



JÖNKÖPING UNIVERSITY  
*School of Engineering*

Doctoral Thesis

# **The Development and Use of Product Platforms in Single-Family Industrialized House Building**

Djordje Popovic

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# **The Development and Use of Product Platforms in Single-Family Industrialized House Building**

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Doctoral Thesis in Production Systems

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Published by  
School of Engineering, Jönköping University  
P.O. Box 1026  
SE-551 11 Jönköping  
Tel. +46 36 10 10 00  
[www.ju.se](http://www.ju.se)

Printed by Stema Specialtryck AB 2020

ISBN 978-91-87289-58-3



# The Development and Use of Product Platforms in Single-Family Industrialized House Building

# Abstract

Single-family industrialized house building is a trade characterized by a complete predefinition of products with off-the-shelf solutions offered to a market niche. Limited customization is included in the offerings in the form of a modular configuration of predefined components. A high level of prefabrication, often including volumetric elements, enables high efficiency in product variant realization processes, specifically, product specification, manufacturing, and on-site assembly. However, as the current markets are dynamic and often volatile, such offerings do not suffice in securing the success of business. Instead, offerings that include flexible product concepts with lower levels of predefinition and the concurrent achievement of high efficiency in processes using volumetric element prefabrication are needed. In this research, realizing this is characterized as the adoption of high-level mass customization. The main value of the presented research for the practice is support for single-family industrialized house building in adopting high-level mass customization.

The main enablers for the adoption of both lower and higher levels of mass customization are product platforms. The research on the development and use of product platforms has, however, been conducted mainly in multi-family industrialized house building. The differences in the types of offerings and customers between single-family and multi-family industrialized house building, reveal a research opportunity to study the development and use of product platforms in single-family industrialized house building. More specifically, the knowledge gaps include a lack of understanding regarding: the development and use of product platforms from a business model perspective, challenges for the development and use of product platforms when adopting high-level mass customization and support in addressing the identified challenges.

Therefore, the research purpose is to add to the knowledge on the development and use of product platforms and support that enables the adoption of high-level mass customization in single-family industrialized house building. The Design Research Methodology framework was used to plan and design the research. The research was conducted iteratively through four stages named: research clarification, descriptive study I, prescriptive study, and descriptive study II. The results provide an increased understanding regarding the development and use of product platforms in single-family industrialized house building through a coherent description of the product platform alignment phenomenon and the identified challenges when high-level mass customization is adopted. The results also increase knowledge regarding support in the development and use of product platforms that address the identified challenges. This part of the results is twofold.

Firstly, an information modelling method is proposed, and it demonstrates how product platform use can be modelled in the design process of single-family industrialized house building. Secondly, the results demonstrate how the design module construct can be modelled using the design assets throughout the design process. To exemplify the design module construct, a configuration of the flexible volumetric elements and the panelized elements they are composed of is proposed. Process efficiency during the predefinition and modify-to-order specification of design modules is addressed. The presented research makes knowledge contributions to the theoretical fields of product platforms, building information management and business models.

**Keywords:** House-building industry, Modern methods of construction, Production strategy, Platform-based development, Product lifecycle management, PLM, BIM, Engineer-to-order.

# Sammanfattning

Villaindustrin är en branch som kännetecknas av fullständigt fördefinierade produkter med standard lösningar som erbjuds till en marknadsnisch. En begränsad anpassning ingår ofta i erbjudandena i form av en modulär konfiguration av fördefinierade komponenter. En hög prefabriceringsnivå, ofta bestående av volymelement, möjliggör hög effektivitet i produktvarianternas realiseringsprocesser, i synnerhet i produktspecifikation, tillverkning och montage på byggsplats. Eftersom de nuvarande marknaderna är dynamiska och ofta volatila räcker emellertid inte sådana erbjudanden till för att säkerställa framgångsrika affärer. Istället behövs erbjudanden som inkluderar flexibla produktkoncept med lägre nivåer av fördefinition och som samtidigt uppnår en hög effektivitet i processer med användning av prefabricering av volymelement. I denna forskning kännetecknas denna realisering av användandet av höggradig mass-kundanspassning eller mass customization. Den industriella nyttan av den presenterade forskningen är att skapa stöd för villaindustrin att uppnå en höggradig mass customization.

De viktigaste möjliggörarna för att uppnå mass customization är produktplattformar. Forskning om utveckling och användning av produktplattformar har emellertid huvudsakligen bedrivits inom industriellt husbyggandet av flerfamiljshus. Skillnaderna i olika typer av erbjudanden och kunder mellan industriellt husbyggandet av flerfamiljshus och villaindustrin påvisar en forskningsmöjlighet att studera utvecklingen och användningen av produktplattformar inom villaindustrin. Mer specifikt inkluderar kunskapsgapen en brist för förståelse av: utveckling och användning av produktplattformar ur ett affärsmodellperspektiv, utmaningar för utveckling och användning av produktplattformar vid användning av höggradig mass customization och stöd för att hantera de identifierade utmaningarna.

Denna forskning syftar därför till att öka kunskapen om utveckling och användning av produktplattformar och stöd som möjliggör införandet av höggradig mass customization i villaindustrin. Design Research Methodology ramverket användes för att planera och designa forskningen. Forskningen genomfördes iterativt genom fyra stadier: (1) klargörande av forskningsuppgift, (2) beskrivande studie I, (3) föreskrivande studien och (4) beskrivande studie II. Resultaten ger en ökad förståelse för utveckling och användning av produktplattformar i villaindustrin genom en sammanhängande beskrivning av produktplattformens anpassningsfenomen och de identifierade utmaningarna som uppstår vid höggradig mass customization. Resultaten ger ökad kunskap om stöd vid utveckling och användning av produktplattformar som hanterar de identifierade utmaningarna. Denna del av resultaten omfattar två delar. För det

första föreslår en metod för informationsmodellering som visar hur produktplattformanvändning kan modelleras i konstruktionsprocesser inom villaindustrin. För det andra visar resultaten hur design modul kan modelleras med hjälp av designtillgångarna under hela konstruktionsprocessen. För att exemplifiera ett design modul koncept föreslår en konfiguration av de flexibla volymelementen och de planelementen som de är sammansatta av. Processeffektivitet under produktfördefinition och modify-to-order produktspecifikation av designmoduler adresseras. Den presenterade forskningen ger kunskapsbidrag till de teoretiska områdena produktplattformar, BIM och affärsmodeller.

# Acknowledgements

Now when I'm at the very end of my PhD studies, and looking back over the last five years, I realize how many times the process has been truly tough and challenging. I often remembered what the late Neil Peart once wrote:

*'You can do a lot in a lifetime  
If you don't burn out too fast  
You can make the most of the distance  
First you need endurance  
First you've got to last...'*

Apart from all the knowledge, I understand now how much endurance one gains through this experience. The endurance to face challenges in the years to come. I am very grateful for that. Here I would like to thank all the people who have been part of that experience in one way or another.

To begin with, I acknowledge that I have been supervised by such a great team. Firstly, I would like to thank my main supervisor Prof. Fredrik Elgh for finding a good balance between a direct guidance, how much he challenged me and how much he let me make the decisions related to the research. Thank you, Fredrik, for the kindness, for sharing your experience and expertise and that you always found time in your busy schedule whenever I needed an advice. Prof. Tobias Schauerte, thank you for always bringing a great spirit, for all the valuable advices and inputs you gave, for sharing your knowledge regarding Industrialized House Building and for facilitating the expansion of my personal network. Prof. Carin Rösiö, thank you for always showing kind consideration for my progress. You gave the words of encouragement and valuable advices and inputs when needed. Not to mention, how troublesome our on-line supervision meetings would have been if it wasn't for your speakerphone. Thank you, Prof. Mats Winroth and Dr. Lars Eliasson for being a part of this team in the first half of my PhD studies. Carl-Johan Sigfridsson, I am very grateful that you had enough patience to be a part of the process from the very beginning. Thank you for your great spirit, positive attitude and for sharing your knowledge, specifically regarding building systems but also in all other possible aspects of housing production at OBOS. You and many more people in OBOS such as Leif Isacson, Mathias Karlstad, Jakob Forsberg, Peter Stenfelt and others from R&D have kindly shared their knowledge and made the collection of empirical data so much easier. Thank you all.

I would also like to thank OBOS, the Knowledge foundation and the School of engineering in Jönköping for the financial support. My PhD studies are part of

ProWOOD research school, well-managed by Dr. Jenny Bäckstrand, Prof. Jimmy Johansson and Dr. Malin Löfving. Together with them, I would also like to thank the former members of ProWOOD management: Prof. Kristina Säfsen, Prof. Peter Johansson and Johan Palm for giving me this opportunity and making the process smoother. All you fellow PhD students from ProWOOD and PPD department, we shared great experiences during the joint travels, and had fun and interesting discussions, during all those fika and lunch occasions. Thank you! Special thanks goes to Tim Heikkinen, for both taking part in my research and for being such a tough workout buddy.

Paula Lernstål Da Silva, Olof Hildorf Granath and Prof. Salem Seifeddine thank you for the positive attitude, support and guidance all along the way. I would also like to express my gratitude to all other academics, professionals and practitioners from the School of Engineering in Jönköping, Linnaeus University, and a number of universities and companies in Sweden and other countries whom I connected with and from whom I learned much.

When it comes to my family, my girlfriend Julia and my friends, I don't even know how to describe how much your support and love mean to me. You shared both good and bad with me throughout this journey and there are simply no words to describe how grateful I am for that. At least not in these pages. Thank you.

*Djordje Popovic*

Jönköping, August 2020.

## Appended papers

**Paper A** Djordje Popovic, Åsa Fast-Berglund and Mats Winroth (2016). *Production of customized and standardized single-family timber houses – A comparative study on levels of automation*. Proceedings of the 7th Swedish Production Symposium (SPS), 25-27 October, Lund, Sweden.

Djordje Popovic planned the study, collected and analysed the literature and empirical data and wrote a major part of the paper. Mats Winroth and Åsa Fast-Berglund wrote parts of the paper and assisted with the proofreading.

**Paper B** Djordje Popovic, Tobias Schauerte and Jimmy Johansson (2017). *Prefabrication of single-family timber houses – problem areas and wastes*. Proceedings of the 25th Annual Conference of the International Group for Lean Construction (IGLC), 9-12 July, Heraklion, Crete, Greece.

Djordje Popovic planned the study, collected and analysed the literature and empirical data and wrote a major part of the paper. Tobias Schauerte provided additional data. Both Tobias Schauerte and Jimmy Johansson participated in writing parts of the paper and assisted with the proofreading.

**Paper C** Djordje Popovic and Carin Rösiö (2019). *Product and manufacturing systems alignment: a case study in the timber house building industry*. Proceedings of the 10th Nordic Conference on Construction Economics and Organization (CEO 2019), 7-8 May, Tallinn, Estonia.

Djordje Popovic planned the study, collected and analysed the literature and empirical data and wrote a major part of the paper. Carin Rösiö wrote a part of the paper and assisted with the proofreading.

**Paper D** Djordje Popovic, Shamnath Thajudeen and Alexander Vestin (2019). *Smart manufacturing support to product platforms in industrialized house building*. Proceedings of the 2019 Modular and Offsite Construction (MOC) Summit, 21-24 May, Banff, Canada.

Djordje Popovic, Shamnath Thajudeen, and Alexander Vestin planned the study, collected and analysed the literature and empirical data and wrote the paper.

**Paper E** Djordje Popovic, Tobias Schauerte and Fredrik Elgh (2019). *Product platform alignment in industrialized house building*. The paper is submitted to an international journal.

Djordje Popovic planned the study, collected and analysed the literature and empirical data and wrote a major part of the paper. Tobias Schauerte supported the work by conducting a part of the data analysis, writing a part of the paper, critically revising the content and the structure of the draft and by proofreading the draft. Fredrik Elgh supported the work by taking part in the theoretical synthesis and the design of the case study, critically revising the content and the structure of the draft, and by proofreading the draft.

**Paper F** Djordje Popovic, Dag Raudberget and Fredrik Elgh (2020). *Product platforms in industrialized house building – information modeling method*. The paper will be a part of proceedings of the 9th Swedish Production Symposium (SPS), 6-9 October Jönköping, Sweden.

Djordje Popovic has done the literature review, synthesized the theory into a method, wrote a major part of the paper, and was the corresponding author. Dag Raudberget supported the work by participating in the discussions regarding the theoretical foundation, wrote a part of the paper, critically revised the content and the structure of the draft, and by proofreading the draft. Fredrik Elgh supported the work by participating in the discussions regarding the theoretical foundation, critically revised the content and the structure of the draft and by proofreading the draft.

**Paper G** Djordje Popovic, Fredrik Elgh and Tim Heikkinen (2020). *Configuration of flexible volumetric elements using product platforms: Information modeling method and a case study*. The paper is submitted to an international journal.

Djordje Popovic has done the literature review, synthesis of the theory, planned the design of the case study, conducted the data collection and analysis, wrote a major part of the paper, and was the corresponding author. Fredrik Elgh supported the work by participating in the discussions regarding the theoretical foundation, wrote a part of the paper, critically revised the content and the structure of the draft and by proofreading the draft. Tim Heikkinen supported the work by participating in the discussions regarding the theory and the analysis of empirical data, and by proofreading the draft.

## Additional papers, not included in the thesis

Djordje Popovic, Peter Meinlschmidt, Burkhard Plinke, Jovan Dobic and Olle Hagman (2015). *Crack detection and classification of oak lamellas using online and ultrasound excited thermography*. Pro Ligno, 11(4), 464-470.

Djordje Popovic and Mats Winroth (2016). *Industrial timber house building – levels of automation*. Proceedings of the 33rd International Symposium on Automation and Robotics in Construction (ISARC), 18-21 July, Auburn, Alabama, USA.

Tobias Pahlberg, Matthew Thurley, Djordje Popovic and Olle Hagman (2018). *Crack detection in oak flooring lamellae using ultrasound-excited thermography*. Infrared Physics & Technology. 88, 57-69. <https://doi.org/10.1016/j.infrared.2017.11.007>.

# List of abbreviations

AEC – architecture, engineering and construction  
BIM – building information modelling (management)  
BM – business model  
BOM – bill-of-materials  
BPMN – business process modeling notation  
CAD – computer aided drafting  
CAM – computer aided manufacturing  
CTO – configure-to-order  
DP – design platform  
DRM – design research methodology  
DS I – descriptive study one  
DS II – descriptive study two  
ERP – enterprise resource planning  
ERS – exchange requirement specification  
ETO – engineer-to-order  
IDM – information delivery manual  
IHB – industrialized house building  
MC – mass customization  
MEP – mechanical, electrical and plumbing  
MTO – modify-to-order  
PAM – product architecture model  
PS – prescriptive study  
RC – research clarification  
R&D – research and development  
UML – unified modelling language

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# 1. Introduction

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*At the outset of this chapter, industrialized house building is introduced on a general level and a problem area is outlined. After this, a description of the research background will be given to demonstrate the need for research from a scientific point of view. A clarification of the purpose, research questions and scope follows, and the chapter is concluded with an outline of the thesis.*

---

## 1.1. Problem area

Industrialized house building (IHB) is a term used to label the production of single-family and multi-family housing with integrated supply chains, where project-oriented methods traditionally used in the architecture, engineering and construction (AEC) industries are combined with the product- and process-oriented methods used in manufacturing industries (Lessing et al., 2015). The main reason why IHB has been increasingly adopted in many countries over the past two decades is the inefficient process of traditional project-oriented house building caused by vertical fragmentation and short-term relations between actors and one-of-a-kind housing (Hall et al., 2019).

