly seated in the bracket.

	Parameters	Dimensions
1	Material grade of plate	S355J0
2	Number of screws in primary element	24
3	Number of screws in secondary element	24
4	Tolerance of glulam width	2 mm
5	Tolerance of glulam length	5 mm
6	Dimension of screw in primary element	WFD 8 X 100
7	Dimension of screw in secondary element	WFD 8 X 70
8	Option : Predrilling	Yes
9	Option : Sub-assembly	Yes
10	Thickness of plates	5 mm
11	Minimum edge distance : Parralel to grain	80 mm or 7 times diameter of screw which comes higher
12	Minimum edge distance : Perpendicular to grain	25 mm or 3 times diameter of screw which comes higher
13	C to C distance of screws : Parralel to grain	5 times diameter of screws
14	C to C distance of screws : perpendicular to grain	4 times diameter of screws
15	Coating	Galvanised / Clear coat
16	Option: Reccessed in secondary beam	Yes, 3 sides
17	Bending radius	2 mm

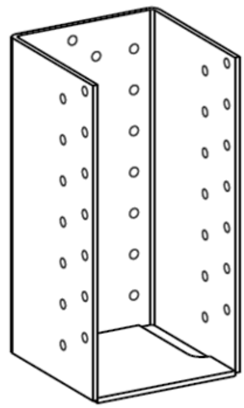

Figure 15: Standard parameters and dimensions for bracket connection.

The second stage was the testing phase and the use of the algorithm in the BIM environment. There are four steps to follow when using parametric modelling in BIM, 1. Select the primary member, 2. Select the secondary member, 3. Add the number of screws in the primary and secondary members, 4. Select the type of screws. These parameters served as the input values provided in a dialogue box, as shown in Figure 16.

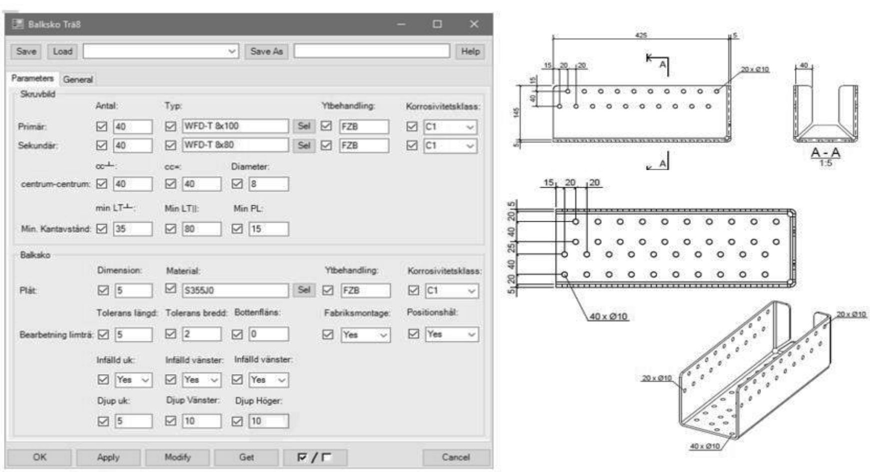

Figure 16: Parametric representation of bracket connection.

The results show that design automation facilitates easy and fast modelling of connectors and ensures producibility (Elgh, 2007). The same connector variants can be generated in different parts of the building in case the beam size is the same. The rules are characterized to allow for easy adaption, saving the designers time and effort of re-designing the same connectors. Design flexibility can be achieved with the support of the parametric modelling approach as the algorithm would take care of more advanced geometry entailed in the different bracket connections (Suh et al., 2007). The analysis shows that the parametric modelling can be related to a platform theory explained by Meyer (1997), from which a stream of different variants of connectors can be developed and produced with an emphasis on the knowledge assets defined by Robertson and Ulrich (1998). Flexibility in connector design has been demonstrated to rapidly generate solutions in delivering both predicted and unpredicted needs (Suh et al., 2007) which results in the formation of a flexible building system. Herein, by predefining the knowledge assets and establishing the standard execution process, different bracket variants can be derived from the same platform. This study presents the development of a flexible product platform with parametric modelling that can be subsequently used to design building components having engineer-to-order characteristics. The paper concluded that the parametric modelling is a promising design automation tool provides a path forward to improve the design process and offer a flexible building system to generate customized building components.

4.5 Contributions of the appended papers

Paper I and II were more oriented towards understanding the current state of practice and challenges while paper III and paper IV were more focused on the study aims and defining a future state. The first paper was more exploratory of the concept, understanding the current situation and providing clarification of research direction with a single case. The second paper was comprehensive and carried out a cross-case analysis with three involved companies to explore the existing challenges and identify CSF in the design phase. This paper provides a clear understanding and a general view of challenges and CSF in the design phase of the IHB industry. The third paper was a detailed study of the design phase including the mapping process and outline support solutions towards improving the current state of the design development process. Finally, the fourth paper was also a detailed study on a building component with the application of one of the selected solutions from the previous study for adding more efficiency to the design process.

The contribution of the appended papers is shown in Table 4.

Table 4: Contributions of the appended papers to the research questions.

Papers	**RQ1:** What are the state of the art and current practices in the design phase of the industrialised house building industry when using a product platform approach?	**RQ2:** What are the challenges and critical success factors that should be considered in the design phase of the industrialised house building?	**RQ3:** What means can be used to support the design phase of industrialised house building when introducing a product platform approach?
Paper I	**X**		
Paper II		**X**	
Paper III	X	X	**X**
Paper IV			**X**

X- Major contribution & X- Minor contribution

Paper I- Major contribution to answer RQ1

Paper I contributed to RQ1 by exploring the state of the art, understanding of current practices and defined the use of product platform approach in the design phase. Moreover, this paper outlined the absence of theoretical knowledge that defines the principles to be considered by IHB companies when introducing a product platform approach.

