JÖNKÖPING UNIVERSITY
*School of Engineering*

Licentiate Thesis

# Smart Manufacturing for the Wooden Single-Family House Industry

Alexander Vestin

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Smart Manufacturing for the Wooden Single-Family House Industry

# Abstract

To meet the demand of future building requirements, and to improve productivity and competitiveness, there is a need to modernize and revise the current practices in the wooden single-family house industry. In several other sectors, intensive work is being done to adapt to the anticipated fourth industrial revolution. The manufacturing industry has already begun its transformation with concepts such as smart manufacturing and Industry 4.0. So far, smart manufacturing has not been discussed to any significant extent for the wooden single-family house industry, even though it might be a way for this industry to improve productivity and competitiveness.

The research presented in this thesis aims at increased knowledge about what smart manufacturing means for the wooden single-family house industry. This requires investigating what smart wooden house manufacturing is, what challenges that might be associated with it, and how smart wooden house manufacturing can be realized. At the core of this thesis is the conceptualization of smart wooden house manufacturing—when realized, it is expected to contribute to improve the competitiveness of the wooden single-family house industry.

The findings presented here are based on three Research Studies. Two studies were case studies within the wooden single-family house industry. The third study was a traditional literature review.

The findings revealed two definitions and 26 components of smart wooden house manufacturing. At large, smart wooden house manufacturing emphasizes digital transformation with a focus on digital information flow, how to add information, information compilation, and information distribution between systems/programs and departments. Some of the challenges associated with smart wooden house manufacturing are, e.g. culture, competence and manual transfer of information between systems.

The findings indicate similarities of smart wooden house manufacturing within certain components of industrialized house building and Industry 4.0, these components could enable the realization of smart wooden house manufacturing.

**Keywords:** smart wooden house manufacturing, smart manufacturing, Industry 4.0, smart factory, industrialized house building

# Sammanfattning

För att möta efterfrågan på framtida byggkrav och för att förbättra produktiviteten och konkurrenskraften finns det ett behov av att modernisera och revidera nuvarande tillvägagångssätt inom träsmåhusindustrin. I flera andra sektorer arbetas det intensivt med att anpassa sig till den förväntade fjärde industriella revolutionen. Tillverkningsindustrin har redan påbörjat sin omvandling med koncept som smart manufacturing och Industry 4.0. Hittills har smart manufacturing inte diskuterats i någon större utsträckning för träsmåhusindustrin, även om det kan vara ett sätt för denna industri att förbättra produktiviteten och konkurrenskraften.

Forskningen som presenteras i denna avhandling syftar till ökad kunskap om vad smart manufacturing innebär för träsmåhusindustrin. Detta kräver undersökning av vad smart trähustillverkning är, vilka utmaningar som kan vara förknippade med det och hur smart trähustillverkning kan realiseras. Kärnan i denna uppsats är begreppsframställningen av smart trähustillverkning—när det realiserats förväntas det bidra till att förbättra konkurrenskraften för träsmåhusindustrin.

Resultaten som presenteras här är baserat på tre forskningsstudier. Två studier var fallstudier inom träsmåhusindustrin. Den tredje studien var en traditionell litteraturstudie.

Resultaten avslöjade två definitioner och 26 komponenter av smart träshustillverkning. Sammanfattningsvis betonar smart trähustillverkning digital transformation med fokus på digitalt informationsflöde, hur man lägger till information, sammanställning av information och informationsfördelning mellan system / program och avdelningar. Några av utmaningarna associerade med smart trähustillverkning är t.ex. kultur, kompetens och manuell överföring av information mellan system.

Resultaten indikerar likheter mellan smart träshustillverkning inom vissa komponenter av industriellt husbyggande och Industry 4.0, dessa komponenter skulle kunna möjliggöra realiseringen av smart trähustillverkning.