IHB companies prefabricate parts of houses, such as assemblies, panelized elements and volumetric elements in controlled factory environments, which improves subsequent on-site construction in terms of cost, quality and lead time (Bertram et al., 2019). Moreover, IHB companies often control the design process together with the prefabrication and hence vertically integrate these in the supply chain (Hall et al., 2019). However, the consequence is that IHB companies must restrict the flexibility of their offerings using standardization. Highly standardized offerings that target market niches are commonly developed in single-family IHB (Johnsson, 2013). The simple and prompt product specification process of highly predefined single-family houses is often combined with prefabrication in volumetric elements and rapid on-site assembly, resulting in high product variant realization efficiency (Lidelöw et al., 2015). Nevertheless, niche markets are becoming more volatile, and single-family IHB companies must increase the flexibility of their offerings and at the same time retain efficiency in their processes. The practical goal of the research presented in this thesis is to investigate possible support for single-family IHB companies in solving this issue.

In general, the concurrent fulfilment of greater product flexibility in offerings and greater efficiency in product realization processes is addressed in the literature on product platforms and mass customization (MC). However, such scientific discourse has thus far in the IHB context taken place chiefly in the context of multi-family IHB (Bonev et al., 2015; Jansson et al., 2014; Jensen et al., 2015; Lessing et al., 2015).

## 1.2. Background

The development and use of product platforms have proven to be an effective means of realizing MC (Pirmoradi et al., 2014), i.e. satisfying various customer needs and requirements through offerings manufactured with near-mass production efficiency (Pine, 1993). Developing and using a product platform is a multidisciplinary endeavour which requires the consideration of strategic, marketing, engineering, information technology (IT), manufacturing and management aspects (Jiao et al., 2007; Pirmoradi et al., 2014). Therefore, it is necessary to consider these aspects in a combined manner, e.g. a standalone engineering design without an analysis of market conditions may not result in successful designs (Pirmoradi et al., 2014). The fit of product platforms within IHB business models has been studied from a strategic perspective (Hall et al., 2019; Lessing & Brege, 2018). The main findings show that an IHB company should, according to the external business environment, continuously align its product platform with the market position and the offering. Using these three building blocks, Brege et al. (2014) coined the IHB business model construct. However, knowledge on the alignment between the business model building blocks and the external business environment when product platforms are developed and used in single-family IHB is missing.

The development and use of product platforms in IHB has mainly been studied in the design process of multi-family buildings (Bonev et al., 2015; Jansson et al., 2014). In this context, the design process takes place in the projects, i.e. after the customer order decoupling point where product variants are configured according to product platforms mainly based on predefined process assets (Jansson et al., 2014). Alternatively, developing predefined product components from which product variants are configured in projects is common in single-family IHB (Johnsson, 2013; Lessing & Brege, 2018). The research done on the development and use of product platforms in single-family IHB is scant. The focus is mainly on modularization and the development of predefined product components (Da Rocha et al., 2015; Jensen, 2014; Veenstra et al., 2006). A common practice, currently present in single-family IHB, of predefining whole products and/or the product components, such as volumetric elements that can be combined in a limited number of ways, is challenged in current markets where the need for

customization and design changes is increasing (Kolarevic & Duarte, 2019). Hence, further research on product platforms in single-family IHB is needed to increase the knowledge on how product platform and different sets of assets (Robertson & Ulrich, 1998), that is, apart from the predefined product components, can be developed and used to enable the development of offerings that include flexible product concepts with lower levels of predefinition and the achievement of high efficiency in processes using volumetric element prefabrication. The concurrent realization of these two goals is framed in this research as high-level MC. The underlying reasoning is in line with the findings of Jansson et al. (2019) who conclude that increased design flexibility in combination with the potential to decrease lead times due to the high degree of prefabrication and rapid on-site assembly can widen the market scope.

The formalization of product platform knowledge, and its management, using IT applications, i.e. information management, is necessary to enable the efficient reuse of product platform assets during the design and manufacturing of product realization (Eriksson & Emilsson, 2019; Jensen et al., 2012; Malmgren et al., 2011). However, a foregoing step and a crucial enabler of information management is information modelling. Hvam et al. (2008) identify information modelling based on a thorough analysis of products and processes as a necessary step that enables the development of IT system applications. Building information modelling (BIM) is a technology and associated set of processes developed for construction products in AEC industries, by which building models are produced, communicated and analysed (Sacks et al., 2018). However, applications of BIM technology are focused on projects (Jupp, 2016) and product variant specification, and it remains unclear how the reuse of the predefined assets of product platforms can be modelled in single-family IHB (Lessing et al., 2015).

### 1.3. Purpose and research questions

The purpose of the research reported in this thesis is to add to the knowledge on the development and use of product platforms and support that enables the adoption of high-level MC in single-family IHB. Fulfilling this purpose is attended by answering following three research questions:

- ***RQ1: How are product platforms developed and used in single-family IHB from a business model perspective?***

By answering this research question, a holistic understanding is obtained on how product platforms are developed and used as part of the single-family IHB business model and in relation the external business environment.

- ***RQ2: What are the challenges for the development and use of product platforms in single-family IHB when adopting high-level MC?***

Adding to the holistic understanding obtained by answering RQ1, the challenges of developing and using product platforms when adopting high-level MC are identified between the single-family IHB business model and the external business environment.

- ***RQ3: How can the development and use of product platforms be supported in single-family IHB to address the identified challenges?***

The answer to this research question is a prescriptive part of the conducted research, where the identified challenges a single-family IHB company meets when developing and using product platforms for high-level MC are addressed with developed support.

### 1.4. Scope

In total, four research studies were conducted, of which three included the collection and analysis of empirical data. These three empirical studies were conducted in the context of Swedish single-family IHB. Common to the empirical studies was a case company that offers turnkey single-family housing prefabricated in assemblies, panelized elements, and volumetric elements with timber as structural elements. However, in study 1 and study 2, empirical data was collected and analysed in additional single-family IHB case companies (paper B, paper D and paper E). In terms of product realization, the scope of the research in both the empirical and literature studies was focused on the design and manufacturing phases. Nevertheless, in study

2, a holistic understanding was built over the whole product realization as business models and the external business environment were studied.

## 1.5. Thesis outline

The thesis is composed of two parts, a frame and seven appended papers. The frame of the thesis consists of seven chapters. It coheres the research conducted and reported in the papers through an overall purpose and research questions.

The introduction chapter (1) of the thesis frame provides the problem area and background of the research, specifically, the context, the problem, the current understanding and the lack of knowledge. After that, the purpose and research questions are outlined. At the end, the scope is described.

The frame of reference is presented in the next chapter (2). It includes theory descriptions of product platforms and MC, information modelling, changeable manufacturing systems and business models. The chapter concludes with the identified knowledge gaps and the research opportunity statement.

The research methods chapter (3) introduces the design research methodology (DRM) framework and gives a description of the research methods used and the data collection and analysis applied in the empirical studies. The research strategy shows how the DRM stages, studies, papers, research questions and research focus relate to each other.

The introduction to the empirical foundation is given in the following chapter (4). Descriptions of the case companies are given according to the three building blocks of an IHB business model (Brege et al., 2014).

A summary of the results are given in the fifth chapter (5). The presentation of the results is structured according to the three research questions.

The sixth chapter (6) contains a discussion of the results and applied methods. First, the results are discussed regarding how they connect to each other and how they provide answers to the research questions. After that, the connection of the results with the frame of reference is given through knowledge contributions. Following is an evaluation of the proposed support together with the industrial implications. Finally, the methods used are discussed in terms of research quality and research process.

Conclusions are provided in the last chapter (7). The main conclusions according to the three research questions and research contributions are outlined. Moreover, the research's limitations and directions for possible future work areas are given.



## 2. Frame of reference

---

*In this chapter, the fields of theory to which the knowledge contributions are made, specifically, product platforms, business models and building information management, are introduced. Additionally, the theoretical constructs used for the analysis of the empirical data are defined and described in general and in the IHB context. The chapter concludes with the research opportunity in which the theoretical points of departure and knowledge gaps to which the research presented in this thesis makes knowledge contributions.*

---

### 2.1. Product platforms and mass customization

Robertson and Ulrich (1998) define a product platform as a collection of four sets of assets, including components, processes, knowledge and people/relationships, that are shared by a set of products. Components are assets that can be divided into elements such as product designs and the corresponding manufacturing tools and fixtures. Fabrication and assembly equipment for the manufacturing of components and the design of production and supply chain processes constitute process assets. Knowledge assets are composed of elements such as design know-how, mathematical models and testing methods. People/relationship assets refer to the relationships among the members of a team, between teams or organizations and within supplier relationships and human resources (ibid.). Using their product platforms, companies can balance between the commonality and distinctiveness embedded within the component and process solutions. Companies can then offer products tailored according to customer-specific requirements while concurrently achieving economies of scale in production (Meyer & Lehnerd, 1997). The flexibility of a product platform can be expressed through the bandwidth of a solution space (Salvador et al., 2009) embodied in component and process assets (Johannesson et al., 2017). The bandwidth can be modular or scalable (parametric) and enables the configuration of product variants (ibid.) as a means of customization.

In the manufacturing industry, product platforms are established as one of the main enablers for the adoption of MC (Pine, 1993; Robertson & Ulrich, 1998; Zhang, 2015). MC emerged as a response to the market conditions that occurred at the end of 1980s. An increased variety in customer demands and requirements began to challenge manufacturing companies to deliver customized offerings, however, using efficient and mass production-like processes (Pine, 1993). A common way of describing the relation between MC and the design process in the IHB literature is through the positioning of the customer order decoupling point (Jensen, 2014). The point separates the forecast-driven product design process from the product specification with customer involvement. In single-family IHB,

the forecast-driven product design process refers to the development of a predefined offering, such as catalogue houses (Johnsson, 2013). Hence, in this thesis, the forecast-driven product design process is interchangeably referred to as offering development (paper E) and product predefinition processes (paper F and paper G).

In IHB, product variants are often specified through the scalable and modular configuration of product platform components with standardized interfaces, such as standard, variant and design modules (Jensen, 2014). Standard modules are fully predefined and reused in product variants through a select-a-variant specification process. Variant modules are also predefined but can be combined through a modular bandwidth and standardized interfaces to create different product variants in a configure-to-order (CTO) specification process. Design modules enable higher flexibility in product design as, in addition to the modular bandwidth enabled by standardized interfaces, they also embody a scalable bandwidth. The dimensional scaling of design modules is governed by building system constraints. Hence, design modules are associated with the parametric configuration conducted as part of a modify-to-order (MTO) specification process (Jensen et al., 2015). However, the ingoing components within the design modules are not predefined and require additional engineering activities during product specification, in other words, an engineer-to-order (ETO) specification process (Olofsson et al., 2016). Therefore, MTO is a combination of the CTO and ETO specification processes (Jensen, 2014). The configuration of design modules is a way of adopting high-level MC. This is in line with the geometrical adaptation of single-family housing according to customer requirements, which Khalili-Araghi and Kolarevic (2020) argue is the needed level of MC in this industry.

The central aspects of product platform development in IHB are building systems and prefabrication methods (Lessing, 2006). Building systems are robust technical systems based on market, legal, production and supply chain requirements and constraints (Lessing et al., 2015). These requirements and constraints define the solution space of a building system based on which product distinctiveness and adaptability to contingencies (Pan et al., 2007) are achieved during the customization in the design process. In multi-family IHB, the building systems are directly configured in projects using ETO specification (Jansson et al., 2014). In contrast, in single-family IHB, building systems are used for the development of offerings according to the forecast for a market niche (Johnsson, 2013). These offerings are composed of catalogue product designs and variant modules that are then configured during product specification (Jensen, 2014) and prefabricated using optimized manufacturing systems (Johnsson, 2013). The prefabrication method represents the level to which the building parts are manufactured in the factory environment (Lessing, 2006). A house can be

prefabricated in assemblies (lowest level), panelized elements (medium level) and/or volumetric elements (highest level) (Bertram et al., 2019).

Organizations of IHB companies are two-dimensional, including product and project dimensions (Lessing et al., 2015) which are connected to the development and use of product platforms (Bonev et al., 2015; Jansson et al., 2014). Meeting project-specific parameters, such as specific customer requirements, is achieved by applying design support methods (Jansson et al., 2014) during the configuration of product platform assets in building projects (Bonev et al., 2015). These empirical studies were conducted in the context of multi-family IHB, hence the offering development perspective as a characteristic of single-family IHB is missing. The connection between product and project dimensions in single-family IHB was addressed by Thuesen and Hvam (2011) who studied the experience feedback from projects that is used for the continuous and incremental development of product platforms. Furthermore, Malmgren et al. (2011) investigated how customer requirements can be matched by configuring building systems without the need for ad-hoc solutions. The authors introduced the upstream flow of constraints along the product realization that defines the building system solution space and the downstream flow of customer requirements.

## 2.2. Information modelling

This section of the frame of reference is divided into three parts, as follows: building information modelling (BIM), information delivery manual (IDM) framework and the design platform (DP) modelling method. The motivation for the choice of the IDM and DP is elaborated in the literature review sections of paper F and paper G.

### 2.2.1. Building information modelling

BIM technology was initially developed to support the digital modelling and management of construction products in projects including the generation, communication and analysis of models (Sacks et al., 2018). The core of BIM technology is characterized by object-based parametric modelling and a shift in the exchange of information from file-based to object-based. To enable CTO and MTO specification and a lower degree of product component predefinition, the flexibility of product platforms must be increased by incorporating object-based parametric modelling governed by the building system's constraints (Jensen et al., 2015; Khalili-Araghi & Kolarevic, 2020; Sandberg et al., 2008) in BIM environments (Piroozfar et al., 2019; Sacks et al., 2018). A formalization of product platform knowledge and its integration with IT systems is needed as this can enable efficiency and quality in

product specification (Jensen et al., 2019; Khalili-Araghi & Kolarevic, 2020; Piroozfar et al., 2019; Sandberg et al., 2016). Finally, this can enable digital manufacturing as a way to achieve a fit between building systems, IT systems and automated manufacturing systems (Hall et al., 2019; Lessing et al., 2015). Botton et al. (2016) state that specifying product structures that are connected to lifecycle data is a missing link in the current BIM applications. This information-centric approach is a characteristic of the product lifecycle management (PLM) systems used in manufacturing industries (Sacks et al., 2018).