Paper II- Major contribution to answer RQ2

Paper II contributed to RQ2 by identifying the general challenges from the IHB industry and by outlining the critical success factors in the design phase of the IHB process.

Paper III- Major contribution to answer RQ3 and minor contribution to RQ1 and RQ2

Paper III mainly contributed to RQ3 by outlining a methodology with new support tools and methods to improve the current state of the IHB design process. Moreover, the paper also contributed in small capacity to RQ1 and RQ2 in terms of design mapping and analysing the existing building system support in the design process and provided an overview of the magnitude of the design challenges.

Paper IV- Major contribution to answer RQ3

Paper IV contributed to RQ3 by introducing a detailed support development in the design process. A computer-supported tool was developed as part of this study with the help of a company representative, as well as a flexible product platform to support the design process of IHB.

5. Discussion

In this chapter, the findings from the appended papers of this thesis are discussed in relation to the three research questions and followed by a discussion of research method. This is followed by the discussion of the scientific and industrial contribution made by this study. The chapter ends with the presentation of the limitations of this research.

5.1 Discussion and answering research questions

The practice of using platform approach in product development is well known and has been considered as a successful approach applied in many industries. The use of the platform has gained attention in research focusing on IHB industry as well. However, the concept requires more attention in the application and use in order to gain the full advantages in the design phase of the IHB sector. Therefore, the research underlying this thesis aims to outline the means to support and improve the design phase of IHB by using a product platform approach. Also, the research contributes to enriching the existing knowledge bank regarding essential and priority aspects to ensure competitive advantages. This is an important step to plan the implementation of improvement and development activities. The product platform concept offers a broader definition in the context of studies conducted. In this work, the product platform approach is discussed from the viewpoint of platform assets defined by Robertson and Ulrich (1998) as part of the platform development.

This thesis as a whole aim to answer three research questions for all study purposes and this chapter discusses and connect the results obtained from the study.

5.1.1 Research question 1

What are the state of the art and current practices in the design phase of the Industrialised house building industry when using a product platform approach?

The first RQ1 aimed to provide a better understanding concerning the use and definition of product platform in the IHB design phase. Also, it explores the current practices in design execution. Paper I provided an overview of the design by mapping the process involved and Paper III thoroughly analysed the existing support tools and methods used by the designers to execute different projects. The results used to answer this question from Paper I and III are mainly gathered from a literature review and semi-structured interviews at a single case company.

The state of practice concerning the design process is presented in Section 4.1. The result summarizes that the application of a component-based platform approach is not feasible for the case company, primarily attributed to the high customization in product and complexities in product development (Johnsson, 2013). This is evident in high uncertainties in the design process as the designers are constantly working with unique projects, necessitating the management of several requirements. Thus, from a designer's perspective, the design phase can be considered as a puzzle, especially in terms of the conceptual and system-level design phases. Correspondingly, solving a puzzle requires a clear goal and adequate support to deliver appropriate solutions. The design phase comprises three stages i.e., conceptual phase, systems design, and detailed design (Mukkavaara, 2018). However, the involvement of designers in the first phase is relatively less as the idea conceptualisation of the building is mostly done by the customers. Currently, most of the processes in the design are not supported by appropriate methods and tools. The result from Paper I provided a general overview of platform assets defined by Robertson and Ulrich (1998) in the design process. Additionally, a deeper analysis of these assets as presented in Paper III help to understand the state of the art regarding the use of the product platform approach. This study justifies the lack of key design assets that are not completely described in the BS to operate as more like a product platform. Currently, the use of process, knowledge and relationship assets projects an unstructured and weak framework or model lacking several important parts of platform-based development.

Paper I also identified that the company is functioning both with a combination of an ETO and MTO with a partially defined component-based platform (Hansen, 2003). However, extensive engineering works are warranted for most of the projects to demarcate the characteristics of building system to be ETO based (Gosling and Naim, 2009). This finding was also supported by Paper III, with the design process mapping. It confirms that a combination of production approach is better suited for the case company (Hansen, 2003; Winch, 2003). The deeper analysis of the building system conducted in Paper III reveals that the predefinition of building components to different levels would benefit the standardisation of process and product structuring (Lessing, 2015). This would enable the company to reuse the knowledge for informed decision-making in the robust process design capabilities (Salvador et al., 2009). The research gap analysis outlined in Paper I indicate the lack of knowledge concerning the use of product platform for companies having a combination of production strategies. A good definition of platform assets defined by Robertson & Ulrich (1998) and support methods described by Jansson et al. (2014) together constitute a path forward for sustainable platform development for the case company. Also, platform development requires the introduction of adequate support tools and methods in the design process. Correspondingly, when using a platform approach in IHB projects, design support methods are essential for day-to-day engineering work (ibid).

5.1.2 Research question 2

What are the challenges and critical success factors that should be considered in the design phase of the Industrialised house-building?

The RQ2 aimed to identify the existing challenges in the design process of IHB and to increase the understanding regarding critical success factors (CSF) in the design process. CSF here refers to the important aspects to be necessarily considered in the process (Rockart, 1980). Designers need to adopt a systematic view of essential aspects to be considered in the different design phases, such as conceptual, system-level and other corresponding processes. The challenges and critical success factors were examined with the help of Paper II and the data for CSF evaluation was obtained from interviews with designers from three IHB companies.