**Keywords:** smart wooden house manufacturing, smart manufacturing, Industry 4.0, smart factory, industrialized house building

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Alexander Vestin
Jönköping, April 2020

# List of appended papers

## Paper I

VESTIN, A., SÄFSTEN, K. & LÖFVING, M. 2018. On the way to a smart factory for single-family wooden house builders in Sweden. *Procedia Manufacturing*, 25, 459–470.

**Contribution of the first author:** Vestin contributed to the design of the study, conducted the interviews and literature review, performed the data analysis, prepared the material for the workshop, and planned and held the workshop. Vestin also wrote most of the paper, was the corresponding author, and presented the paper at the conference in Stockholm.

**Contribution of the second author:** Säfsten contributed to the study design, reviewed the material for the workshop, provided comments and advice, and supported the workshop as a documenter. Säfsten contributed to the writing of the paper, reviewed the paper, and provided advice for how to write and revise certain parts of the paper.

**Contribution of the third author:** Löfving contributed to the study design, wrote and reviewed the paper, and provided advice for how to write and revise certain parts of the paper.

## Paper II

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

**Contribution of the first author:** Popovic helped to conduct the literature review, interviews, data analysis, and contributed to writing the paper. Popovic was the corresponding author.

**Contribution of the second author:** Thajudeen conducted part of the literature review and some of the interviews. Thajudeen analyzed his part of the data and contributed to writing the paper.

**Contribution of the third author:** Vestin conducted part of the literature review, some of the interviews, and part of the data analysis. Vestin also helped to write the paper and presented it in Canada at the conference. The paper won best paper award runner-up.

### Paper III

VESTIN, A., SÄFSTEN, K. & LÖFVING, M. 2019. Smart single-family wooden house factory – A practitioner's perspective. Submitted to the journal *Construction Innovation.* To be published, accepted with minor revisions.

**Contribution of the first author:** Vestin designed the study, conducted the literature review and the interviews, transcribed all the data, performed the first stage of the analysis, conducted the final analysis, planned the workshops and prepared the material, held both workshops, wrote most of the paper, and was the corresponding author.

**Contribution of the second author:** Säfsten reviewed and provided advice on the planned study, supported the literature review with advice, conducted the final analysis, reviewed the planned workshop and provided comments and advice, contributed to writing the paper, reviewed the paper, and provided comments and advice on how to write certain parts of the paper.

**Contribution of the third author:** Löfving reviewed and provided advice on the planned study, reviewed the planned workshop and provided comments and advice, supported the workshop as a documenter, contributed to writing the paper, reviewed the paper, and provided comments and advice on how to write certain parts of the paper.

### Paper IV

VESTIN, A., SÄFSTEN, K. & LÖFVING, M. 2019. Revealing the content of Industry 4.0: A review of literature. *SPS 2020 Jönköping*. To be published, accepted.

**Contribution of the first author:** Vestin planned the literature review, conducted the literature review and the analysis of the papers, wrote most of the paper, was the corresponding author, and will present the paper.

**Contribution of the second author:** Säfsten supported the literature review with advice, supported the analysis of the papers with comments and advice, contributed to writing the paper, reviewed the paper, and provided comments and advice on how to write certain parts of the paper.

**Contribution of the third author:** Löfving supported the analysis of the papers, contributed to writing the paper, reviewed the paper, and provided comments and advice on how to write certain parts of the paper.

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# 1. Introduction

*The first chapter introduces the research background, the problem area, the study purpose and aim, and the research questions.*

## 1.1 Background

A lack of housing in Sweden has created the need for heavily expanded housing construction both now and in the immediate future (Boverket, 2016, Brege et al., 2017, Palmgren et al., 2017, Schauerte et al., 2014). According to Boverket (2016) and Palmgren et al. (2017), the latest forecast shows a ten-year building requirement (2016–2025) of 710,000 residential housing, with an estimated requirement of 88,000 housing units per year for 2016–2020 and 54,000 housing units per year for 2021–2025. According to the Swedish Construction Federation (Byggindustrier, 2017), the predicted number of housing construction beginning in 2017 was no more than 66,000. However, Brege et al. (2017) argue that the bottlenecks in construction will be so large that building 70,000–80,000 housing units will be difficult to achieve. This also affects the Swedish wooden single-family house industry.