### 2.2.2. Information delivery manual

IDM is a framework developed by buildingSMART International (Sacks et al., 2018) which can be used to model and specify information exchanges taking place during the specification processes of buildings. Hence, IDM modelling can facilitate the development of BIM applications (Ramaji et al., 2017). IDM modelling is composed of three parts – information model, process mapping and clarifying how information is exchanged throughout the process using exchange requirement specification (ERS). A product-oriented IDM was developed by Ramaji et al. (2017) where the aim was to expand BIM applications to the industrialized construction of multi-storey modular buildings. The product architecture model (PAM) was developed to be used as an information model suited for modular building systems (Ramaji & Memari, 2016). The PAM is a generic class-model of physical and mechanical properties and process constraints. Using object-based modelling, building components objects of a specific multi-storey modular building can be instantiated. Moreover, the hierarchy and interactions between them can be specified.

### 2.2.3. Design platform

André et al. (2017) developed a DP modelling method to be a comprehensive object-based modelling approach for product platforms in companies realizing customized products (André & Elgh, 2018). It has been developed in cooperation with ETO manufacturing companies as a support for their product platforms. DP supports the generic modelling of a product platform using the product structure and design assets of a company. In turn, the modelling of product variants in the design process by the instantiation of predefined and non-predefined product components is enabled. Predefined product components are modelled with a computer-aided design (CAD) model (solution resource), while non-predefined product components are modelled using various design assets employed in the design process to develop a solution for the product component. The design assets can be assessment, synthesis and geometry resources, constraints, processes and projects. The DP phenomenon model is shown

in Figure 1, while information modelling is done by means of object-based modelling using unified modelling language (UML) notation (Rumbaugh, 2005).

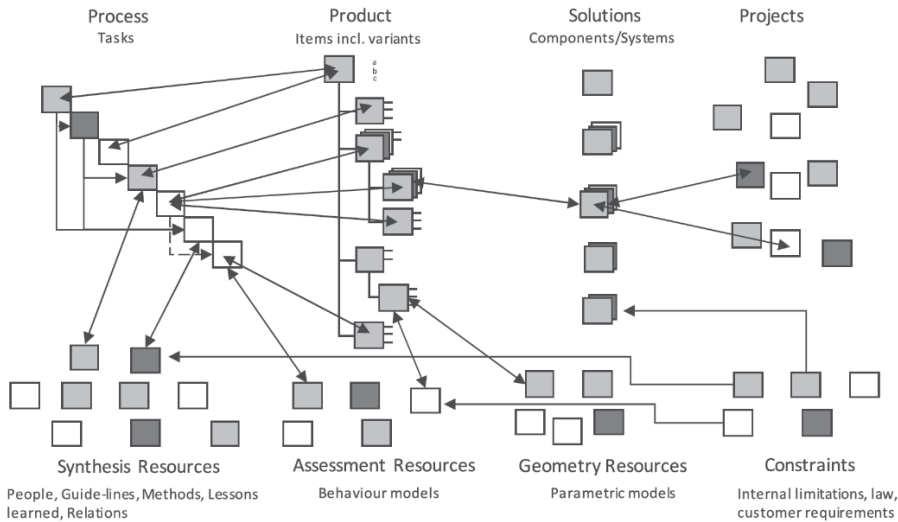


Figure 1 DP phenomenon model. Figure by André et al. (2017)

DP supports generic product platform modelling when it is not possible to predefine whole products and their modular composition as in the traditional component-based product platforms developed in make-to-order manufacturing industries (André & Elgh, 2018). In such case, the design solutions of products and some of their parts that are subjected to customization are defined during the specification processes after the customer order decoupling point. Up until the point of design solution specification, the products and/or their parts can be modelled using other design assets (Elgh et al., 2018).

## 2.3. Changeable manufacturing systems

Manufacturing systems are aggregated into component and process assets of product platforms (Robertson & Ulrich, 1998). The changeable manufacturing systems theoretical field is associated with the fields of product platforms and MC (ElMaraghy et al., 2013). Changeability can be defined as the ability of a manufacturing system to change its functionality and/or capacity while not affecting quality and with little penalty in terms of time and cost. However, a change can happen either within the boundaries of the system or through physical reconfiguration. To describe how changeability is seen in relation to the types of flexibility and manufacturing systems, Table 1 is given.

Table 1 Changeability and dedication in relation to types of flexibility and manufacturing systems.

<i>Type of flexibility</i>	<i>Changeability</i>		<i>Dedication</i>
	General flexibility	Customized flexibility or reconfigurability	Focused flexibility
<i>Type of manufacturing system</i>	Flexible manufacturing systems	Reconfigurable manufacturing systems	Dedicated manufacturing systems

Focused flexibility refers to the ability of a manufacturing system to handle a very narrow range of functionality and predefined fixed capacity. It is related to dedicated manufacturing systems. Alternatively, there are flexible manufacturing systems that have a wide range of functionalities and scalable capacity. These manufacturing systems are considered to have a priori built-in general flexibility. Finally, reconfigurability is the ability of a system to efficiently adapt in terms of changeable functionality and scalable capacity to cope with product, process and/or production variety. These reconfigurable manufacturing systems achieve so-called customized flexibility through the rearrangement of structural components (ElMaraghy et al., 2013; Terkaj et al., 2009).

## 2.4. Business models

The theoretical construct of a business model is used to describe how a company operates in a market to create value (Casadesus-Masanell & Ricart, 2010). Since business models are rather dynamic constructs that have to be adjusted to fluctuating market demands, customer needs and other changes in the external business environment (Achtenhagen et al., 2013), the continuous development of the business model according to the company strategy is needed (DaSilva & Trkman, 2014). Hence, the success or failure of a company mostly depends on the alignment between its business model (Sjödén et al., 2020) and the external business environment (Foss & Saebi, 2015). The alignment describes the interplay or fit among business model building blocks and the external business environment (Mintzberg, 1993) by detailing the connections between them (Ritter & Lettl, 2018). The external business environment consists of market needs, legal requirements and situational contingencies as well as political, economic, social and cultural elements (Sutherland, 2004).

IHB companies come across situational contingencies during product specification, that is, in projects. Common situational contingencies are special customer requirements and site conditions (Aitchison, 2017). However, legal requirements often become part of situational contingencies when local planning

authorities in a municipality responsible for issuing building permits interpret them in a different way (Viking & Lidelöw, 2015).

The first to investigate business models in IHB were Brege et al. (2014). An IHB business model can be structured using three building blocks of offering, market position and operational platform. Through an offering, a company makes a value proposition by which the customer needs and legal requirements in a market are met in the form of products and services. The market position of a company represents the target market segments for the offering, the supply chain role and the company's relationships through which an offering is communicated, negotiated and developed (Lessing & Brege, 2015). Operational platform represents companies' resources, competences, external resources from suppliers and partners and processes through which these elements are organized and used (Lessing & Brege, 2015).

Within the literature on IHB business models, a product platform is viewed as a narrower term than an operation platform. However, the scope of operational platforms, as defined above, is in line with the product platform definition by Robertson and Ulrich (1998) which is used in this research. For this reason, instead of 'operational platform', the term 'product platform' will be used together with offering and market position as the building blocks of a business model in the results and discussion.

Along with the IHB business model construct definition, Brege et al. (2014) also investigated the fit between the three business model building blocks and the external business environment. The focus of the empirical investigation was on IHB companies that had manufacturing resources as a central element of the product platform. Lessing and Brege (2015) and Lessing and Brege (2018) added knowledge through their empirical studies on IHB companies having offering as their central building block. These studies together provided a basic understanding on the fit among business model building blocks and the external business environment, however, a deeper analysis regarding product platform development and use is missing.

## 2.5. Knowledge gaps and research opportunity

The existing literature in the IHB context has mostly focused on business model types and structures and the fit and interplay between business model building blocks and the external business environment (Brege et al., 2014; Lessing & Brege, 2015, 2018). In contrast, the literature on product platforms in the IHB context does not provide a coherent description of the development and use of product platforms and what the challenges are from a business model perspective when high-level MC is adopted. Joint analysis of the literature on business models and product platforms in the IHB

context reveals a knowledge gap that can be addressed by describing the phenomenon of product platform alignment. Aiming to fill this knowledge gap by synthesizing a model based solely on the literature does not ensure that all the important aspects for product platform development and use in single-family IHB are considered. Hence, the frame of reference is taken as a point of departure in this research and is complemented with an empirical study.

The application area of the product-oriented IDM framework is the prefabrication of multi-storey modular buildings. However, the framework supports the formalization of product model, process and information exchange knowledge taking place in a fragmented supply chain where different actors are in control of different product realization phases. Consequently, the PAM, used for generic product and product variant modelling, supports the formalization of modular building systems knowledge. The scope of the product platform is, however, wider and includes other predefined component, process, knowledge and people/relationships assets (Robertson and Ulrich 1998, Jansson et al. 2014). Hence, the scope of the product-oriented IDM does not suffice to model the product platform development and use in single-family IHB. The shortcoming of the PAM can be addressed with DP, which enables both generic product platform modelling and the instantiation of predefined and non-predefined product components. The knowledge gap related to how the product-oriented IDM framework can be adjusted and expanded to enable the modelling of product platforms in single-family IHB is conjoined with the knowledge gaps related to DP, i.e. not providing means of process and information exchange modelling and not yet being applied in the single-family IHB context. Hence, there is a research opportunity for knowledge contribution to synthesize an information modelling method by replacing the PAM from the product-oriented IDM (Ramaji et al., 2017) with the DP (André, 2019) to enable the modelling of product platform use in the design process of single-family IHB.

Combining lower predefinition levels of an offering that include geometrical configuration with the volumetric elements prefabrication as means of adopting high-level MC in single-family IHB has not yet been addressed in the literature (Larsen et al., 2019). Jensen (2014) studied different modularization strategies for MC that can be applied to predefinitions and the consequences for the product variant specification processes. However, it remains unclear how lower levels of predefinition in product offerings and high prefabrication levels in manufacturing can be combined while achieving high efficiency and quality in the design process. The theoretical construct of design modules is used as the unit of analysis and the point of departure (paper G). Previous research on the design module theoretical construct (Jensen, 2014) focuses on the product architecture, i.e. a component asset of an IHB product platform. There is a knowledge gap associated with the information modelling of the design modules throughout the whole

design process of single-family IHB. As the design modules and the components they are composed of are not predefined and need to be specified after the customer order decoupling point, they need to be modelled using design assets other than solution resources (André & Elgh, 2018) throughout the design process. Moreover, the lack of a holistic consideration of the design process in the past research (Jensen, 2014; Ramaji et al., 2017), which includes both predefinition and product specification processes, is addressed.



### 3. Research methods

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*In this chapter, the DRM framework and the case study method used are introduced. The research strategy is then described to explain how the framework was used in this research, that is, how the framework stages, studies, papers, research questions and research focus relate to each other. The chapter is concluded with brief descriptions of the four conducted studies as detailed descriptions of the research steps can be found in the appended papers.*

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#### 3.1. Design research methodology

The research presented in this thesis was designed and planned according to the DRM framework (Blessing & Chakrabarti, 2009). The framework ties together the methods used for the data collection and analysis and the conducted studies. The framework was chosen to plan and design the research as the purpose was to increase the understanding on and synthesize the support for the development and use of product platforms in single-family IHB when adopting high-level MC, i.e. both descriptive and prescriptive qualitative studies were required.

The DRM was established by Blessing and Chakrabarti (2009) who propose the following four stages of the research process (Figure 2): research clarification (RC), descriptive study I (DS-I), prescriptive study (PS) and descriptive study II (DS-II). The RC stage is used to define the goals that the research is expected to fulfil. Other objectives are to define the focus of the project as well as the main research questions and problems, the relevant disciplines and the areas to be reviewed in addition to the areas of scientific and practical contribution. During the RC stage, the focus for the DS-I should be provided. To increase the understanding on the current state in the area of interest and key factors, the DS-I stage is conducted by reviewing the literature on empirical research, via conducting the empirical research and through reasoning. In this way, the basis for the PS stage is provided for the development of the support. In the PS stage, the understanding from the DS-I stage and the key factors are addressed. The support is developed according to the key factors in a systematic way, and an evaluation plan is developed to be used in the DS-II stage. In the DS-II stage, another empirical study is conducted, and the focus lies on the application and evaluation of the support. The first goal is application evaluation, aiming to identify whether the support can be used for the task for which it was developed and whether it has the expected effect on the key factors. The second goal is an evaluation of the developed support, in which possible improvements for the support might be identified.

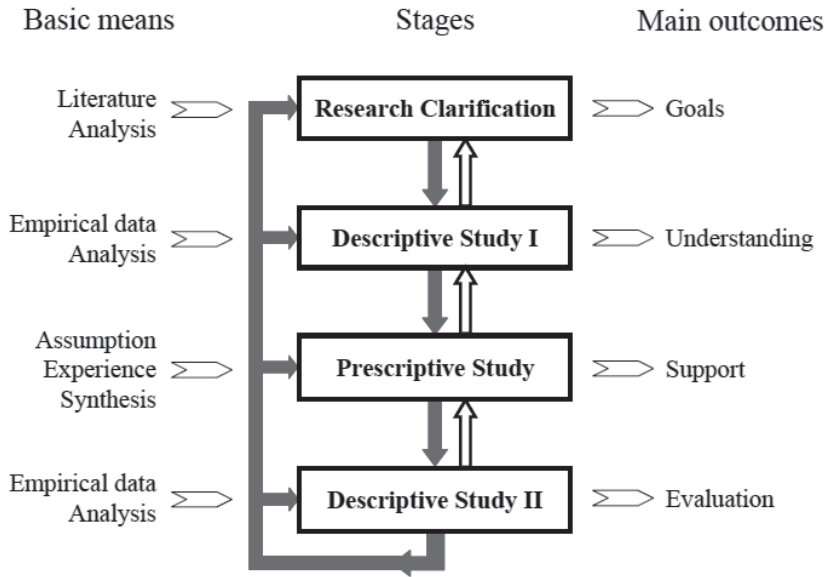


Figure 2 Overview of the DRM process. Adapted from Blessing and Chakrabarti (2009).

According to Blessing and Chakrabarti (2009) the four stages of the DRM framework are commonly combined in research projects in seven different ways depending on the scope and breadth of each study. There are three types of the DRM stages, as follows: (1) a review-based study based on a literature review only, (2) a comprehensive study in which the literature review is complemented with an empirical study, i.e. the researcher conducts an empirical study and develops and/or evaluates the support and (3) an initial study, in which the researcher takes the first few steps of a particular stage, shows the consequences of the results and prepares the results for other researchers to continue with the work. In this thesis, the following combination of stages was planned and designed:

- the RC stage and its iterations were review-based,
- the DS-I stage and its iterations were comprehensive,
- the PS stage was review-based, and
- the DS-II was initial.

Duffy and Andreasen (1995) differentiate the following three model classes in relation to the real world: phenomenon models, information models and computer models (Figure 3). Phenomenon models are descriptive and are developed based on an analysis of empirical data collected in the real world. In this research, the

phenomenon model is developed in study 2 and reported in paper E. A phenomenon model can be developed in a more detail using formal ways of representation in information models. Information models can then be used as a support for the development of computer models. A method for information modelling is proposed in this research as part of the PS stage in study 3. In study 4, the information modelling method was applied, and information models were developed.