As mentioned earlier, the results used to answer the RQ 2 were obtained from three companies working with different building systems and a literature review. The challenges identified from the individual case companies are presented in Section 4.2.1. Paper II examined the challenges faced by the designers in different design phase stages. Customization and distinctiveness in products were found as a common challenge faced by the IHB industry (Jansson, 2010) with companies constantly striving to align requirements with pre-defined BS settings. The lack of a complete understanding of the offerings among salespeople was discussed in the interviews with a focus on their significance (Söderholm, 2010). Apart from these, the common challenges faced by the industry are the strict legal regulations (Larsson et al., 2014), use of inoperable CAD systems by stakeholders (Andersson and Lessing, 2017), poor information flow (Hjort et al., 2014), minimal documentation of knowledge (Malmgren et al., 2010) and systematic reuse of process. The analysis indicates that the challenges are not unique or specific to a particular company, but evident as a general issue across the IHB industry. However, the challenges identified from this study could be managed by developing a platform-based product development approach with support tools and methods in the design phase. The study reveals extensive efforts made in the design process of companies for improving the general maturity level in IT systems by introducing more digitalization, reusing of process and knowledge, formalizing the building system to be more flexible and adapt to changes. This shows that the implicit development of the platform approach is a continual process in these companies.

The CSFs study functions as a means for improving the effectiveness of the current state of the process (Chan and Chan, 2004). The CSF scrutinized in this paper is listed in Section 4.2.2 and demonstrates its connection with the challenges identified. The literature review shows that the investigation and evaluation of CSF in the IHB process has not been studied thoroughly and less attention has been paid explicitly to the design phase. Moreover, for the IHB process, the CSFs demonstrates a recent shift from the performance indicators such as time, cost and quality aspects to a broader list of success factors (Halttula et al., 2017). From a practitioner's perspective, it is recommended to identify few CSFs in the design process by involving the experienced designers. Then, the factors should be prioritized and develop individual support for each factor for improvement in the current design process (Wuni and Shen, 2019). Herein, the designers can use these developed supports as a decision-making support tool or evaluation tool while providing solutions for different requirements. The critical factors identified from this study are broad with focused as well as multi-dimensional views.

This study infers settings of partially or fixed production possess by a company as the key element for identifying the CSF. Thus, CSF in the design process for IHB may not change over time, unless there is any alteration for production which is not the case for the traditional construction process. A cross-case analysis shows that manufacturability and assembly factors were identified as common CSF for all case companies (Yuan et al., 2018). This implies that those factors are key to the IHB process with dedicated support. For example, the DFMA approach would be required for an effective IHB design. DFMA approach not only helps to reduce cost and lead time but also increases the quality and safety aspects (Gerth et al., 2013). However, these factors were less highlighted in the theory and the designers interviewed as part of the study were found to be less aware of these factors. Most of the CSFs scrutinized in this study were found to align with the factors researched in the existing literature. However, production influenced design was acknowledged as an important aspect by Company B and basically serves as a channel to exchange key knowledge between production and design.

The factors identified in the study have been used by the designers in their daily work. However, the factors continue to lack a systematic refinement or assessment to offer full advantage of its application in the process. As a conclusion, to achieve higher efficiency in the design process, IHB companies rigorously need supporting tools and methods aligned with these critical factors that improve the technical and process platform (Jansson (2013).

5.1.3 Research question 3

What means can be used to support the design phase of the industrialised house building when introducing a product platform approach?

The RQ3 aimed to address tools and methods in supporting the design phase when using a product platform approach. This was fulfilled by conducting two different studies showcased in Paper III and Paper IV. These findings were mainly used to answer this research question and accomplish the study aims. The RQ1 and RQ2 indicate the implicit working of the case company with the platform approach in the design process. Besides, the RQ3 mainly explores the expansion and explicit development of support for the design to achieve the improved state of platform development. A methodology was developed from paper III and presented in Section 4.3.2. This study was undertaken in the prescriptive research section, with the support of findings collected from a workshop conducted with the designers and management team at the case company. Additionally, Paper IV presents a more detailed support development for the design process and findings were mainly gathered from a workshop section and semi-structured interviews presented in Section 4.4.1.

The literature review in this thesis presents several explanations and theories pertinent to the use and implementation of the product platform. However, the application of platform theory introduced by Robertson and Ulrich (1998) is more suitable for the platform development at the case company. This is because the case company referred to in this study leverages a combination of strategies with predominantly unique requirements from the customer (ETO characteristic), where only a few building parts meet the criteria for configuration or modularization approach. For instance, the theory explained by Hvam et al. (2008) is not completely applicable to this case and can be considered more as a subset of the platform approach. It can be applied for specific cases where companies can predefine the building components that can be configured into different solutions to meet customer requirements, for example, standardised module houses.

The results from the papers indicate the possibility and potential for the implementation of the platform approach at the case company. Paper III presents the expansion of a building system into a product platform for improved design and manufacture of building components. Here the existing building system support in the design process was analysed within the context of platform assets (Robertson and Ulrich, 1998) to identify the potential improvement opportunities. This is followed by the development of principle support solutions to improve the current state of the design process as part of platform development at the company. This process showcases continuous improvement of the design process by strengthening the capability of both technical and process platforms of the BS. In the implementation phase, the solutions have been ranked and grouped under three main areas for improvement, together with the support of the workshop participants. A project team was also formed as part of the study to manage and implement these solutions and realistically implement platform development. Consequently, improvement activities targeting the front-end control and process improvement were started. Firstly, the architect guide was established to guide the external architects by including the details and use of components.

This support enhanced the knowledge asset of a building system setting a standard in the early design, followed by detailed mapping of the design process for improved visualisation of improvement opportunities by designers. At the core of the product platform approach lies the predefinition of assets, particularly processes.

Paper IV presents a computer-supported tool development with the support of the designer at the case company. It presents the use of parametric modelling approach in designing building components having engineer-to-order characteristics and flexible product platform (Suh et al., 2007). It highlights the advantage of a rule-based approach and enables design automation to reduce the time and cost in addition to ensuring higher quality (Lee Hansen and Vanegas, 2003, Eastman et al., 2009). Parametric approach results in a scalable platform (Simpson et al., 2014). However, a fully parametrised platform is unlikely to be realised due to the complexities in design. These supports developed in the design would eventually increase the flexibility of the building system where it can effectively respond to uncertainties (Suh et al., 2007). A flexible platform can quickly and efficiently respond to changing market needs (Li et al., 2013).