Wood as a building material is increasing in popularity because of its sustainable features (Lindgren and Emmitt, 2017, Mahapatra et al., 2012, Tighnavard Balasbaneh et al., 2018) as well as its potential to help fulfil global sustainability goals (Brege et al., 2017). Sweden's wooden house industry comprises 533 companies with a total of 6,619 employees; they have a combined estimated production value of finished wooden houses of 20 billion Swedish Krona (SEK) (Swedish Federation of Wood and Furniture Industry [TMF], 2020). In 2019, 10,000 wooden single-family houses were started and 4,772 were delivered (TMF, 2020). According to TMF (2020), the 2020 forecast for started wooden single-family houses is 9,500. This forecast shows a negative trend compared to 2016, when delivered wooden single-family houses amounted to 6,505; this number reached 6,717 in 2017 (TMF, 2019). The primary cause for the negative trend is credit restrictions from banks and administrative sluggishness in granting building permits (TMF, 2020).

The Swedish industry for wooden single-family houses is highly competitive (Lindblad et al., 2016a, Schauerte et al., 2014). Only about half of the existing firms are needed to serve the market (Lindblad et al., 2016a) and the vast majority of firms have low operational and financial risks (Lindblad and Schauerte, 2015). Furthermore, the manufacturing development in this industry are relatively low, especially when compared to other industries (Eliasson, 2011) and productivity is also low (Barbosa et al., 2017). Although, the industry has a long history of prefabrication, with its foundations tracing back to the 1780s (Waern, 2008).

Brege et al. (2017) estimate that in 2025, the single-family house industry will produce 13,000 houses with a turnover of 15 billion SEK. With rising production costs and a low level of manufacturing development, firms in the Swedish industry for wooden single-family houses will face severe problems in productivity (Schauerte and Lindblad, 2015). The industry needs to improve its productivity to reach the estimated number of houses for 2025 (Brege et al., 2017). It also needs to develop their manufacturing to achieve an industrialized prefabrication process (Stendahl, 2009). The companies that are successful in the innovative development of their manufacturing system, is expected to improve their competitiveness and advance their positions in the market (Brege et al., 2017, Lindblad and Schauerte, 2015).

## 1.2 Problem area

Wood as a frame material is popular in the single-family house industry. In 2015, 9,000 single-family houses were produced in Sweden, 90% of which were produced using wood (Brege et al., 2017). There are typically three ways to build a wooden single-family house: (1) with the traditional on-site loose timber, where the wood is used as a load-bearing structure; (2) with prefabricated wall elements; and (3) with prefabricated modules.

Companies combine different levels of on-site and off-site activities depending on their offerings of customized/standardized houses and their building methods (Lidelöw et al., 2015). There are several challenges associated with building on site, such as the high number of specialists involved, inclement weather, quality assurance, productivity, delivery time, safety, and wastage (Goulding et al., 2015, Lessing, 2006). To address these challenges, construction activities can be transferred to a controlled environment (i.e., off-site) (Steinhardt and Manley, 2016). Off-site manufacturing, also called prefabrication, is the practice of building parts in a more controlled environment, usually a factory, and then shipping and assembling them on site (Pan and Goodier, 2012).

Despite a long tradition of prefabrication in Sweden (Waern, 2008), there is room for development in today's wooden single-family house industry. Historically, the industry has been slow to engage in activities to improve its productivity; it is now falling behind in terms of its use of machinery and automation equipment (Eliasson, 2011, Vestin et al., 2018). The current problem is that several practices from the on-site way of working are still dominant in the factories, leading to low productivity. Craftmanship methods are still largely used, even though the houses are built in a factory environment (Brege et al., 2004, Eliasson, 2011, Vestin et al., 2018). To meet the demand of future building requirements (Boverket, 2016, Brege et al., 2017, Hemström et al., 2017, Palmgren et al., 2017), and to improve productivity and competitiveness, this sector needs to modernize and revise its practices (Barbosa et al., 2017, Eliasson, 2011, Vestin et al., 2018).