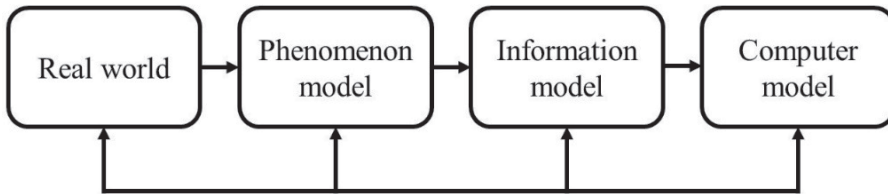


Figure 3 DRM according to Duffy and Andreasen (1995).

### 3.2. Case study research

Collecting empirical data using case study research allows the researcher to gain an understanding of the studied phenomenon in a real-life context when the boundary between the phenomenon and the context is not sufficiently clear (Yin, 2013). In addition to descriptions of phenomena, case study research can also be used for the theory building and theory testing (Cavaye, 1996). Theory building is usually related to inductive approaches of investigating a phenomenon using grounded theory. In contrast, theory testing using case study research requires a deductive approach, where theoretical propositions are derived from either an existing theory or from the results of another empirical data analysis (Williamson, 2002).

In terms of philosophical traditions, both the positivists and the interpretivists use case study research. While the positivists in their use of case study research focus on controlled observations and deductions, replicability and generalizability, the interpretivists focus on the evolution of in-depth descriptions of specific cases to understand and describe phenomena. The concept of external validity, i.e. generalization, in contrast to predictive ability, refers to the value of in-depth descriptions of phenomena and research reliability that enables the studying and comparison of the phenomenon in other settings (Walsham, 1995).

A case study design can be holistic if one unit of analysis is used or embedded if two or more units of analysis are used. Moreover, a case study design can be single or multiple if the units of analysis are analysed in one context or two or more contexts, respectively (Yin, 2013). To define units of analysis, identify knowledge gaps and define research questions, a comprehensive literature review

must be conducted. Suitable data collection and analysis techniques must be selected for the case study research so the adequacy and validity of the evidence collected can be established (Williamson, 2002).

### 3.3. Research strategy

In this chapter, a description is given as to how the papers (A–G), the four conducted studies, the research questions, the research's focus regarding product platform is clarified and the stages of the DRM framework are connected (Figure 4). The research process was not linear but iterative. The RC and DS-I stages were undertaken in two iterations. Reporting on study 1, papers A and B address the initial RC and DS-I stages, while paper C addresses the first iteration. Papers D and E (study 2) address the second (final) iteration. Study 3, reported in papers F and G, addresses the PS stage, while study 4 is reported in paper G and addresses both the PS and DS-II stages. The research focus regarding product platform has shifted throughout the conducted studies from the manufacturing phase to the design phase of the product realization process in single-family IHB. Study 2 has a holistic research focus regarding product platforms. The data collection and analysis from each study are briefly introduced below. References are made to the appended papers for detailed descriptions of the data collection and analysis.

#### 3.3.1. Study 1

Study 1 resulted in papers A, B and C. The complete data collection and the data analysis for papers A and B took place during the first part of the researcher's PhD studies (before the Licentiate degree was obtained), while the data analysis for paper C took place at the beginning of the second part (right after obtaining the Licentiate degree). The study addresses the initial and the first iteration of the comprehensive RC and DS-I stages, i.e. both the literature review and the empirical data collection and analysis (in a case study) were conducted. The focus of paper A and paper B in terms of product realization was on manufacturing, while the focus of paper C was on both the manufacturing and design phases. The empirical data collection technique used in study 1 included video recordings, informal interviews, observations, documents and secondary data from four master thesis projects (paper B). Workshops were conducted for the validation of the empirical data and discussion of the results.

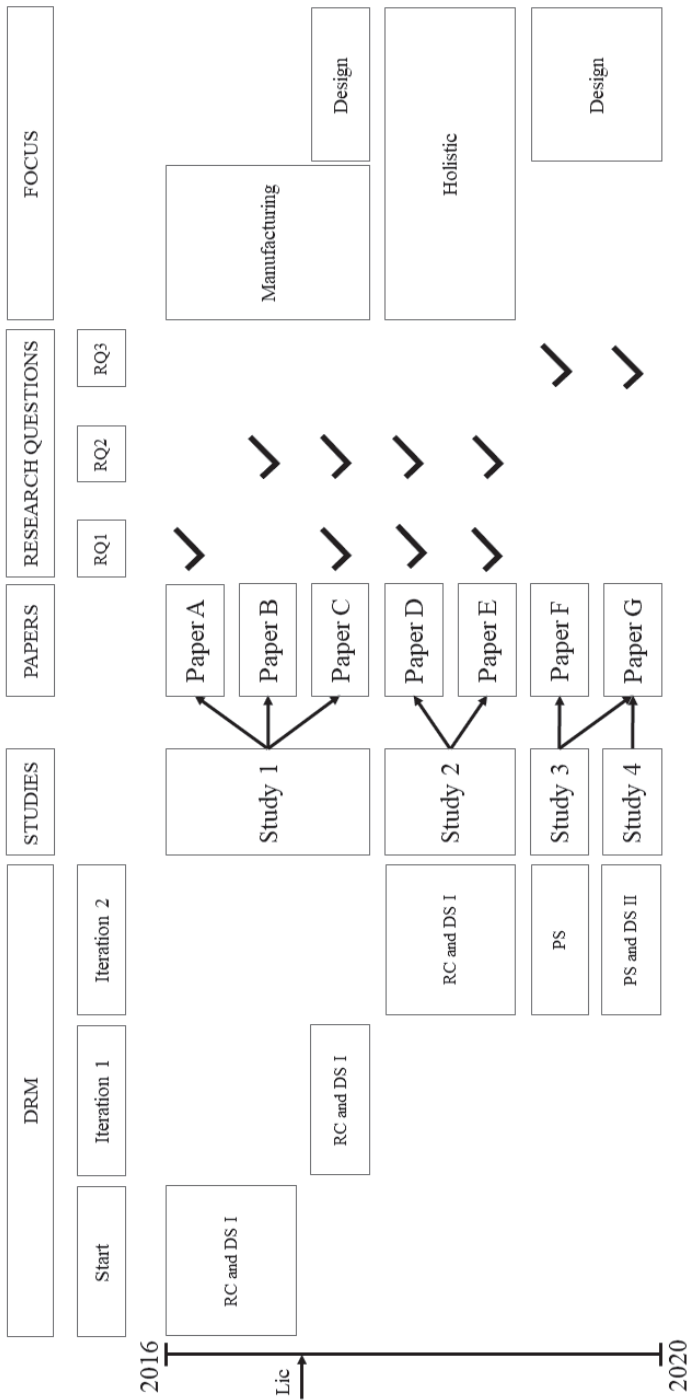


Figure 4 Research strategy.

### 3.3.2. Study 2

Study 2 encompasses the second and final iteration of the RC and DS-I stages. The study is comprehensive as both literature review and empirical data collection and analysis were conducted with a holistic focus in terms of product realization. The study is reported in paper D and paper E. The empirical data collection was conducted with two fellow PhD students who do research in the IHB context in similar research fields but with different focuses. Moreover, the literature review and empirical data analysis for paper D were conducted in this collaboration. The empirical data (used for the analyses in both paper D and paper E) were collected in two companies. The semi-structured interviews were chosen to collect the major part of the empirical data. A part of the data was collected through observations in the manufacturing facilities. The additional sources of data were in the form of recorded interviews and meetings on various occasions related to the development of both new building systems and manufacturing systems. Moreover, documents regarding design processes, product families, building systems and manufacturing systems were studied. Finally, a contextual pre-understanding was built through observations made during numerous visits to the manufacturing facilities. In both papers, a multiple embedded case study design was applied as several units of analysis. In paper E, the units of analysis, specifically, the business model building blocks and the external business environment elements and the alignment between them, were used to describe product platform alignment phenomenon. Workshops were conducted in both companies as a final verification step to ensure the validity of the results.

### 3.3.3. Study 3

Study 3 is a review-based study with a focus on the design phase, and it addressed the PS stage of the DRM framework. The support for the product platform use in the design process of single-family IHB was proposed based on the literature review and inputs from study 1 and study 2, i.e. the identified challenges and internal and external factors. Study 3 was reported in paper F and paper G. The method conducted in the study is composed of the following three parts: a literature review, an analysis of the relevant information modelling methods and a synthesis of the information modelling method that suits the product platform use in the design process of single-family IHB, i.e. addressing the challenges when adopting high-level MC.

### 3.3.4. Study 4

Study 4 addresses the PS and DS-II stages of the DRM framework and resulted in paper G. In study 4, the literature review from study 3 was complemented by an additional literature review, specifically, literature on the design module construct and

high-level MC. The empirical data were collected through a series of interviews with open-ended questions with the personnel, two workshops and document analysis. A single embedded case study design was implemented by applying the proposed information modelling method on the collected empirical data and the proposed design process that includes the configuration of flexible volumetric elements. Hence, a review-based PS from study 3 was complemented with the single embedded case study in study 4. The units of analysis were the proposed information modelling method and the design module construct. DS-II was initial as the evaluation of the proposed support was based on a workshop technique organized with the participants from the company.



## 4. Empirical foundation

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*To provide the contextual understanding of the conducted research, a holistic description, i.e. a description of the business models and their elements in two single-family IHB companies based on empirical data, is given. Hence, market position, offering and product platform are briefly described.*

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The two IHB companies selected are Swedish producers of single-family houses. The companies sell houses across the whole Swedish market and hence deliver houses to different climate zones. They are direct competitors of each other, with two very similar business models each. The market positions and offerings are very similar between the two pairs of business models. The differences, however, can be seen when comparing their product platforms. With two business models combined, Company 1 produces on average 1300 houses per year, while Company 2 produces 500 houses per year (Table 2).

Table 2 General description of case companies.

<i>Company</i>	<i>Houses /year</i>	<i>Number of employees</i>	<i>Business model</i>	<i>Prefabrication of</i>	<i>Degree of predefinition</i>
1	~1300	793	BM 1a	Volumetric elements	High
			BM 1b	Panelized elements	Low
2	~500	252	BM 2a	Panelized elements	High
			BM 2b	Panelized elements	Low

### 4.1.1. Market position

Both Company 1 and Company 2 have vertical integration across their supply chains, guaranteeing product quality and delivery in all outlined business models. Subcontractors are hired locally where the houses are built for the processes of foundation preparation and finishing work. Moreover, consultancy firms are engaged as suppliers of engineering services in the design process. BM 1a and BM 2a target a market niche where customers are young families of lower to medium income. In contrast, BM 1b and BM 2b target a broader market, where customers are medium- to high-income families.

### 4.1.2. Offering

The offerings of BM 1a and BM 2a include catalogues of predefined house models and customization options, where the modular configuration of a predefined

assortment and simple floor plan adjustments by adding or removing inner walls are available. In contrast, the offerings of BM 1b and BM 2b are more flexible and include catalogue house models that have a lower level of predefinition than the catalogue designs in BM 1a and BM 2a. In BM 1b and BM 2b, the customization options include the configuration of high-standard predefined assortment and the modular and scalable configuration of geometry. The offering of BM 2b even includes customization where customers can require unique solutions, e.g. choosing from outside the predefined assortment.

### 4.1.3. Product platform

Both companies have developed building systems based on timber-frame structural components, from which assemblies and panelized elements are prefabricated. Moreover, panelized elements are combined with other systems, such as kitchen, bathroom and mechanical, electrical and plumbing (MEP) systems to prefabricate volumetric elements in the case of BM 1a (described in paper G). In terms of design flexibility and process efficiency, MEP systems are one of the main differentiating factors between panelized elements and volumetric elements prefabrication. In panelized elements prefabrication (BM 1b, BM 2a and BM 2b), MEP systems are completed on-site by subcontractors, while in volumetric elements prefabrication, MEP systems are pre-assembled in the factory environment. Despite the process efficiency benefits of volumetric elements prefabrication, the design flexibility is limited due to the required level of detail for fabrication information and outsourced processes of MEP systems' dimensioning and their integration with structural systems. The building systems within each company, for example the exterior wall elements, share commonalities to a large degree as they address the same legal requirements and codes, customer needs, BIM applications, other IT systems and manufacturing systems. A detailed description of the building system for exterior wall elements in Company 1 is given in paper C.

The current manufacturing systems in Company 1 were bought at the end of the 1980s and were optimized according to a building system that was used for the design of standard-type houses at that time. The development of the building systems and the choice of suppliers for materials and assortment were influenced by changes in customer needs, legal requirements and codes. However, the manufacturing systems were not developed with a concurrent progress alongside the building systems. This has negatively affected the efficiency of the manufacturing system. Detailed descriptions of exterior wall assembly lines in Company 1 are given in paper A and paper C.

Regarding product realization, there are very few process commonalities in Company 1 between the two business models, mainly due to different degrees of the predefinition and prefabrication used. The two business models of Company

2 share many process commonalities in the phases following manufacturing as the company uses prefabricated houses in assemblies and panelized elements. Company 1 has over time digitalized parts of its processes through various IT systems, such as BIM applications and an ERP system. The main BIM applications Autodesk Revit® used as 3D CAD modelling and hsbcad® used for fabrication data. The company has developed an automatic unidirectional information exchange between the two BIM applications as well as automatic quantity take-off between hsbcad® and the ERP system. Company 2 currently only uses Autodesk Revit® and no separate BIM fabrication application due to the low use of digital manufacturing. Nevertheless, the company utilizes object-based parametric modelling to a higher degree within Autodesk Revit® compared to Company 1. BIM models are enriched with information that enables design analysis. The detailed design process for BM 1a is given in paper G.

By using IT systems, parametric models and automatic information exchanges between BIM applications, both companies have to a certain degree formalized the knowledge regarding their product platform assets, which enables efficient reuse in processes. However, most of the knowledge is still held by the individuals in the research and development (R&D) group as well as the operational staff in the form of know-how and experience to manage the processes. Both companies tend to keep long-term and stable relationships with their suppliers, which positively affects the quality of their products, shorter lead times and lower product prices. Suppliers deliver materials, assemblies and assortment options as well as design analysis and synthesis services, such as different performance and functional analyses and MEP systems engineering.



## 5. Results

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*The results are structured below according to the research questions they address. References are made to the papers these results are parts of and the studies within which the research was conducted.*

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### 5.1. Product platform alignment

The first part of the results provides the answer to RQ1 – *How are product platforms developed and used in single-family IHB from a business model perspective?* The phenomenon of product platform alignment can be used to describe how product platforms are developed and used in single-family IHB from a business model perspective. The product platform alignment model (Figure 5) is synthesized based on the analysed empirical data collected in study 2. The model is presented solely in paper E; however, it is also in line with the findings reported in papers A, C and D (Figure 4). Product platforms in single-family IHB are developed and used through five alignment modes. The development of product platforms takes place in alignment modes 1, 2 and 5, while the use of product platforms takes place in alignment modes 3 and 4 (Figure 5).

**Alignment mode 1.** The top management (5) of a single-family IHB company makes a strategic choice regarding market position (4). The choice defines the target market/s (1), the role in the product realization and the legal responsibility (2). Current and future customer needs (1) and market risks/opportunities (3) are analysed. A set of requirements and constraints is formulated by the R&D department (6), which are used as input for the development of building system(s) (8).