5.2 Discussion of research approach and quality

The DRM framework provides guidance and the overall steps concerning how to conduct research in the design field. This framework underscores the systematic approach adopted by the researcher in following a step-by-step process for performing the research. The basic means and main outcomes of each stage are presented in the paper for easy reference and comparison with results derived in existing or future studies. In this applied research, the methodology is concerned with developing methods and tools for supporting the design process. A case study approach was adapted in each stages of DRM, for instance, three single case study and a multiple case study were conducted to complete a cycle of DRM framework. However, the evaluation part of the DSII stage only entailed an initial evaluation. The first and second studies in the initial two stages were explorative to gain knowledge about the current situation, challenges, and critical factors. These comprise the Descriptive Phase I outcomes according to the framework (Blessing and Chakrabarti, 2009). The third and fourth studies were comprehensive studies to outline support solutions, as well as assess one of the solutions in detail. The second study entailed an evaluation of three cases with different building systems to develop a comprehensive and broad understanding of challenges and CSF in the design phase of IHB.

The main case company for this research possess a post and beam-based building system where requirements are unique and have an ETO nature. The main difference between the case companies entailed in this research is that while two companies offer a complete solution, the main case company acts as a supplier of main building components for multi-storey wooden house buildings. The ambition of the company was to adopt a more industrialised approach and cater to transforming market demands by offering a complete solution to ensure optimal efficiency in the design process reducing lead time and costs. The results show that introducing a product platform approach in the design process is the way forward to becoming more efficient and successful in the IHB market. This study presents corroborating inferences with existing theories while concurrently providing a modified theoretical explanation of the phenomenon found in the studied cases (Yin, 2014). The existing design process and support were investigated to describe and relate them with the existing product platform theories and develop knowledge derived from the study cases.

The validation and verification of these developed methods, models, and tools should be performed in their intended settings (André, 2019). The methods and tools developed as part of this research were iteratively shown and discussed with the designers at the case company. Moreover, the designers were actively involved in most studies. To further strengthen the research quality, the paper explored different factors described in Section 2.3 in Chapter 2. The construct validity of this research was achieved by analysing and evaluating the multiple sources of data from different respondents, in terms of method triangulation and source triangulation (Williamson, 2002). For the studies, different respondents from the same company were interviewed and different data collection methods were used, such as interviews, workshops, document analysis (Karlsson, 2010). Moreover, the study results were presented to the participants for clarity of all study purposes. Triangulation by using more than one method of data collection helped achieve internal validity in this research (Voss, 2010). Additionally, informing all participants about the research study aims for each paper also increased the internal validity (Karlsson, 2010). Moreover, the relationships between empirical data and previous research were discussed in studies. The external validity of this research is limited as single case study was steered for several investigations (Voss, 2010). Thus, making it difficult to achieve the generalizability of findings. However, for the second study, a multiple case approach was adopted to increase the generalization of obtained results. For instance, multiple case studies were conducted in Paper II. Apart from that, the assessment of the applicability of results obtained from other papers (Paper I, II, III) is applicable in some cases to improve the generalization of the result. In order to increase the reliability of this research, proper documentation was implemented for all the supporting empirical data and materials, such as interview recordings, transcribed data and analysed documents (Yin, 2014). A case study database was created by including the data related to the summaries of each case, cross-case analysis to support transparency in the research process and to improve the research reliability (Williamson, 2002).

Ethical norms are imperative for planning and conducting research activities. The research predominantly takes into consideration the key research ethics principles proposed by Bell et al. (2018), i.e., the informed consent, principles of no harm of participants, and respect of privacy. The objectivity mainly focuses on the representation or strive for honesty in all scientific communications. All research papers maintained objectivity by honestly reporting the data, results, methods, and procedures. It also emphasizes the prevention of bias in data collection, analysis, and writings, as well as the other aspects, related to the research for ensuring objectivity. The authorship of the research study and its results are in accordance with the regulations of the research world. The criteria, such as scientific contribution and responsibility acceptance were the two necessary aspects to qualify. The misconducts such as fabrication of data or results related to the research, falsification of research materials, records or processes and plagiarism were avoided not only during the study but also during the paper production and publication. Also, the researcher ensured creativity and flexibility in writing and reporting. The papers and publications as part of this research study feature open access in order to facilitate public sharing of the knowledge and understanding gained from the studies.

5.3 Scientific and industrial contribution

The research presented in this thesis contributes to increasing knowledge in the spheres of science and the industry. From a scientific perspective, this research offers a verily current understanding of the present time challenges while equitably highlighting the importance of success factors in the IHB design phase (Paper II). The scientific contribution includes the addition of knowledge to the platform theory in general, as well as its application, on the design phase of IHB. This work identifies a lack of theoretical knowledge in this field regarding the robustness of combined production strategies and corresponding applicability to IHB companies (Paper I). The contribution of this research widens the theoretical field of the use of the product platform approach in an ETO context while expanding the advantage of developing support methods and tools for design work improvement in customized requirements. Moreover, the results (Paper III) show the relevance of expanding a building system to a product platform improving design efficiency. In addition, the results (Paper IV) demonstrate the development of a flexible product platform with a rule-based approach to facilitate design automation generating customer-specific building components.

From an industrial perspective, this research provides an enhanced and improved understanding of the product platform theory in the IHB industry. Generally, for the IHB sector, this study contributes to expanding the knowledge of the product platform approach and its application in the design process towards augmented productivity. The case company has been directly involved in several studies as part of this research, learning the importance of the platform assets (Robertson and Ulrich, 1998) and their use in the design process towards being considered a design asset. The company was also provided with a methodology including support solutions for improving the current state of the design process. Moreover, the study conducted a demonstration of potential methods and tools (Paper III) used in the design phase when applying a product platform approach. In general, the research sheds valuable insight into critical success factors for the design process by identifying potential challenges and improvement opportunities (Paper II). The established methodology can be used as a decision-making tool by the designers for developing solutions and improving the current state of building.