In the last few decades, the larger housing industry has embarked on industrial house-building (IHB) to increase productivity and competitiveness (Lessing et al., 2015). IHB emphasizes a process focus rather than a project focus and so far dominates the business-to-business sector of the housing industry (Lessing, 2006, Lidelöw et al., 2015).

In several other sectors, e.g. manufacturing industry, intensive work is being done to adapt to the anticipated fourth industrial revolution. It is expected to significantly change the world's technical, economic, and social systems, leading to a paradigm shift in production (Dombrowski and Wagner, 2014). The manufacturing industry has already begun its transformation. As one example, the German government launched the project Industrie 4.0 to tap into the fourth industrial revolution (Kagermann et al., 2013) and to support competitiveness (Thoben et al., 2017). Industrie 4.0 is described as a new paradigm for improving productivity and flexibility through digitalization; it is expected to fundamentally improve the industrial processes involved in manufacturing, engineering, material usage, supply chain, and life cycle management (Kagermann et al., 2013). Beginning in 2011, when Industrie 4.0 was launched at the Hannover Fair, the fourth industrial revolution is sometimes referred to as Industry 4.0. Several similar initiatives have been launched, such as "smart manufacturing" in the US and "smart factory" in Korea (Kang et al., 2016, Thoben et al., 2017). Industry 4.0, smart manufacturing, and other concepts have close proximity and are often used synonymously to denote the fourth industrial revolution (Hermann et al., 2016, Kang et al., 2016, Mittal et al., 2019, Thoben et al., 2017). In smart manufacturing, information technology and knowledge are interwoven with industrial equipment and processes, products, and systems (Ghobakhloo, 2018, Kang et al., 2016, Kusiak, 2018, Mittal et al., 2019, Oztemel and Gursev, 2018).

So far, smart manufacturing in relation to the housing industry has not been discussed to any significant extent. It might be a way for the housing industry to fulfill future housing needs as well as to improve productivity and competitiveness. Researchers have started to outline the implications of the fourth industrial revolution in the general context of the construction industry (Dallasega et al., 2018, Love and Matthews, 2019, Oesterreich and Teuteberg, 2016, Schimanski et al., 2019, Woodhead et al., 2018). However, there is still limited knowledge about the fourth industrial revolution's implications for the housing industry.

Other industrial sectors have turned to smart manufacturing to denote ideas that support productivity and competitiveness (Thoben et al., 2017). One question that remains unanswered is what the concept of smart manufacturing implies for the housing industry, and more specifically, for the wooden single-family house industry. The question is whether there is such a thing as smart wooden house manufacturing.

## 1.3 Purpose and research questions

The purpose of the research presented in this thesis is to contribute to improve the competitiveness of the wooden single-family house industry. The idea is to develop the concept smart wooden house manufacturing to capture what a company in the house building sector need to consider in order to meet the expected future demands, and thereby allow them to be competitive on the market. This thesis is the first step in developing the concept of "smart wooden house manufacturing," which, when realized, is expected to contribute to improve the competitiveness of the wooden single-family house industry.

In order to achieve the purpose, given the above-mentioned idea, the thesis aims to increase the knowledge about what smart manufacturing means for the wooden single-family house industry. This requires investigating what smart wooden house manufacturing is, what challenges might be associated with it, and what enablers there might be for realization of smart wooden house manufacturing.

Following the purpose and aim, three research questions have been formulated:

RQ1: What is smart manufacturing in the wooden single-family house industry?

RQ2: What are the challenges related to smart manufacturing in the wooden single-family house industry?

RQ3: What are the enablers for realization of smart wooden house manufacturing?

At the core of this thesis is the conceptualization of smart wooden house manufacturing. When developing a concept, it is essential to identify potential attributes/components of the phenomenon. This can be done through a review of the literature, case studies, and interviews with practitioners, to name a few examples (Podsakoff et al., 2016).