**Alignment mode 2.** As inputs for the development of building systems, the requirements derived from the external business environment in the product dimension are complemented by the constraints of the following product platform elements: manufacturing systems (9), chosen suppliers' offerings and relationships (10) and IT systems (11). However, an interplay takes place between these elements, the building system (8) and the R&D department (6) if the requirements from the external business environment do not match the solution space of the product platform.

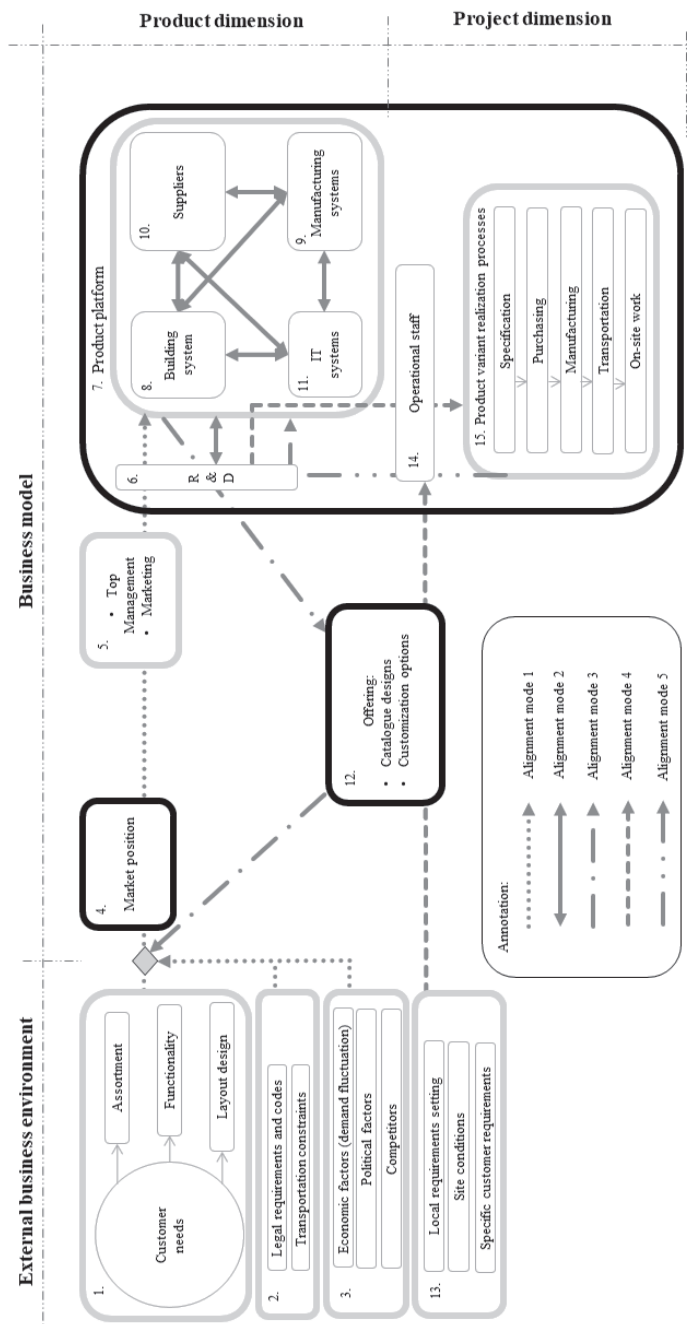


Figure 5 Product platform alignment model.

**Alignment mode 3.** An offering (12) is developed using product platforms, specifically, the R&D department and consultancy firms perform architectural and engineering designs based on the product platform solution space. The developed offerings can concurrently enable efficient product variant realization and be flexible to match the requirements of the external business environment in the product dimension. A company usually offers a catalogue of predefined products and basic customization options, such as the modular configuration of predefined assortment options and layout changes. High-level customization in contrast, requires lower product predefinition. These customization options imply modular and scalable configurations of geometry and are included in highly flexible offerings.

**Alignment mode 4.** The product specification is realized by operational staff (14) when the customer enters the supply chain. This is the use of product platforms in the project dimension that covers the whole product variant realization process (15). The offering is matched with the requirements of the external business environment in the project dimension (13). Besides the specific customer requirements, additional requirements for product specification can be caused by other situational contingencies, i.e. the local requirement setting and the site conditions. Depending on the customization options offered and the match between these parameters and the parameters of the situational contingencies, additional architectural and engineering design might be required during product specification. In such case, the operational staff, R&D department and consultancy firms cooperate to develop a platform-based product variant.

**Alignment mode 5.** The situational contingencies and their parameters can influence each phase of product variant realization. After each phase, the operational staff can provide experience feedback for the R&D department regarding the effects and consequences of adjusting to these parameters. Experience feedback can then be used as input for the potential improvement and further development of a product platform.

## 5.2. Challenges

This part of the results provides an answer to RQ2 – *What are the challenges for the development and use of product platforms in single-family IHB when adopting high-level MC?* The challenges for the development and use of product platforms in single-family IHB when adopting high-level MC are common to both Company 1 and Company 2, as determined from study 2. The identified challenges are caused by both internal and external factors, i.e. the business model and the external business environment factors. The identified internal and external factors and challenges (Table

3) are reported in paper E and partly in paper D, based on the empirical data collected in study 2. However, some internal and external factors were also identified in study 1 and reported in paper B and paper C.

Following is the description of the five identified challenges for the development and use of product platforms in single-family IHB when adopting high-level MC:

- 1) Both companies currently face the challenge of achieving the seamless information exchange that is a consequence of how product platform information is managed between R&D, operational staff and IT systems. Moreover, the resistance to change towards digital development and IT system integration is another internal factor causing this challenge.
- 2) Developing optimized solutions for the product and component predefinitions in offerings aiming at a market niche (BM 1a and BM 2a) and achieving efficiency in these processes is a challenge. During the development, the R&D department of a company cooperates with engineering design consultancy firms, where the knowledge on both legal requirements and constraints stemming from the product platform solution space are combined through an iterative process with long lead times and that lacks structure. The low extent of formalized product platform knowledge hinders its efficient reuse during an offering development.
- 3) The offerings aiming at market niche, i.e. with a high level of predefinition, are sensitive to demand fluctuations, political decisions and changes in competition with other companies. These market risks and opportunities are considered when the product platform and the offerings are developed. However, when the changes occur, customers gain more negotiating power regarding specific requirements, according to which changes need be made to the already optimized and predefined product designs for the high level of prefabrication, often in volumetric elements. However, it is a challenge to lower the level of predefinition and achieve efficiency in the product specification processes. This challenge also occurs due to the contingent site conditions and the variation of legal requirements across climate zones. Developing optimized and predefined product designs according to the climate zone in the market(s) with highest sales minimizes the design variation but causes over-/under-dimensioned solutions in other markets.

Table 3 Challenges for the development and use of product platforms in single-family IHB when adopting high-level MC.

	<i>Challenge</i>	<i>Internal factors</i>	<i>External factors</i>
1	Achieving seamless information exchange	Management of product platform information  Resistance to change	
2	Achieving efficiency when developing product predefinitions	The extent of formalized product platform knowledge  Optimized and highly predefined product designs for a market niche	Changes in customer needs  Changes in legal requirements and building codes
3	Achieving efficiency during product specification	Optimized and highly predefined product designs for a market niche  Volumetric element prefabrication	Demand fluctuations, political decisions, and changes in competition  Specific requirements that include dimensional configuration  Variation of legal requirements across climate zones  Contingent site conditions
4	Keeping the configuration of product variants within product platform solution space	The extent of formalized product platform knowledge	Specific requirements that include dimensional configuration  Local requirements setting
5	Adjusting product platform solution space	Focused flexibility of manufacturing systems	Changes in customer needs  Changes in legal requirements and building codes

- 4) Customers often have specific requirements that extend outside the product platform solution space; in other words, unique solutions are required. An interpretative local requirement setting is a common phenomenon that occurs when the design of a house is evaluated by the municipality officials for the building permit and can result in similar requirements for the design changes. Consequently, due to the low extent of product platform knowledge formalization, there is a challenge in keeping the configuration of product variants within the product platform solution space.
- 5) New customer needs emerge, and new legal requirements are introduced frequently, which can cause a need for a company to adjust their product platform solution space. However, often, only building systems are developed without any change in manufacturing systems as companies cannot always afford the investments needed, and the manufacturing systems have automated equipment (paper A) with a focused flexibility that cannot be adjusted (paper C). New building system solutions are ‘pushed’ to manufacturing, which in consequence results in lower manufacturing process efficiency (paper B).

### 5.3. Support

The results providing the answer to RQ3 are presented in this section – *How can the development and use of product platforms be supported in single-family IHB to address the identified challenges?* The results are divided into two parts, as follows: (1) information modelling method and (2) configuration of flexible volumetric elements.

#### 5.3.1. Information modelling method

Based on the literature review (study 3), an information modelling method is proposed and introduced (paper F). A detailed description of the method is found in paper G. The information modelling method enables the modelling of product platform use in the design process of single-family IHB. The method is a synthesis between the DP (André, 2019) and the IDM, as presented by Ramaji et al. (2017), and consists of the following three parts: process modelling, information exchange modelling and product platform modelling. The first two parts of the method are based on the IDM while the DP is used as a product platform information model (Figure 6).

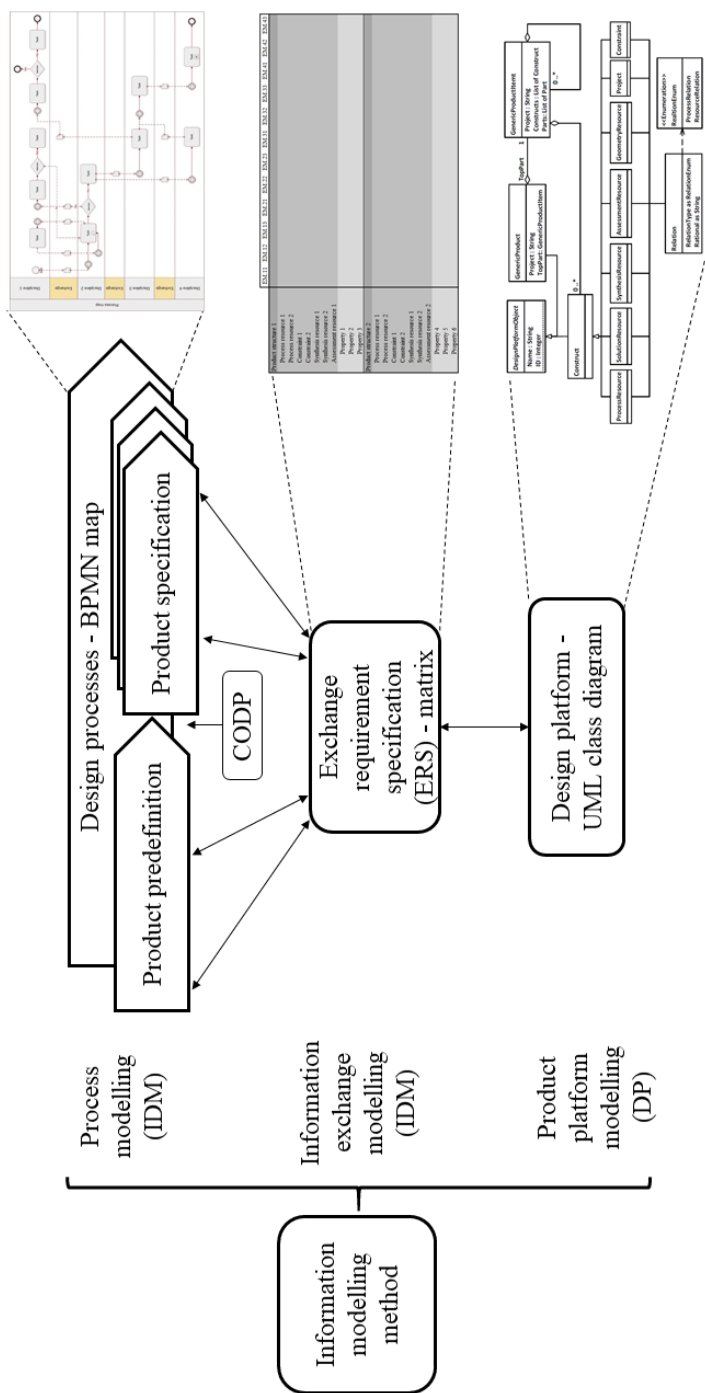


Figure 6 Proposed information modelling method.

As the IDM prescribes, the modelling of design processes is done by using business process modelling notation (BPMN) maps. The BPMN maps are a formalized way of representing how task units, exchange models and disciplines involved are connected. The exchange models connect the task units between two different disciplines and indicate when the information exchanges occur. The content of the exchange models cannot be represented in a BPMN map. Instead, each exchange model has a unique three-part code that is also found in the exchange requirement specification (ERS) which, as demonstrated in Figure 7, provides a description of exchange models' content, i.e. the DP objects. The exchange models and the DP objects are organized and presented in the ERS as columns in the sequence they appear on the BPMN process map. The DP objects are instantiated throughout the design process from the generic DP model (Appendix B). Each DP object contain two types of attributes, product structure and design asset attributes. These attributes and the DP object classes are organized and presented in the ERS as rows. A single cell in the ERS represents an information unit which is marked with an inclusion status. Three types of inclusion statuses as defined by Ramaji et al. (2017) are as follows: (G) when the information unit is generated, (M) when the information unit is received and modified and (T) when the information unit is received and transferred without any modification. As the already-developed design assets are reused when modelling new predefinitions and/or variants, a 'reuse' inclusion status (R) is the fourth type of inclusion status for the information units introduced in this research.

When a standard component is modelled, it has a solution resource (BIM model) as a design asset. Moreover, all its substructures also have solution resources. These DP objects are predefined and reused in the design process of a product variant. Alternatively, non-standard and non-predefined components are flexible and are modelled using various design assets other than solutions, which are reused, generated, modified and/or transferred throughout the design process.

### 5.3.2. Configuration of flexible volumetric elements

The configuration of flexible volumetric elements is proposed as a means to combine the product realization efficiency achieved using the prefabrication of houses with volumetric elements and the offering flexibility achieved using the prefabrication of houses with panelized elements. However, such approach shifts parts of the architectural and engineering design from product predefinition to product specification. A full predefinition of a product's geometry is avoided in the proposed approach, and instead early design assessments and object-based parametric modelling that complies with the building system constraints are conducted to enable the efficient specification of product variants (Appendix A).

Annotation:  
G - generated  
M - modified  
T - transferred  
R - reused

DP object classes and attributes	Design process											
	Product predefinition						Product specification					
	Conceptual design			Parametric design			Configuration			Detailed design		
	PE.1	EA.1	AP/E.1	PEA.1	AK.2	KA.2	AP.2	PA.3	EA.3	AM.3	MA.4	AE.4
House part												
Subpart												
Design asset												
Flexible VE												
Exterior wall 1												
Exterior wall 2												
Interior wall 1												
Interior wall 2												
Floor												
Ceiling												
Constraint 1												
Constraint 2												
Requirement 1												
Requirement 2												
3D CAD object												
Parametric object												
BIM object												
Fabrication object												
Constraint (Building system)												
Assessment resource (Energy)												
Assessment resource (Structural)												
Geometry resource (Param. model)												
Synthesis resource (hmlx link)												
Process (Prel. Tech. Ass.)												
Project												
Solution resource (BIM model)												
House part												
Subpart												
Design asset												

Flexible VE object and its attributes  
instantiated from the design platform model

Figure 7 ERS example for a flexible volumetric element.