These tools serve as operational support for daily works and help to develop diverse solutions meeting the changing market demands.

5.4 Limitations

This research focuses on the design phase of the IHB using timber in Swedish construction sector. Other countries working with the development of an industrialised building can leverage the current study results, with caution towards findings specific to the Swedish construction sector. As mentioned earlier, the CSF is dependent on the production system of the company and hence, the development of support for designing is based on the factors identified. The empirical studies in this research were performed at a particular case company, working with a post and beam type of building system, thus highlighting the findings' dependability on the post and beam system. However, other types of building systems were also considered for answering RQ 2 with the help of Paper II.

The research presented in this thesis mainly utilised case study methodology and literature reviews. The research Papers I, III, and IV which contributed to answering RQ 1 and RQ 3, employed a single case study and corresponding literature review. As such, the generalization of findings can be considered limited in certain contexts. However, the literature review of previous studies was used to answer the RQs in the successful completion of accomplishing specified study aims. In Paper III, only management and challenges concerned with supports have been presented for the analysis of building system support for design with platform assets. Moreover, the study is limited from presenting a discourse on quantitative analysis concerning the current robustness of each support.

6. Conclusions

This chapter summarizes the development of platforms and their corresponding uses for industrialised house building, with proposals indicating further research in the field.

This thesis presents the preliminary findings aimed to outline necessary means towards supporting and improving the design phase of the Industrialised house building by using a product platform approach. The result obtained from this study supports the development activities entailed in the implementation of the platform approach in industrialised house construction.

The following section presents summarized points derived from the study inferences:

- The direct application of the traditional component-based product platform approach is not optimally applicable in IHB design. This can be attributed to the fact that the customer requirements predominantly demonstrate an inclination towards ETO characteristics.
- For some companies in IHB, a complete solution is developed through leveraging a combination of predefined, modified, and engineered systems and components. As such, a combination of production strategies, such as CTO, MTO, and ETO might suit better and aligned to solution development.
- There is an evident lack of theoretical knowledge concerning the use and application of the product platform approach in IHB-based companies working with the combination of production strategies.
- The current housing industry challenges have been discussed from literature, as well as practitioner's perspectives, which is crucial before the development and implementation of the platform approach.
- Paper II presents 20 critical success factors that need to be considered by designers during the different development stages of design.
- This research discusses the importance of manufacturability and assembly factors and highlights the research need on the DFMA approach in the IHB design process.

- The results show that a building system can be considered as part of a product platform in light of the necessity of an adequate support in the design process to maintain a sustainable platform.
- The methodology developed for the design process is a way to realize the implementation of the platform-based product development in IHB company to reduce the lead time and cost.
- The support solutions reinforce the capabilities of technical, as well as process platforms, resulting in continuous improvement of the design process and building system.
- A flexible product platform can be developed through parametric modelling and to design building components featuring engineer-to-order characteristics.
- The application of parametric modelling can potentially automate the design process of custom components, further increasing the design efficiency in the IHB.
- The principle solutions in combination with established methods and tools are in line with the platform assets, as defined by Robertson and Ulrich (1998). Therefore, the implementation of the platform approach is recommended to support the design process of IHB.

6.1 Future research

This thesis aimed to outline means to support and improve the design phase of industrialised house building by using a product platform approach. Also, to increase the understanding of different factors necessary for using a platform approach in the IHB sector. The results achieved are mainly based on a single case company. Hence, additional comparative (with current study findings) empirical studies focusing on the IHB industry can necessarily broaden relevant knowledge. Thus, the applicability of the methodology developed from this study can be tested in multiple and disparate building systems to verify how well it aligns with various design settings. Moreover, developing individual support for the solutions listed (Paper III) to improve the different platform assets connected to building systems can serve as underlying principles for future studies from an industrial perspective. The results obtained from Paper IV reveal the significance of the parametric modelling approach to designing lead time. Therefore, the case company can generate algorithms for different types of connectors used in building systems for a significant impact on design improvement. Furthermore, investigations involving different critical success factors of the design process and the development of individual support for these factors could be considered for future studies. Some of the interviews indicated the importance of the DFMA approach in the design process opening up a potential opportunity to explore newer avenues in the IHB context. Future research should, therefore, focus on the development of a framework by combining the product platform to develop a platform-based DFMA approach in IHB as a support for the design process.

7. References

Alkahlan, B.S., 2016. *Integrated Design and Manufacturing [IDM] Framework for the Modular Construction Industry* (Doctoral dissertation, Virginia Tech).

Andersson, N. & Lessing, J. 2017. The Interface between industrialized and project based construction. *Procedia Engineering,* 196**,** 220-227.

André, S. 2019. *The Design Platform Approach–Enabling platform-based development in the engineer-to-order industry.* Jönköping University, School of Engineering.

Bell, E., Bryman, A. & Harley, B. 2018. *Business research methods*, Oxford university press.

Blessing, L. T. & Chakrabarti, A. 2009. *DRM: A Design Reseach Methodology*, Springer London.

Bonev, M., Wörösch, M. & Hvam, L. 2015. Utilizing platforms in industrialized construction. *Construction Innovation,* 15**,** 84-106.

Boverket 2014. Svenska byggkostnader i en internationell jämförelse & Myndigheten för samhällsplanering byggande och boende. 1 ed.: Boverket, Publication Service.

Boverket 2016. Reviderad Prognos Över Behovet Av Nya Bostäder Till 2025 [Uppdated Forecast of the Need for New Accomodation by 2025]. Boverket.www.boverket.se

Brege, S., Nord, T. & Stehn, L. 2017. *Industriellt byggande i trä-nuläge och prognos mot 2025*, Linköping University Electronic Press.