## 1.4 Scope and delimitations

This research scope is limited to the construction of residential buildings with a wooden frame, aimed for single-family, manufactured off-site, and produced/assembled on-site (Figure 4).

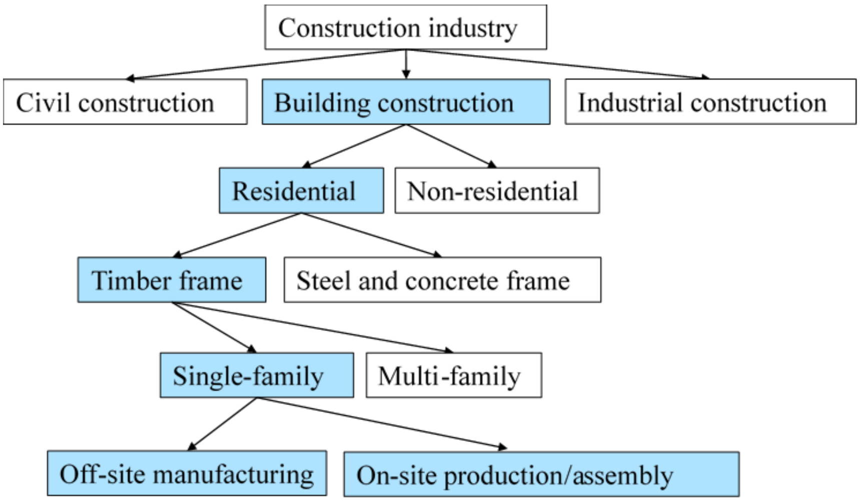


**Figure 1. Scope and delimitation (inspired by Popovic, 2018).**

To conceptualize smart wooden house manufacturing, every part of the process involved in manufacturing a wooden single-family house will be considered.

## 1.5 Thesis outline

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

**Chapter 1: Introduction**

This chapter presents the background of the research area, followed by a description of the main problem area. It then describes the study purpose and aim and research questions. The chapter ends with an outline of the thesis scope.

**Chapter 2: Frame of reference**

This chapter presents the frame of reference for this licentiate thesis. It is structured as follows: introduction to the wooden single-family house industry, Manufacturing development approaches in the housing industry and manufacturing industry.

**Chapter 3: Research methodology**

In this chapter, the research methodology is introduced. Then, the three separate studies are presented. The quality of the research is discussed, and the ethical considerations are outlined.

**Chapter 4: Findings from the appended papers**

This chapter presents a short overview of the appended papers. It further introduces the empirical findings from the three studies. It relates the findings to the four appended papers of this licentiate thesis.

**Chapter 5: Discussion**

This chapter discusses the findings and proposes a first step for the conceptualization of smart wooden house manufacturing. It relates the main empirical findings to the frame of reference in this thesis. It also includes reflections on the chosen methodology.

**Chapter 6: Conclusion**

This chapter presents the main conclusions, outlines the scientific and industrial contributions of this thesis. It ends by recommendations for future research.

# 2. Frame of reference

*With a purpose to improve competitiveness for the wooden single-family house industry, understanding about both the house industry sector and how to develop manufacturing is required as a foundation. In this chapter the current situation in the wooden single-family house industry is presented, followed by a brief overview of selected approaches for manufacturing development.*

## 2.1 Wooden single-family house industry

The wooden single-family house sector has a long history of off-site manufacturing and on-site production/assembly (Schauerte, 2010). Prefabrication efforts can be traced back to the 1780s (Waern, 2008). In cooperation with the sawmills and furniture industries, standard houses were developed to serve the needs of the Swedish population after World War 1 (Schauerte, 2010). During this time, technical advances were achieved, and by 1930, more than 20 Scandinavian companies offered prefabricated wooden catalogue houses (Smith, 2009).