Due to the compliance of parametric models and their scalable bandwidth with the building system constraints, the amount of required engineering in the detailed technical audit of a product variant can be reduced to the assessment tasks regarding the fulfilment of performance and functional requirements. Another potential efficiency increase can be achieved in the product specification if the company, instead of the consultancy firm, conducts the modelling of the MEP system solution in their architectural design BIM model. The fabrication model can then be generated using the proprietary link between the architectural design and fabrication BIM applications, which automates the integration between the structural and MEP systems within the panelized elements. Given that the object-based parametric modelling task establishes the modular and scalable bandwidth of the flexible volumetric elements and the set of panelized elements that is governed by the building system constraints, the proprietary link would generate valid solutions for the fabrication model.

An example of ERS is given in Figure 7 to describe how information exchanges occur in the proposed design process for the configuration of flexible volumetric elements and the use of product platforms in single-family IHB (Appendix A). The product structures and the design assets of a 'Flexible VE' from the DP model (Appendix B) are presented as rows in the ERS. It is an example of how the design modules can be modelled using the design assets throughout the design process.

A flexible volumetric element is generated during the product predefinition part of the design process (AP/E.1 exchange model). The design assets that describe it are transferred contingent constraints and requirements, a 3D CAD object of the conceptual design of the house and the preliminary technical assessment process that is reused. Other attributes describing it are the generated ingoing product structures, specifically, the panelized elements it is composed of. An input and a support for the development of a new parametric object for the flexible volumetric element, are the existing design assets that are reused, i.e. the previous parametric model, the previous project and or the previous solution, such as a BIM model (P/EA.2). The flexible volumetric elements and the set of panelized elements it is composed of are configured and modelled with BIM objects, which are their solution resources (AE.3). However, the BIM objects might need modification in cases where the reuse of assessment resources indicates that the configuration does not fulfil the functional and/or performance requirements. The proprietary link (.hmlx) is reused as part of the flexible volumetric element object in the AF.4 exchange model. A fabrication solution for the structural system integrated with the MEP system within the panelized elements (Fabrication object) is then developed automatically.

## 6. Discussion

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*At the outset of this chapter, the results are connected and discussed in relation to how and to what extent they provide answers to the research questions. Moreover, when associated to the points of departure in the chosen scientific fields, as presented in the frame of reference, the way in which the results add knowledge contributions to these scientific fields is discussed. After that, initial evaluations of the prescriptive parts of the research and industrial implications are presented. Finally, the conducted research methods are discussed in terms of research quality and research process.*

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### 6.1. Connecting the results

The focus of the result answering RQ1 is holistic as it provides in-depth strategic knowledge of the development and use of product platforms in single-family IHB by investigating the phenomenon of product platform alignment. In contrast, the focus of the result answering RQ3 provides in-depth design phase knowledge, demonstrating how the development and use of product platforms can be supported to address the identified challenges when adopting high-level MC, that is, the result answering RQ2. Hence, the connection between the results answering RQ1 and RQ3 can be made through the result answering RQ2 (Figure 8).

The proposed support is composed of the following two parts: (1) an information modelling method and (2) the configuration of flexible volumetric elements. Both parts of the support are meant to address a set of challenges each by impacting the internal factors. The first part of the support (1) addresses challenges 1–4 by impacting the following internal factors in a single-family IHB business model: the management of product platform information, the extent of formalized product platform knowledge and optimized and predefined product designs for a market niche. The second part of the support (2) addresses challenges 2 and 3 by impacting the following internal factors in a single-family IHB business model: optimized and predefined product designs for a market niche and the volumetric element prefabrication (Figure 8). Alternatively, the identified challenges are related to the development and/or use of product platforms. Hence, the rationale of how the proposed support is related to the development and use of product platforms in single-family IHB is possible to describe (section 6.2.3).

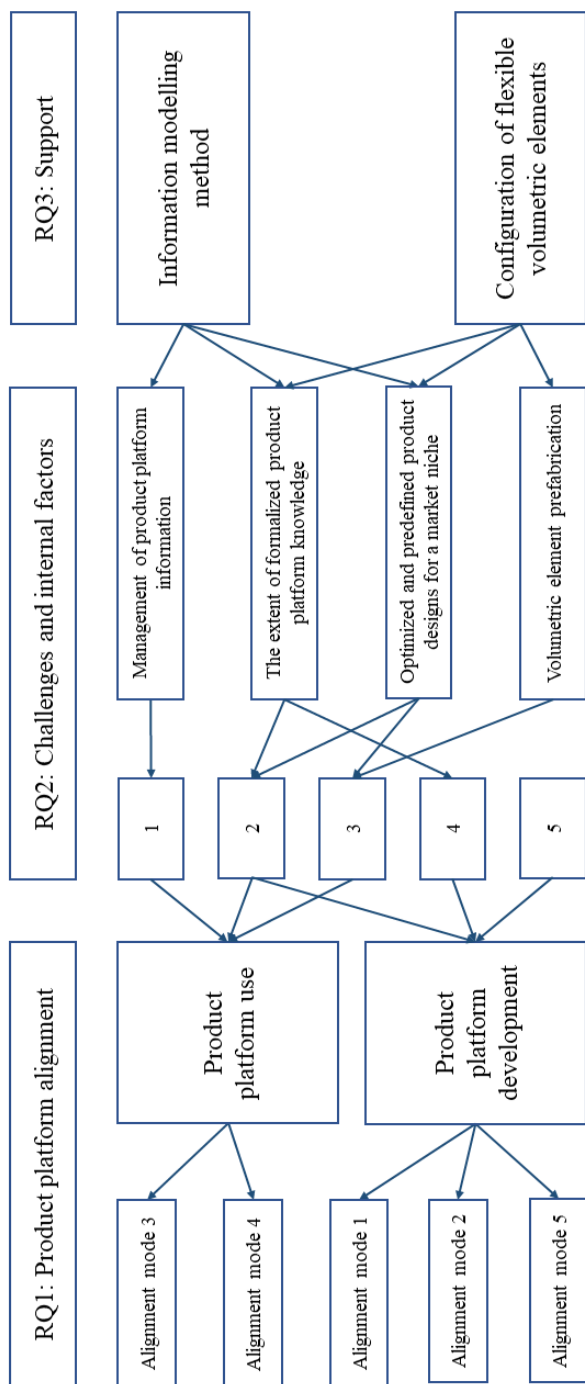


Figure 8 Connections between the results.

## 6.2. Answering the research questions

Answers to research questions can be provided by the results to differing extents. Whether and to what extent the results presented in Chapter 5 provide answers to the research questions is discussed in the following paragraphs.

### 6.2.1. RQ1

*‘How are product platforms developed and used in single-family IHB from a business model perspective?’*

Knowledge about the development and use of product platforms in IHB from a business model perspective has been previously studied, and the knowledge is dispersed across the literature about IHB business models (Brege et al., 2014; Hall et al., 2019; Lessing & Brege, 2015, 2018) and product platforms in IHB with a strategic focus (Bonev et al., 2015; Jansson et al., 2014; Johnsson, 2013; Lessing et al., 2015). However, these case studies were chiefly conducted in the multi-family IHB context. In this research, the knowledge about the development and use of product platforms in IHB from a business model perspective was encompassed into the phenomenon of product platform alignment. The product platform alignment phenomenon is considered relevant to answer RQ1 as studying the fit and interplay between product platform elements, offering, market position and the external business environment can be used to clarify how the development and use of a product platform takes place in a single-family IHB company.

Hence, in study 2 the empirical data collection was conducted in two single-family IHB companies, and the product platform alignment model was synthesized based on an empirical data analysis using the theoretical constructs derived from the literature (Aitchison, 2017; Brege et al., 2014; Robertson & Ulrich, 1998; Sutherland, 2004; Viking & Lidelöw, 2015). The model was divided into five alignment modes, and by describing each of these modes the answer to RQ1 was provided. The way the product and project dimensions occur in the phenomenon and divide the business model is in line with the findings of Lessing et al. (2015). Moreover, product and project dimensions can be identified in the external business environment (Figure 5). However, in addition to the risks and opportunities that a single-family IHB company can face in the market being considered during product platform development (alignment mode 1 and alignment mode 2), the changes in economic, political and/or competition factors influence product platform use when product variants are specified (alignment mode 3). Hence, this part of the external business environment is positioned at the interface between product and project dimensions. This result also builds upon the existing knowledge with a detailed description of the phenomenon in single-

family IHB, which has been missing. Moreover, the empirical part of study 2 also included the validation of the product platform alignment model and identified alignment modes by the case companies to ensure the phenomenon captures the industrial practice. Hence, the product platform alignment model provides a comprehensive answer to RQ1.

### 6.2.2. RQ2

*‘What are the challenges for the development and use of product platforms in single-family IHB when adopting high-level MC?’*

The answer to RQ2 enriches the description of the product platform alignment phenomenon as the identified five challenges are encountered by the case companies in relation to the alignment modes when the described combinations of internal and external factors occur. The identified five challenges are the summaries based on the empirical data analysis primarily in study 2 and secondarily in study 1. RQ2 was not explicitly asked during the interviews in the case companies (study 2); however, the interviewees pointed out these challenges in connection with the need for customization, increased flexibility and efficiency in the processes, that is, internal and external factors. Hence, the identified five challenges matched with what the adoption of high-level MC entails in their business models. Moreover, the challenges are in line with what has been reported in the previous research focusing on MC in IHB. The following discussion is about how each of the five identified challenges relates to MC, thereby clarifying how these results provide an answer to RQ2.

Achieving seamless information exchange becomes a challenge when the management of product platform information between R&D and operational staff is not structured and understood equally by all individuals. The use of various IT and BIM applications, where product platform information can be stored inconsistently, additionally hinders achieving seamless information exchange. Seamless information exchange is also recognized as a prerequisite for MC adoption by Jensen et al. (2019).

The issue with predefined product designs for a market niche is the risk of investing a substantial amount of time and resources into the development of offerings that might not match what customers want. The complete architectural and engineering design must be done before the customer order decoupling point (Johnsson, 2013). Consequently, optimized product designs with chiefly integral architectures are developed (Jensen, 2014) to be prefabricated in panelized and volumetric elements. However, to adopt high-level MC, a single-family IHB company must be able to introduce new and flexible product designs when

changes in the external business environment occur while using less time and resources than it commonly does during product predefinition process.

The efficient specification of products through dimensional configurations that can rapidly be manufactured off-site and assembled and finished on-site is what customers value (study 2) and what is considered to be a prerequisite for the adoption of high-level MC (Khalili-Araghi & Kolarevic, 2020; Larsen et al., 2019). Optimized and predefined product designs for a market niche in combination with volumetric element prefabrication cannot be customized or adapted without significant penalties in cost and time (Jensen, 2014; Lessing et al., 2015).

Keeping the configuration of product variants within the product platform solution space is a prerequisite for the adoption of MC (Larsen et al., 2019). How an interaction takes place between the customers and the operational staff at the front end of product variant realization is a complex phenomenon that cannot be comprehensively covered within the scope of this thesis. However, what study 2 indicates is that the knowledge about product platform assets, such as building system constraints, cannot be distributed efficiently to sales personnel and other operational staff if it is solely held by R&D individuals. The lack of formalized product platform knowledge also causes this challenge when the local planning authorities require design changes for the approval of the building permit.

The identification of the fifth challenge – adjusting the product platform solution space – is supported by the results of study 1. The conducted observations and analysis of the levels of automation (paper A) and waste in manufacturing systems (paper B), and the alignment with the building system and design phase in terms of the information required to run the operations in the manufacturing system (paper C), point to the challenge of developing the manufacturing system concurrently with the IT and building systems. This challenge is also identified in the literature study conducted by Larsen et al. (2019), and the case studies conducted by Hall et al. (2019), and Johnsson (2013).

### 6.2.3. RQ3

*‘How can the development and use of product platforms be supported in single-family IHB to address the identified challenges?’*

The connections between the proposed support and the development and use of product platforms in single-family IHB are described in section 6.1. More specifically, addressing the identified challenges was motivated by describing which of the internal factors is impacted by the support (Figure 8). Therefore, to explain the extent to which this result provides an answer to RQ3, the discussion

of how and to what extent the proposed support impacts the internal factors is given in the following paragraphs.

The information modelling method is a synthesis between the DP (André, 2019) and the IDM (Ramaji et al., 2017). As the IDM was developed to support information management by modelling the information exchanges of a modular building system throughout the design process, replacing the PAM (Ramaji & Memari, 2016) with the DP expands the scope of the IDM to enable the modelling of product platform use. The DP enables the modelling of the generic product structures and design assets by using UML diagrams. The BPMN maps demonstrate the sequence of the tasks and the connections between the disciplines via the exchange models in the design process. Finally, the ERS is a matrix describing the content of the exchange models, i.e. describing how DP objects are instantiated throughout the design process. Hence, implementing the proposed information modelling method provides the formalization of product platform knowledge in a UML class diagram (Appendix B). Such generic representation of product platform knowledge (Bruun et al., 2015) can be used as a foundation for the setup of a PLM system (Sacks et al., 2018), which in turn can be used for efficient product platform information management (André, 2019; Johannesson et al., 2017). The indirect impact of the support on this internal factor suggests that the first challenge – achieving seamless information exchange – is not fully addressed by the support. Consequently, the answer to RQ3 is not comprehensively provided in this respect.

Optimized and predefined product designs developed for a market niche in combination with a variety of external factors (as described in section 5.2) cause challenges in regard to achieving efficiency when developing product predefinitions (challenge 2) and during product specification (challenge 3). The proposed information modelling method enables the modelling of customizable products that cannot be fully predefined through the instantiation of DP objects during both product predefinition and product specification. This capability of the method can impact the change of strategy where optimized and predefined product designs are replaced with product designs that are less predefined and more flexible as it can clarify how the modelling of such products can be done throughout the design process. The ERS, as exemplified in Figure 7, and the process map (Appendix A) can aid the R&D and operational staff in visualizing (Ramaji et al., 2017) and creating a joint understanding of how a flexible product design can be modelled, what the available design assets to be reused are and what the design assets to be developed throughout the design process are. These design assets are used to model product components that are developed according to the customer-specific requirements. Such components can expand the product platform and be available for the future reuse (André, 2019). Hence, from the three internal factors, the management of product platform information and

optimized and predefined product designs for a market niche are indirectly impacted, while the extent of formalized product platform knowledge is directly impacted by the information modelling method (Figure 8).

The proposed design process for the configuration of flexible volumetric elements and the use of product platforms in single-family IHB (paper G) is the second part of the support that directly impacts optimized and predefined product designs for a market niche and volumetric element prefabrication. The proposed design process is in line with the view Khalili-Araghi and Kolarevic (2020) have on MC in single-family IHB. The support is derived from a combination of the design processes of two business models in company 1, BM 1a and BM 1b (paper E and paper D). The advantages of these two types of design processes in terms of the adoption of high-level MC are combined, i.e. the efficiency of product variant realization achieved by means of volumetric element prefabrication (BM 1a) is combined with the modular and scalable configuration during product specification (BM 1b).