Brege, S., Stehn, L. & Nord, T. 2013. Business models in industrialized building of multi-storey houses. *Construction Management and Economics***,** 1-19.

Cederfeldt, M. and Elgh, F., 2005. Design automation in SMEs–current state, potential, need and requirements. In *DS 35: Proceedings ICED 05, the 15th International Conference on Engineering Design, Melbourne, Australia, 15.-18.08. 2005*.

Chan, A. P. & Chan, A. P. 2004. Key performance indicators for measuring construction success. *Benchmarking: an international journal,* 11**,** 203-221.

Denscombe, M. 2014. *The good research guide: for small-scale social research projects*, McGraw-Hill Education (UK).

Eastman, C., Lee, J.-M., Jeong, Y.-S. & Lee, J.-K. 2009. Automatic rule-based checking of building designs. *Automation in construction,* 18**,** 1011-1033.

Eastman, C., Teicholz, P., Sacks, R. & Liston, K. 2011. *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*, John Wiley & Sons.

Ekholm, A. and Wikberg, F., 2008, September. Design with architectural objects in industrialised house-building. In *eWork and eBusiness in Architecture, Engineering and Construction, Proceedings of the 7th European Conference on Product and Process Modelling (ECPPM) 10-12 September* (pp. 213-22).

Elgh, F. 2007. *Computer-supported design for producibility: principles and models for system realisation and utilisation.* Chalmers University of Technology.

Eurostat 2020. House price index – annual data (available online *http://bit.ly/2gIGfx4*).

Gerth, R., Boqvist, A., Bjelkemyr, M. & Lindberg, B. 2013. Design for construction: utilizing production experiences in development. *Construction Management and Economics,* 31**,** 135-150.

Gosling, J. & Naim, M. M. 2009. Engineer-to-order supply chain management: A literature review and research agenda. *International Journal of Production Economics,* 122**,** 741-754.

Haller, M., Lu, W., Stehn, L. & Jansson, G. 2015. An indicator for superfluous iteration in offsite building design processes. *Architectural Engineering and Design Management,* 11**,** 360-375.

Halman, J. I. M., Hofer, A. P. & Van Vuuren, W. 2003. Platform-Driven Development of Product Families: Linking Theory with Practice. *Journal of Product Innovation Management,* 20**,** 149-162.

Halttula, H., Haapasalo, H., Aapaoja, A. & Manninen, S. 2017. Early Involvement and Integration in Construction Projects: The Benefits of DfX in Elimination of Wastes. *International Journal of Management, Knowledge and Learning,* 6**,** 215-237.

Hansen, B. L. 2003. *Development of industrial variant specification systems.* IKON Tekst & Tryk A/S.

Hjort, B., Lindgren, J., Larsson, B. & Emmitt, S. Success factors related to industrialized building in Sweden. *CIB International Conference on Construction in a Changing World,* 2014.

Höök, M., 2005. *Timber volume element prefabrication: production and market aspects* (Doctoral dissertation, Luleå tekniska universitet).

Höök, M., 2008. *Lean culture in industrialized housing: a study of timber volume element prefabrication* (Doctoral dissertation, Luleå tekniska universitet).

Höök, M. & Stehn, L. 2008. Applicability of lean principles and practices in industrialized housing production. *Construction management and Economics,* 26**,** 1091-1100.

Hvam, L., Mortensen, N. H. & Riis, J. 2008. *Product customization*, Springer Science & Business Media.

Jabi, W. 2013. *Parametric design for architecture*, Laurence King Publishing.

Jansson, G., 2010. *Industrialised housing design efficiency* (Doctoral dissertation, Luleå tekniska universitet).

Jansson, G., 2013. *Platforms in industrialised house-building* (Doctoral dissertation, Luleå tekniska universitet).

Jansson, G., Johnsson, H. and Engström, D., 2014. Platform use in systems building. *Construction Management and Economics*, *32*(1-2), pp.70-82.

Jansson, G., Söderholm, E. and Johnsson, H., 2008. Design process organisation at industrial house builders: a case study of two timber housing companies in Sweden. In *Annual ARCOM Conference: 01/09/2008-03/09/2008* (Vol. 1, pp. 135-144). Association of Researchers in Construction Management.

Jensen, P., 2010. *Configuration of modularised building systems* (Doctoral dissertation, Luleå tekniska universitet).

Jensen, P., 2014. *Configuration of platform architectures in construction* (Doctoral dissertation, Luleå tekniska universitet).

Jensen, P., Olofsson, T. & Johnsson, H. 2012. Configuration through the parameterization of building components. *Automation in Construction,* 23**,** 1-8.

Jiao, J., Simpson, T. & Siddique, Z. 2007. Product family design and platform-based product development: a state-of-the-art review. *Journal of Intelligent Manufacturing,* 18**,** 5-29.

Johnsson, H. The building system as a strategic asset in industrialised construction. Nordic Conference on Construction Economics and Organisation: 13/04/2011-15/04/2011, 2011. Danish Building Research Institute, Aalborg University, 541-552.

Johnsson, H. 2013. Production strategies for pre-engineering in house-building: exploring product development platforms. *Construction Management and Economics***,** 1-18.

Jonsson, H., 2017. *Production Strategy in Project Based Production within a House-Building Context* (Vol. 1892). Linköping University Electronic Press.

Karim Jallow, A., Demian, P., N. Baldwin, A. & Anumba, C. 2014. An empirical study of the complexity of requirements management in construction projects. *Engineering, Construction and Architectural Management,* 21**,** 505-531.

Karlsson, C., 2010. Researching operations management. In *Researching Operations Management* (pp. 20-55). Routledge.

Khalili-Araghi, S. & Kolarevic, B. 2020. Variability and validity: Flexibility of a dimensional customization system. *Automation in Construction,* 109**,** 102970.