Prefabrication, refer to the practice of building parts of a house in a controlled environment, usually in a factory, and then shipping them and assembling them on-site (Lessing, 2006, Pan and Goodier, 2012). Companies combine different levels of on-site and off-site activities depending on their offerings of customized or standardized houses and their building methods (Lidelöw et al., 2015). There are usually two different types of prefabrication: (1) Wall elements were prefabrication can include almost all interior installations and fittings (Smith, 2009); (2) It can also refer to modules where prefabrication includes integrated interior systems with completed electrical and plumbing systems, wallpaper, parquet, tiling, etc. (Smith, 2009). Due to the high degree of prefabrication involved, ready-module houses are the most cost-effective alternative on the market for wooden single-family houses (Schauerte, 2010).

Prefabrication is seen as a means of improving the quality of the final product, as production settings are protected from weather, and assembly is easier to control. Yet the prefabricated module shape sets architectural boundaries and limits interior arrangements, which might limit overall customization. Ready-module houses are mainly marketed to young families who have tight budgets but still want to buy a house. In contrast, higher-income segments may choose wooden houses that are produced with more flexible, less standardized, and thus more expensive prefabrication techniques than those used for ready-modules (e.g., wall elements). In short, there are prefabricated house alternatives for all market segments.

Prefabrication is dominant in the market. It is culturally rooted in hundreds of years of Swedish history, and the markets are accustomed to the practice, making prefabricated houses more affordable overall (Smith, 2009). Some researchers suggest that this method of production is more beneficial than strictly on-site production in terms of cost savings, improvements in quality, internal and external logistics, and working environment (Mahapatra and Gustavsson, 2008, Stehn and Brege, 2007).

### *2.1.1 The market and industry for wooden houses*

Sweden's wooden house industry, including multiple-family and single-family homes, comprises 533 companies with a total of 6,619 employees. Of these, 119 companies have more than 5 employees; 277 have only one employee. As mentioned in the introduction, this market is highly competitive and has room for improvement (Eliasson, 2011, Vestin et al., 2018).

The market suffered a major blow from 1993–1994 when the real estate bubble burst in Sweden and the economy went into a deep recession. Many entrepreneurs and manufacturers went bankrupt during this time. At the same time, building standards changed from being based on technical requirements to being function-based. Furthermore, the government removed all governmental subsidies. The combination of removed subsidies and the recession caused construction activity to hit its lowest point in several decades (Lidelöw et al., 2015).

The market in the industry is highly fluctuating and has shifting market conditions. From 2007–2012 (i.e., in the aftermath of the global financial crisis), the number of finalized wooden single-family houses in Sweden decreased from about 12,100 units to 4,800 units per annum (TMF, 2014). A typical way for the industry to handle the fluctuating market, is to resign employees, which means losing skill sets that would be needed as soon as the market recovers (Eliasson, 2014).

One consequence of the latest economic crisis was that the Swedish National Bank introduced that the consumer now has to pay 15% of a property’s purchase sum in cash. This especially affects younger households that often cannot contribute such a large sum of money, which in turn affects sales in the wooden single family-house industry (TMF, 2013).

With rising production costs and insufficient manufacturing development, firms in the industry are facing severe productivity problems (Lindblad and Schauerte, 2015). The current industry’s production facilities and systems have created rising production costs and low resource utilization (Lindblad et al., 2016a). As mentioned in the introduction, there is a need to modernize and revise the practices in this sector (Barbosa et al., 2017, Eliasson, 2011, Vestin et al., 2018).

### *2.1.2 Current manufacturing challenges in the wooden house industry*

Manufacturing development in this industry is at a rather low level, especially compared to other industries (Schauerte et al., 2013). In the case of prefabrication, several companies have yet to seize the benefits of moving production to factories to improve productivity (Eliasson, 2011). As noted, relatively few companies in the wooden single-family house industry fully utilize the possibilities and advantages of prefabrication (Andersson et al., 2007, Brege et al., 2004, Eliasson, 2011). Production facilities range from manual to semiautomated, however, fully automated solutions also exist (Lindblad et al., 2016a). Overall, the industry is falling behind other industries in terms of manufacturing development (e.g., the use of machinery and automation equipment) (Eliasson, 2011, Vestin et al., 2018).