By applying the information modelling method on the empirical data (study 4) and the proposed design process that includes the configuration of flexible volumetric elements, the modelling of design modules (Jensen, 2014) using design assets throughout the design process of single-family IHB is exemplified (paper G). Their configuration is in line with an MTO specification process as the solution is developed by configuring the parametric model into a BIM model (Figure 7). Moreover, the MEP systems solution and its integral architecture with the structural systems within these elements can be unique solutions (fabrication model) developed in an ETO specification process. Hence, the optimized designs are made on a lower level of product structure (Appendix B). This is also in line with the design module theoretical construct (Jensen, 2014). The proprietary (.hmlx) link in Company 1 is a synthesis resource that automates the integration between the structural and MEP systems. It is an example of formalized engineering knowledge realized in a BIM application (Sandberg et al., 2016).

The discussion regarding the answer to RQ3 presented above suggests that the proposed support addresses challenges 2–4 to a great extent, while challenge 1 is addressed to a lesser extent. Challenge 5 is not addressed by the support, which is discussed in section 6.6 and is also a part of the research limitations (section 7.1).

### 6.3. Knowledge contributions

A coherent description of the product platform alignment phenomenon is synthesized by applying theoretical constructs (units of analysis) from the fields of product platforms and business models (sections 2.1 and 2.4) on the empirical data collected in two Swedish single-family IHB companies (study 2). The knowledge contribution is made by introducing five alignment modes that are aggregations of identified interplays taking place between product platform, offering, market position and the external business environment. The identified challenges of developing and using product platforms for high-level MC additionally enrich the understanding of the phenomenon. The knowledge contribution is made to the field of product platforms through an increased understanding about the strategic aspects of the development and use of product platforms in the context of single-family IHB (Zhang, 2015). In the field of business models, the knowledge contribution builds upon the work of Lessing and Brege (2018) and Hall et al. (2019).

Knowledge contributions are made to the theoretical fields of product platforms and BIM by synthesizing the information modelling method. A new, modified version of the IDM is introduced as the scope of the product-oriented IDM as presented by Ramaji et al. (2017) is expanded from the modelling and exchange of product information during product specification to the modelling and exchange of product platform information throughout the design process of single-family IHB – both in product predefinition and product specification. This is done by replacing the PAM (Ramaji & Memari, 2016) with the DP information model (André, 2019). Moreover, the ERS, as introduced by Ramaji et al. (2017), is expanded with a new, R, inclusion status for the information units and specifies the position within the exchange models where existing design assets are reused. A contribution is also made to the DP modelling approach. Standalone, the DP does not cover the process and information exchange modelling. Hence, the BPMN process maps and ERS expand the DP in this respect.

The design modules introduced by Jensen (2014) are modular and scalable product platform components. The research presented in this thesis contributes to the field of product platforms by building upon the knowledge on the design modules (Jensen, 2014) by applying the information modelling method and the design module construct on the empirical data collected in study 4. The design module construct is modelled as a flexible volumetric element and the set of panelized elements it is composed of using design assets in the design process of single-family IHB. The knowledge contribution is made by demonstrating how the design module construct can be modelled as a part of a product platform, that is, by use of the design assets in the design process of single-family IHB when adopting high-level MC. The empirical study demonstrates how the flexibility of product concepts in offerings with lower levels of predefinition can be combined

with the volumetric element prefabrication while still achieving efficiency in both product predefinition and product specification. Moreover, the application of the information modelling method and the design module construct support the development of product platforms. As the design process can result in newly developed DP objects such as 3D CAD, parametric, BIM and fabrication objects, a product platform (Appendix B) can be expanded with new design assets, which become available for future reuse (André, 2019). Finally, the contribution is made by applying the DP in a new context – that of single-family IHB (study 4).

## 6.4. Evaluation of the support and industrial implications

The upper management of an IHB company can use the product alignment model to conduct a holistic analysis of business models and identify development opportunities. Moreover, as stated by the building system manager from Company 1 during the validation workshop (study 2), the product platform alignment model can be used by R&D and upper management as a support tool to communicate the holistic and strategic perspective behind the development and use of product platforms across the organization.

The proposed information modelling method was evaluated by the workshop participants regarding practicality, formalism and level of detail. The results of applying the information modelling method on the empirical data, i.e. the BPMN process map (Appendix A), the UML diagram (Appendix B) and the ERS (Figure 7), were presented to the workshop participants. The participants were able to understand well how to read the models and use the method after a brief introduction during the workshop. The processes of product predefinition, product platform and information exchanges were not modelled previously in Company 1, and, correspondingly, the shared opinion was that these lacked structure and possibility for efficient reuse. Only the process modelling of product specification had been previously conducted. For this reason, the shared opinion among the participants was that the method could be used to formalize product platform knowledge and communicate it across the organization using the developed models, such as to newly employed engineers. However, a lower level of detail in the developed models might be required. Another industrial implication of implementing the proposed information modelling method is that the formalized product platform knowledge can be used as input for the development of a database management system, such as a PLM system. The participants agreed that the level of detail should be higher as the user of information in that case is an IT application developer.

Company 1 currently has no database management system through which it can manage the design process workflow and integrate it with the product and resource information. The exchange of DP objects managed by a PLM system could potentially increase both the efficiency and quality of information flow in the design process. Moreover, such comprehensive management of product platforms could enable the availability of the design rationale of the technology development, that is, building and manufacturing systems. The participants of the workshop concluded that the benefits of implementing a PLM system would motivate well for its development cost.

The proposed design process for the configuration of flexible volumetric elements and the use of product platforms in single-family IHB was evaluated regarding its applicability, benefits and risks during the second workshop in Company 1 (study 4). There was a shared view among the participants of the workshop regarding the benefits. By implementing the proposed design process, a new type of flexible offering would be developed that would widen the market scope and thus lower the risk due to the lower amount of time and resources spent during the product predefinition, which is in line with the findings of Jansson et al. (2019). Other identified benefits were reduced time for the maintenance of catalogue designs that comprise the flexible offering and increased quality by using standardized processes. However, the participants also agreed that the flexible volumetric elements could enclose less technically complex parts of the house, such as bedrooms and living rooms. The reason for this limitation is that due to the complexity of MEP systems in the areas where a kitchen, utility room or bathroom is placed, high predefinition and standardization of volumetric elements would be needed. The participants agreed on the risk of identifying too narrow modular and scalable bandwidths for the flexible volumetric elements when all the requirements and constraints of the external business environment and building systems are considered during object-based parametric modelling. Finally, the participants of the workshop concluded that the individuals within R&D and operational staff need to develop a common understanding in regard to the development and use of product platforms when high-level MC is adopted. This would enable the potential benefits of the proposed design process and the product platform use – in other words, the concurrent achievement of efficiency in processes and a flexible offering – to be realized.

## 6.5. Research quality

The research quality can be discussed from a point of view of validity and reliability. Validity represents the extent to which the conducted research correctly answers the research questions and fulfils the research purpose (Kirk & Miller, 1986). The validity of research can be discussed more specifically in terms of internal and external validity. The internal validity of research is related to the extent to which the conducted research measured what it was supposed to measure (Miles & Huberman, 1994). The external validity of research is related to the extent to which the results of the research can be generalized (Meredith, 1998). Reliability refers to the description accuracy of conducted research steps (Kirk & Miller, 1986). It describes the ability of the conducted research and related results to be replicated by other researchers. Following is a discussion about the internal and external validity and reliability of the conducted research.

The internal validity of the conducted research was ascertained by using different techniques and sources during data collection in the conducted empirical studies, specifically, methods and sources triangulation (Williamson, 2002). The methods triangulation was achieved through interviews, observations, document analysis and workshops. Alternatively, the sources triangulation included interviewing different company representatives using the same interview guide and having different individuals present during the validation workshops. The methods and sources triangulation was conducted in study 1, study 2 and study 4. Conducting the validation workshops in the case companies included presenting the outcomes of the research and the empirical data to the participants of the workshops. The validation workshops were conducted for the empirical data and the results from study 1, study 2 and study 4. A limited validation approach was undertaken for the results reported in paper B, where the workshop was organized only in Company 1. The internal validity in study 3 was ascertained through discussion sessions with other scholars from the fields of product platform and information modelling.

Company 1 was used to collect empirical data throughout the entirety of the research, that is, in all four conducted studies. Company 2 was used for the empirical data collection in study 2, and four additional single-family IHB companies were used as case companies as part of study 1, in which secondary data were analysed. In case study research, external validity is often limited due to the inability to conduct research on a statistically significant number of cases that would enable the generalization of the results (Yin, 2013). However, in this research, case studies were conducted for the collection and analysis of empirical data, and the results were based on an in-depth scientific inquiry, where it is left to the reader's judgment whether or not the findings are applicable in another context. The proposed information modelling method, alternatively, is the result

of synthesizing the existing modelling methods from the theory, i.e. the IDM from the AEC (Ramaji et al., 2017) and the DP from the manufacturing industry (André, 2019) contexts. As the IDM enriched the DP in terms of the modelling of processes and information exchanges, by using a BPMN process map and ERS matrix, which are not context-specific (Sacks et al., 2018), the information modelling method could be potentially applied to other types of customized products other than single-family houses. Hence, the results of study 3 and study 4 increase the generalizability of this research.

To ensure the reliability of the conducted research, the data collection and analysis of all four studies are described in detail in the appended papers. Each study has been described in a step-by-step manner, which can enable other researchers to apply the same methodological procedure. However, in qualitative research, such as that presented in this thesis, the analysis of empirical data using a deductive approach can still be biased due to the researcher's background and prior knowledge. This can lead to different research outcomes in terms of results obtained and conclusions drawn. The reliability of the developed support for the development and use of product platforms when adopting high-level MC, that is, of the synthesized information modelling method and the configuration of flexible volumetric elements is ascertained with the detailed description of the support (paper G).

## 6.6. Research process

The research conducted within these PhD studies was partially funded by Company 1, which had influence on the focus of the research, being that it was suited to the needs of the company. The company also provided the main context for the collection of the empirical data. However, to conduct scientific research that results in knowledge contributions, the industrial need must intersect with the existing knowledge gaps derived from the literature, as identified in the frame of reference. Finally, the focus of the research is influenced by the experience, insights and knowledge of the PhD candidate at the time when the research plan is developed. As studies progress, the experience, insights and knowledge of the PhD candidate increase. However, that often affects the change in the focus as well.

From the outset of the PhD studies to obtaining a Licentiate degree, the focus of the research was on the manufacturing phase of the product realization process. Study 1 was conducted, out of which papers A, B and C were written. Although, paper C was written after the Licentiate degree seminar, the literature review and the empirical data from study 1 were used in the analysis. During the Licentiate degree seminar, valuable feedback was received, and the focus of the research shifted towards the design phase of the product realization process. Thereafter, in

studies 2–4, the research was planned and conducted according to the DRM framework. However, the case studies and literature reviews conducted under study 1 regarding the manufacturing phase provided important theoretical background and empirical results for the research conducted after the Licentiate degree seminar towards the end of the researcher's PhD studies. Hence, in the context of this thesis, study 1 provided the initial RC and DS-I and the first iteration of these two DRM stages, as illustrated in Figure 4. The results of study 1 regarding manufacturing systems and processes provided increased understanding of the constraints a manufacturing system imposes upstream in regard to the design of products via building systems and the need for a downstream flow of information from the design phase. This is also in line with the findings of Malmgren et al. (2011). A difficulty of following the DRM framework fully is that, often, a substantial amount of time is required to attain a comprehensive evaluation of the developed support (Blessing & Chakrabarti, 2009). These PhD studies were supported with a funding time limit of four years. Adding that a considerable amount of this time was spent on the RC and DS-I stages, the evaluation of the proposed support was conducted through a workshop in Company 1. Therefore, it was an initial DS-II stage.

A case study design was chosen for the qualitative data collection and analysis in the conducted literature and empirical studies, being studies 1, 2 and 4. The identification of the units of analysis through a literature review, and the empirical data collection and analysis, were hence conducted by the PhD candidate and other researchers who were the co-authors of papers A–G. The drawback of this approach to conducting qualitative research is the inclusion of the subjectivity of the researchers (Yin, 2013). The influence of subjectivity must also be accounted for in the synthesis of the support, that is, the PS stage of the DRM framework.



## 7. Conclusions

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*In the last chapter of this thesis, the main conclusions of the research and contributions are outlined. After that, the limitations of the conducted studies are clarified. Finally, directions for possible future research are given.*

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An important capability for single-family IHB companies of operating on high-level MC is identified, both in the literature and in the empirical studies. This capability can support these businesses in the current, often dynamic and volatile, external business environments. The high-level MC in this research refers to flexible offerings where product concepts are designed for a high prefabrication level but with a lower level of product predefinition to enable the modular and scalable configuration of the house geometry. Therefore, high-level MC implies concurrent realization of flexibility in the offering and efficiency in the product realization processes. Currently, product platforms are used in single-family IHB mostly to develop offerings for a market niche with lower-level MC. High levels of product prefabrication and predefinition are combined with delimited customization options, such as the modular configuration of product assortment. Hence, the purpose of the presented research was to add to the knowledge on the development and use of product platforms and support that enables the adoption of high-level MC in single-family IHB. The purpose is achieved by answering three research questions.

The answer to the first research question – ‘*How are product platforms developed and used in single-family IHB from a business model perspective?*’ – is provided by describing the product platform alignment phenomenon. The main conclusions are as follows:

- The development and use of a product platform can be encompassed by five alignment modes. Alignment modes describe the interplay between product platform, offering, market position and the external business environment.
- The development of product platforms takes place in the product dimension of a single-family IHB company. The inputs for the development of product platforms are from the external business environment in regard to product dimension, including customer needs, legal requirements and codes, transportation constraints, economic factors, political factors and competition. Moreover, inputs are provided from the project dimension when experience feedback takes place during product variant realization.
- Product platforms are used in the product dimension during the development of an offering, i.e. in product predefinition processes, and in the project dimension during the product variant realization.

- The parameters of the external business environment in the project dimension, including the local requirements setting, site conditions and specific customer requirements together with the parameters of the developed offering and product platforms, are inputs for the product specification. However, changes in economic, political and competition factors can lead the product specification outside the product platform solution space.

The answer to the second research question – *‘What are the challenges for the development and use of product platforms in single-family IHB when adopting high-level MC?’* – is provided by five identified challenges. The main conclusions are as follows:

- The identified challenges are caused by combinations of internal and external factors in the investigated companies.
- Achieving seamless information flow and efficiency in product predefinition processes are challenges caused by the way product platform information is managed and the extent of formalized product platform knowledge.
- A business model of a single-family IHB company in which optimized and highly predefined product designs are prefabricated with volumetric elements for a market niche has a high risk of being negatively influenced by changes in the external business environment regarding design process efficiency.
- A narrow flexibility of these offerings often cannot meet the parameters of situational contingencies.
- Adjusting the solution space of product platforms to changes in customer needs, legal requirements and building codes often requires significant investments due to the dedicated resources, such as manufacturing systems characterized by focused flexibility.