Kudsk, A., Hvam, L., Thuesen, C., Grønvold, M. O. B. & Olsen, M. H. 2013. Modularization in the construction industry using a top-down approach. *Open Construction and Building Technology Journal,* 7**,** 88-98.

Larsson, J., Eriksson, P.E., Olofsson, T. and Simonsson, P., 2014. Industrialized construction in the Swedish infrastructure sector: core elements and barriers. *Construction Management and Economics*, *32*(1-2), pp.83-96.

Lee, G., Sacks, R. and Eastman, C.M., 2006. Specifying parametric building object behavior (BOB) for a building information modeling system. *Automation in construction*, *15*(6), pp.758-776.

Lee Hansen, K. and Vanegas, J., 2003. Improving design quality through briefing automation. *Building Research & Information*, *31*(5), pp.379-386.

Lennartsson, M., 2009. *Modularity in industrialised timber housing: a lean approach to develop building service systems* (Doctoral dissertation, Luleå tekniska universitet).

Lessing, J., 2006. Industrialised House-Building: Concept and processes, Licensiate thesis. *Lund: Lund University*.

Lessing, J., 2015. *Industrialised House-Building-Conceptual orientation and strategic perspectives* (Doctoral dissertation, Lund University).

Lessing, J. & Brege, S. 2015. Business models for product-oriented house-building companies – experience from two Swedish case studies. *Construction Innovation,* 15**,** 449-472.

Li, Z., Cheng, Z., Feng, Y. & Yang, J. 2013. An integrated method for flexible platform modular architecture design. *Journal of Engineering Design,* 24**,** 25-44.

Lindblad, F. 2019. Market development barriers for the Swedish wooden multi-family house industry. *International Journal of Engineering and Technology,* 11**,** 187-195.

Mahdjoubi, L., Brebbia, C.A. and Laing, R. eds., 2015. *Building information modelling (BIM) in design, construction and operations* (Vol. 149). WIT Press.

Malmgren, L., 2014. *Industrialized construction-explorations of current practice and opportunities*. Lund University.

Malmgren, L., Jensen, P. & Olofsson, T. 2010. Product modeling of configurable building systems-a case study. *Journal of Information Technology in Construction (ITcon),* 15**,** 354-368.

Maxwell, D. W. & Aitchison, M. Design-value in the platform approach. IGLC 2017 - Proceedings of the 25th Annual Conference of the International Group for Lean Construction, 2017. 349-356.

McGrath, M.E., 1995. *Product strategy for high-technology companies: how to achieve growth, competitive advantage, and increased profits*. Irwin Professional Pub.

Medjdoub, B. & Bi, G. 2018. Parametric-based distribution duct routing generation using constraint-based design approach. *Automation in Construction,* 90**,** 104-116.
Meyer, M. H. 1997. *The power of product platforms : building value and cost leadership,* New York, New York : Free Press.
Miles, M. B., Huberman, A. M. & Saldaña, J. 2014. Qualitative data analysis: A methods sourcebook. 3rd. *ed: Thousand Oaks, CA: Sage*.
Monizza, G. P., Bendetti, C. & Matt, D. T. 2018. Parametric and Generative Design techniques in mass-production environments as effective enablers of Industry 4.0 approaches in the Building Industry. *Automation in Construction,* 92**,** 270-285.
Monizza, G. P., Matt, D. T. & Benedetti, C. 2016. Programming a Parametric Design Algorithm to Improve Manufacturing Processes' Efficiency: the Case Study of Glued-Laminated Timber. *Journal of Civil Engineering and Architecture,* 10**,** 1203-1212.
Mukkavaara, J. 2018. *Structures for supporting BIM-based automation in the design process.* Luleå University of Technology.
Ohvanainen, J. & Hietikko, E. 2012. Building competitive advantage through platform-based product family thinking: Case powerpacks. *Journal of Industrial Engineering and Management,* 5.
Olofsson, T., Jensen, P. & Rönneblad, A. Configuration and design automation of industrialised building systems. International Conference CIB W78: 16/11/2010-18/11/2010, 2010.
Ozturk, G. B. 2020. Interoperability in building information modeling for AECO/FM industry. *Automation in Construction,* 113**,** 103122.
Palmgren, H., Mogren, R., Gustafsson, R. & Götherström, U. 2019. Boverkets indikatorer. https://www.boverket.se/sv/om-boverket/publicerat-av-boverket/publikationer/2019/boverkets-indikatorer-december-2019/, Accessed 2020/03/20.
Pan, W., Gibb, A. G. & Dainty, A. R. 2012. Strategies for integrating the use of off-site production technologies in house building. *Journal of Construction Engineering and Management,* 138**,** 1331-1340.
Pine, B. J. 1993. *Mass customization*, Harvard business school press Boston.
Raudberget, D., Elgh, F., Stolt, R., Johansson, J. & Lennartsson, M. 2019. Developing agile platform assets–exploring ways to reach beyond modularisation at five product development companies. *International Journal of Agile Systems and Management,* 12**,** 311-331.
Rigger, E., Shea, K. & Stankovic, T. 2018. Task categorisation for identification of design automation opportunities. *Journal of Engineering Design,* 29**,** 131-159.
Robertson, D. & Ulrich, K. 1998. Planning for product platforms. *Sloan management review,* 39**,** 19.