Höök and Stehn (2008) point to the need for a change in construction companies’ organizational culture to better utilize the advantages of industrialized housing production. Knowledge of how to approach and implement such production methods must be gathered and disseminated amongst employees. Stendahl (2009) argues that educated employees can have a positive impact on innovation activities, yet the educational level within the industry is relatively low.

A production requirement, and a big challenge to be mastered in this industry, is cutting costs via modularization whilst being able to use a flexible production system (Andersson et al., 2007). Companies producing wooden single-family houses are forced to handle these issues by increasing their manufacturing development phases and focusing on a higher degree of automation (Andersson et al., 2007). This is, however, connected with investments and risk-taking. As production efficiency is fundamental to a firm’s competitiveness and profitability, many wooden house manufacturers may face profitability—and thus, financial problems—when converting to new production systems.

The wooden single-family house industry needs to improve productivity to meet the demand of future building requirements (Boverket, 2016, Brege et al., 2017, Hemström et al., 2017, Palmgren et al., 2017). Companies that successfully partake in the innovative development of their manufacturing systems are expected to improve their competitiveness and advance in the market (Brege et al., 2017, Lindblad and Schauerte, 2015).

## 2.2 Manufacturing development approaches

There are several ways to develop a manufacturing system to improve competitiveness; this thesis outlines a few possible approaches. As a starting point, it is assumed that manufacturing development should be aligned with market requirements. Therefore, manufacturing strategies was a natural point of departure. In the housing industry, the idea of IHB has long dominated ideas of how to increase competitiveness. Hence, IHB is one of the approaches this thesis investigates. A more recent approach involves the different initiatives (e.g. Industry 4.0, smart manufacturing etc.) related to adapting to the fourth industrial revolution and to supporting competitiveness.

### *2.2.1 Manufacturing strategy*

Customers want good-quality products at the best price in sufficient amounts, and of course, on time. In order to stay competitive, it is necessary to provide production systems that are capable of handling increased demands correctly and efficiently. Providing production systems that support the factors a company has chosen to compete with requires a well-formulated and well-implemented manufacturing strategy (Bellgran and Säfsten, 2009). A manufacturing strategy helps a company to make operational and strategic decisions that follow a logical pattern supporting the company’s corporate strategy and competitive priorities (Hayes and Wheelwright, 1984, Hill and Hill, 2009). A manufacturing strategy involves decisions that shape the producing company’s long-term capabilities in order to remain competitive in the marketplace; this occurs by linking market requirements and production resources (Hayes and Wheelwright, 1984, Hill and Hill, 2009).

A company's competitive priorities, or "order-winners," are used to describe company objectives. A company chooses to compete in the marketplace as well as chooses the types of market it pursues. The four most important competitive factors are cost, quality, flexibility, and deliverability see Table 1.

**Table 1. Competitive factors.**

| Competitive factors | Description |
|---|---|
| Cost | Refers to the ability to produce and deliver at a low cost (i.e., to be cost-efficient). Economies of scale; the cost of supplies, products, and process design; and experience are some sources of cost efficiency (Hayes and Wheelwright, 1984). |
| Quality | Refers to the ability to meet customer needs and expectations by making products that correspond to what the customer wants. Quality is about customer experience (a higher value) or meeting customer specifications (fewer defects). Good-quality production is often synonymous with meeting specification (Hayes and Wheelwright, 1984). |
| Flexibility | Refers to the ability to rapidly and efficiently adapt production to necessary changes. Within production, this is often linked to an ability to manage variable volumes (i.e., volume flexibility) or many variants within a certain volume (i.e., product mix flexibility). There are also a number of other types of flexibility that are not covered here (Hayes and Wheelwright, 1984). |
| Deliverability | Refers to the ability to deliver services and products. The most important factors here are reliability and speed. Reliability is the ability to deliver according to plan; this is of the utmost importance to companies that deliver "just-in-time." Short delivery lead times can be achieved either in the production system or through delivery from stock (Bellgran and Säfsten, 2009). |

Within a given industry, different companies place different emphasis on each of the four competitive dimensions. It is difficult, and potentially dangerous, for a company to try to compete by simultaneously offering superior performance in all of these dimensions (Hayes and Wheelwright, 1984).