The knowledge on the product platform alignment phenomenon and identified challenges was used to synthesize the support, hence answering the third research question: *‘How can the development and use of product platforms be supported in single-family IHB to address the identified challenges?’* The main conclusions are as follows:

- The proposed support is twofold and addresses the identified challenges by impacting internal factors. The development and use of product platforms in single-family IHB are supported when adopting high-level MC.
- The first part of the proposed support is the information modelling method synthesized using the DP and the IDM. Implementing the method can increase the extent of formalized product platform knowledge. Represented

in developed information models, the knowledge can be communicated across the organization and used for the development of product platform management systems, such as a PLM system.

- Both the DP and the IDM are expanded with the proposed information modelling method. The DP information model in UML is complemented by the design process modelling using BPMN process maps and information exchanges of DP objects using the ERS. The previous use of the IDM for the modelling of modular building systems is expanded to the modelling of the product platform design assets.
- The second part of the proposed support is the design process that includes configuration of flexible volumetric elements. The support combines the flexibility of product designs achieved through the design process for the panelized element prefabrication and the efficiency of product variant realization achieved using volumetric element prefabrication.
- Flexible volumetric elements and the panelized elements they are composed of can be developed during product predefinition using object-based parametric modelling governed by the design assets, such as building system constraints and schematic design assessment.
- The developed flexible volumetric elements and the panelized elements they are composed of are used to exemplify the design modules. They are configured during the product specification into BIM models through MTO specification, while the unique solutions for the structural and MEP systems are developed through ETO specification.
- An integral architecture between the structural and MEP systems in the fabrication model can be developed using an automated synthesis resource.

By describing the product platform alignment model, the development and use of product platforms are placed into the perspectives of business models and the external business environment; hence, the strategic aspects of product platforms are studied. The contribution is made to the theoretical fields of product platforms and business models. By proposing the support through the information modelling method and the design process for single-family IHB that includes the configuration of flexible volumetric elements, the knowledge contributions are made to the theoretical fields of product platforms and BIM.

## 7.1. Limitations

In this thesis, the development and use of product platforms in single-family IHB is described from a business model perspective. However, the proposed support for the development and use of product platforms in single-family IHB when high-level MC is adopted has a narrower focus. It focuses on the resources of knowledge which, if formalized, can be shared across product predefinitions and product variants and reused as design assets throughout the design process. As discussed in section 6.1, the prescriptive part of the research, i.e. the synthesized support for the development and use of product platforms in single-family IHB, has addressed a set of identified challenges (1–4 in section 5.2) by impacting the identified internal factors. However, the support does not impact all internal factors, that is, resistance to change and the focused flexibility of manufacturing systems are internal factors not impacted by the support. Impacting the resistance to change is a complex phenomenon that is outside the scope of the research presented in this thesis. The challenge of adjusting the product platform solution space (challenge 5 in section 5.2) is not addressed by the presented support. This was, however, been the focus in researcher's licentiate thesis (Popovic, 2018) where the support framework for the development of off-site manufacturing systems in the IHB context is presented.

The proposed information modelling method was applied and tested on the collected empirical data (study 4) and the proposed design process that includes the configuration of flexible volumetric elements. However, the flexible volumetric elements and the panelized elements they are composed of are modelled with a lower level of detail throughout the design process using several design assets as an example. To fully test the concept of flexible volumetric elements, the information models with higher levels of detail are needed for the development of computer models (Duffy & Andreasen, 1995) such as BIM models. This research can, therefore, be used as a starting point for such possible future research.

The chosen specific context in which the development and use of product platforms was studied is single-family IHB in Sweden. This is the potential limitation as single-family IHB in other countries can differ regarding both internal and external factors. The specific context where the research was conducted should therefore be accounted for when interpreting the results presented in this thesis.

The research was based on qualitative data, and no quantitative data have been collected nor analysed to measure the explicit degree of flexibility and efficiency figures in the current state of product platform use. As the evaluation of the support (DS-II) was based on a workshop, the potential impact of the support in terms of flexibility and efficiency has not been measured.

## 7.2. Future work

Due to the differences between multi-family and single-family IHB business models, potential future work should include conducting the empirical studies in multi-family IHB and investigate the product platform alignment phenomenon in that context. The two contexts of IHB can then be compared in this respect and possibly a more general product platform alignment model could be developed at the level of IHB.

The support for the development and use of product platforms presented in this thesis can be regarded as conceptual and a foundation for further research in this field. Future research can, therefore, focus on the collection and analysis of quantitative data to expand the knowledge on the current state of practice regarding product platform use in single-family IHB. Further use of the information modelling method through empirical studies is suggested to obtain sufficiently detailed information models based on which the development of information management systems for product platforms would be possible. Moreover, quantitative studies can then be conducted to evaluate the impact of such development on product flexibility and process efficiency. Finally, an economic analysis can be performed to estimate the financial justification for the development of a PLM system.

Further validation of flexible volumetric elements and their configuration through the implementation of parametric object-based modelling using BIM applications is suggested for future work. The configuration is governed by the fulfilment of functional and performance requirements that can be managed as ETO specification processes by single-family IHB companies rather than by consultancy firms. If formalized, these assessment resources can be reused and shared between product variants and therefore comprise an additional design asset of single-family IHB product platforms. Hence, the development of the design assets for the product assessment when flexible volumetric elements are configured is suggested for future work. Finally, as the field of changeable manufacturing systems (ElMaraghy et al., 2013) is still to be explored in this context with more descriptive and prescriptive research, this presents yet another opportunity for future work.



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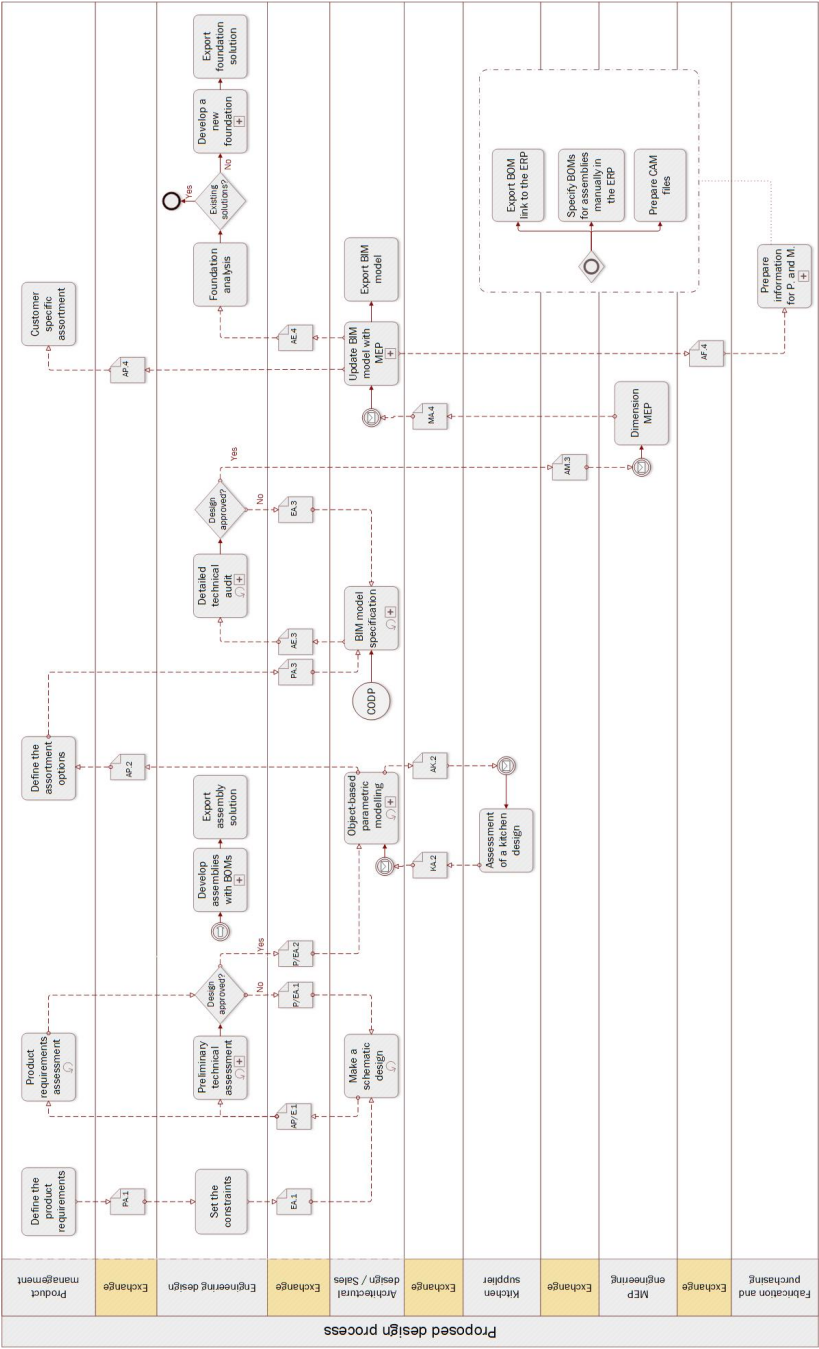
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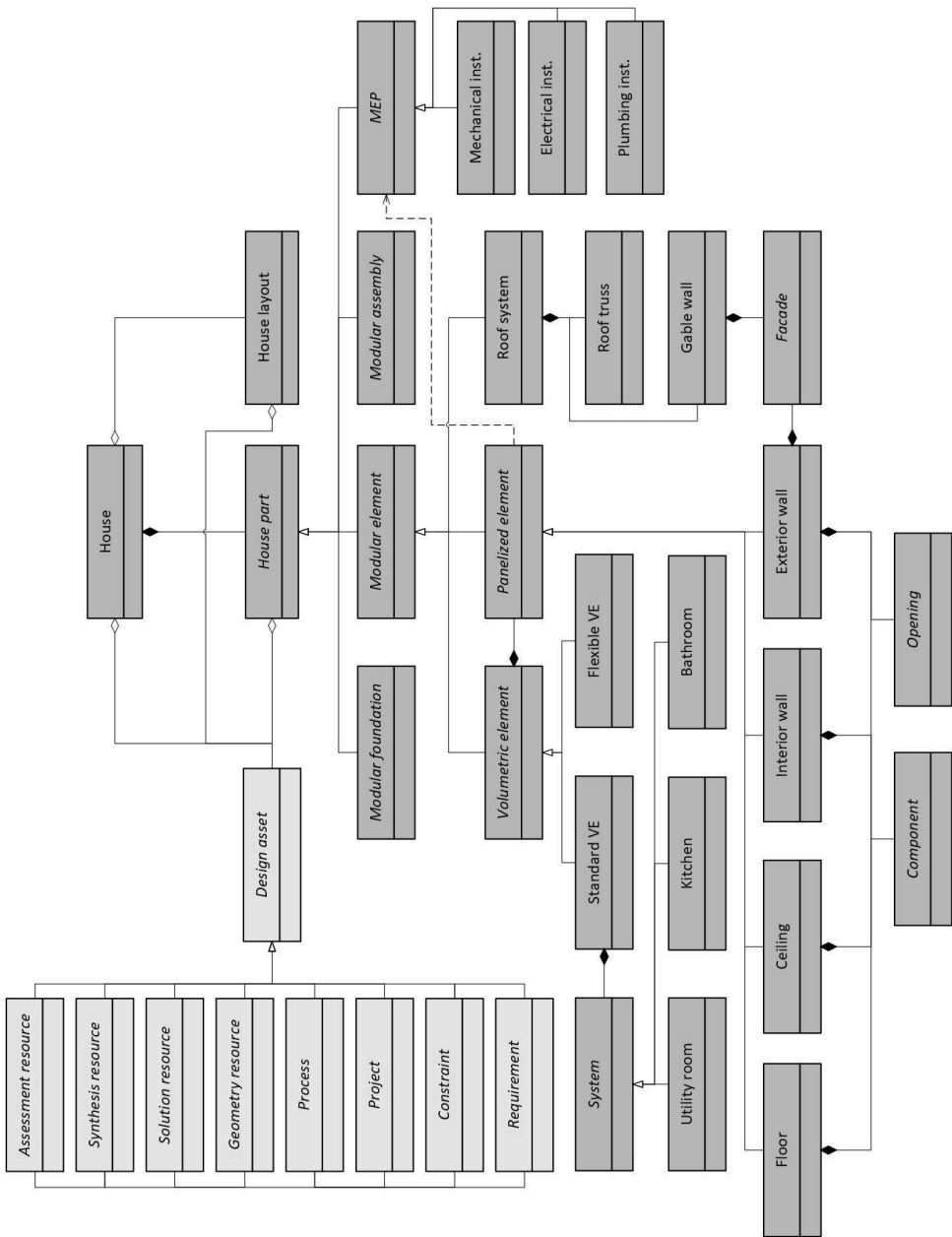
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# Appendix A – Proposed design process



# Appendix B – Design platform model



# The Development and Use of Product Platforms in Single-Family Industrialized House Building

Single-family industrialized house building is a trade characterized by a complete predefinition of products with off-the-shelf solutions offered to a market niche. Limited customization is included in the offerings in the form of a modular configuration of predefined components. A high level of prefabrication, often including volumetric elements, enables high efficiency in product variant realization processes, specifically, product specification, manufacturing, and on-site assembly. However, as the current markets are dynamic and often volatile, such offerings do not suffice in securing the success of business. Instead, offerings that include flexible product concepts with lower levels of predefinition and the concurrent achievement of high efficiency in processes using volumetric element prefabrication are needed. In this research, realizing this is characterized as the adoption of high-level mass customization. The main value of the presented research for the practice is support for single-family industrialized house building in adopting high-level mass customization.

The main enablers for the adoption of both lower and higher levels of mass customization are product platforms. The research on the development and use of product platforms has, however, been conducted mainly in multi-family industrialized house building. The differences in the types of offerings and customers between single-family and multi-family industrialized house building, reveal a research opportunity to study the development and use of product platforms in single-family industrialized house building. More specifically, the knowledge gaps include a lack of understanding regarding: the development and use of product platforms from a business model perspective, challenges for the development and use of product platforms when adopting high-level mass customization and support in addressing the identified challenges.

Therefore, the research purpose is to add to the knowledge on the development and use of product platforms and support that enables the adoption of high-level mass customization in single-family industrialized house building. The Design Research Methodology framework was used to plan and design the research. The research was conducted iteratively through four stages named: research clarification, descriptive study I, prescriptive study, and descriptive study II. The results provide an increased understanding regarding the development and use of product platforms in single-family industrialized house building through a coherent description of the product platform alignment phenomenon and the identified challenges when high-level mass customization is adopted. The results also increase knowledge regarding support in the development and use of product platforms that address the identified challenges. This part of the results is twofold. Firstly, an information modelling method is proposed, and it demonstrates how product platform use can be modelled in the design process of single-family industrialized house building. Secondly, the results demonstrate how the design module construct can be modelled using the design assets throughout the design process. To exemplify the design module construct, a configuration of the flexible volumetric elements and the panelized elements they are composed of is proposed. Process efficiency during the predefinition and modify-to-order specification of design modules is addressed. The presented research makes knowledge contributions to the theoretical fields of product platforms, building information management and business models.



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