Rockart, J. F. 1980. The changing role of the information systems executive: a critical success factors perspective.
Rudberg, M. & Wikner, J. 2004. Mass customization in terms of the customer order decoupling point. *Production planning & control,* 15**,** 445-458.
Sacks, R., Eastman, C. M. & Lee, G. 2004. Parametric 3D modeling in building construction with examples from precast concrete. *Automation in construction,* 13**,** 291-312.
Salvador, F., De Holan, P. M. & Piller, F. 2009. Cracking the code of mass customization. *MIT Sloan management review,* 50**,** 71-78.
Sandberg, M., Johnsson, H. & Larsson, T. 2008. Knowledge-based engineering in construction-the prefabricated timber housing case. *Journal of Information Technology in Construction (ITcon),* 13**,** 408-420.
Sardén, Y. 2005. *Complexity and learning in timber frame housing: the case of a solid wood pilot project.* Luleå tekniska universitet.
Scb 2020. http://www.scb.se/pr0502.
Schauerte, T. Wooden house construction in Scandinavia–a model for Europe. Proceedings of the 16th Internationales Holzbau-Forum, 2010.
Simpson, T. W., Jiao, J., Siddique, Z. & Hölttä-Otto, K. 2014. Advances in product family and product platform design. *New YorN: Springer*.
Simpson, T. W., Marion, T., De Weck, O., HöLttä-Otto, K., Kokkolaras, M. & Shooter, S. B. Platform-based design and development: current trends and needs in industry. ASME 2006 international design engineering technical conferences and computers and information in engineering conference, 2006. American Society of Mechanical Engineers, 801-810.
Singh, V., Gu, N. & Wang, X. 2011. A theoretical framework of a BIM-based multi-disciplinary collaboration platform. *Automation in construction,* 20**,** 134-144.
Söderholm, E. 2010. *Applicability of continuous improvements in industrialised construction design process.* Luleå tekniska universitet.
Sørensen, P. B. 2013. The Swedish housing market: Trends and risks. *Rapport till Finanspolitiska rådet,* 5.
Stehn, L. 2009. Industrilized house building in Sweden. Internationales Holzbau-Forum.
Styhre, A. & Gluch, P. 2010. Managing knowledge in platforms: boundary objects and stocks and flows of knowledge. *Construction Management and Economics,* 28**,** 589-599.
Succar, B. 2009. Building information modelling framework: A research and delivery foundation for industry stakeholders. *Automation in construction,* 18**,** 357-375.

Suh, E. S., De Weck, O. L. & Chang, D. 2007. Flexible product platforms: framework and case study. *Research in Engineering Design,* 18**,** 67-89.

Thuesen, C. & Hvam, L. 2011. Efficient on-site construction: learning points from a German platform for housing. *Const. Innovtn,* 11**,** 338-355.

Tlustochowicz, G., Kermani, A. & Johnsson, H. 2010. Beam and post system for non-residential multi-storey timber buildings: conceptual framework and key issues.

Toppinen, A., Röhr, A., Pätäri, S., Lähtinen, K. & Toivonen, R. 2018. The future of wooden multistory construction in the forest bioeconomy–A Delphi study from Finland and Sweden. *Jrnl of forest economics,* 31**,** 3-10.

Unger, C. 2006. *Industrialised house building: fundamental change or business as usual?* , KTH.

Veenstra, V. S., Halman, J. I. & Voordijk, J. T. 2006. A methodology for developing product platforms in the specific setting of the housebuilding industry. *Research in engineering design,* 17**,** 157-173.

Viklund, E., 2017. *Design approaches in industrialized house building: A creativity perspective* (Doctoral dissertation, Luleå University of Technology).

Voss, C. 2010. Case research in operations management. *Researching operations management.* Routledge.

Welin, L. and Bildsten, L., 2017, June. The housing market in Sweden: a political-historical perspective. In *9th Nordic Conference on Construction Economics and Organization 13-14 June, 2017 at Chalmers University of Technology, Göteborg, SWEDEN* (Vol. 13, p. 494).

Williamson, K. 2002. *Research methods for students, academics and professionals: Information management and systems*, Elsevier.

Winch, G. 2003. Models of manufacturing and the construction process: the genesis of re-engineering construction. *Building Research & Information,* 31**,** 107-118.

Wuni, I. Y. & Shen, G. Q. 2019. Critical success factors for modular integrated construction projects: a review. *Building Research & Information***,** 1-22.

Yin, R. K. (2017). *Case study research and applications: Design and methods*, London : Sage publications.

Yong, Y. C. & Mustaffa, N. E. 2017. Critical Success Factors for Malaysian Construction Projects: An Investigative Review. *International Journal of Built Environment and Sustainability,* 4.

Yuan, Z., Sun, C. & Wang, Y. 2018. Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings. *Automation in Construction,* 88**,** 13-22.

Supporting the Design Phase of Industrialised House Building Using a Product Platform Approach

– A Case Study of a Timber based Post and Beam Building System

In recent years, industrialised house building has gained shares on the Swedish house building market. The market demands for industrialised house building are exceeding the available supply of housing and experiencing a substantial increase in the housing production costs. For industrialised house building, the design has been identified as a critical phase with the systematization of the design a necessary part of industrialisation. Therefore, companies strive towards the inclusion of standardization and controlled processes in the design phase. Product platforms have proved to be related to the standardization of processes and products. Introducing a product platform approach in the design phase of house building could be a way to improve the design and ensure value creation in entire processes. Thus, the aim of this research is to outline means to support and improve the design phase of industrialised house building by using a product platform approach.

A Swedish multi-storey house building company that uses glulam post and beam building system with a focus on platform development was used as the single case study in this research. The company intends to achieve increased efficiency by moving towards industrialized approaches. Empirical data were mainly gathered from interviews, observations, workshops, and document analysis. The findings present the existing challenges in the housing building industry and outlines twenty critical success factors that need to be considered in the design phase. Also, the result outlines support methods and tools that can be used for the improvement of the design phase when applying a product platform approach. Moreover, a flexible product platform can be developed with the support of parametric modelling and used to design building components having an engineer-to-order characteristic. Finally, the results show that a building system can be considered as part of a product platform in light of the necessity of an adequate support in the design process to maintain a sustainable platform. Thus, the contribution includes the addition of knowledge to platform theory in general and its application on the design phase of industrialised house building.

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