### *2.2.2 Industrialized house-building*

IHB is a type of construction that is mainly organized around repetition, leading to a stronger process focus and a reduced project focus (Lidelöw et al., 2015). IHB is used to improve competitiveness in the house-building industry (Lessing et al., 2015); it is more focused on the business-to-business market (Lessing, 2006) than business-to-end-user. There are several characteristic areas contained in IHB. Ågren and Wing (2014) focus on three areas: developed technical systems, off-site production, and the use of information and communication technologies (ICT). In contrast, Goulding et al. (2015) focus on five areas: planning and controlling processes, developed technical systems, off-site production, logistics integrated into the building process, and use of ICT. Barlow (1999) also focuses on five areas: planning and controlling the processes, developed technical systems, off-site production, logistics integrated into the building process, and customer focus. The most holistic framework is the one that Lessing et al. (2015) developed, which focuses on eight characteristic areas: planning and control of the processes, developed technical systems, off-site manufacturing of building parts, long-term relations between participants, supply chain management integrated into the construction process, customer focus, use of ICT, and systematic performance measurement and re-use of experience. Lessing defines IHB as:

> *"A thoroughly developed building process with a well-suited organization for efficient management, preparation, and control of the included activities, flows, resources and results for which highly developed components are used in order to create maximum customer value"* (Lessing, 2006, p. 93)

This definition is complemented with a framework featuring eight characteristic areas that further describe the content and significance of IHB (see Table 2). The framework can be used to determine how industrialized a company is. For more detailed information about the eight characteristic areas and how to use the framework, see Paper I and Appendix 1.

Table 2. IHB characteristic areas (Lessing, 2006).

| IHB: Eight characteristic areas | Description |
|---|---|
| Planning and control of the processes | Having well-implemented process that everyone follows with clearly defined roles and stage-gates |
| Developed technical systems | Having technical systems with the appropriate flexibility |
| Off-site manufacture of building parts | Having an effective environment for off-site manufacturing featuring a high degree of completion |
| Long-term relations between participants | Having long-term relationships with entrepreneurs with good product knowledge to create value for the customer |
| Logistics integrated in the construction process | A well-organized supply chain including pre-assembly and construction site |
| Customer focus | A customer focus to ensure that the right products of the right quality are produced at the right cost |
| Use of information and communication technology | Having modern ICT that supports the different processes with accurate information |
| Systematic performance measurement and re-use of experience | Continuous measurements of the soft and hard parameters for all the participating companies |

### *2.2.3 The fourth industrial revolution*

A fourth industrial revolution is prophesied, and sectors can proactively apply and adjust suggested practices. The fourth industrial revolution is expected to significantly change the world's technical, economic, and social systems, leading to a paradigm shift in production systems (Dombrowski and Wagner, 2014). The fourth industrial revolution is characterized by a high level of complexity and network integration of product and production processes (Lu, 2017).

As mentioned in Section 1.2, manufacturing industry has already begun its transformation with concept such as Industry 4.0, smart manufacturing, smart factory etc. to tap into the fourth industrial revolution and to improve competitiveness (Kagermann et al., 2013, Kang et al., 2016, Thoben et al., 2017). Industry 4.0, smart manufacturing, and other concepts have close proximity and are often used synonymously to denote the fourth industrial revolution (Hermann et al., 2016, Kang et al., 2016, Mittal et al., 2019, Thoben et al., 2017).

Regardless of the large interest from both industry and academia, one downside of the immense literature on initiatives that tap into fourth industrial revolution, is the ambiguity surrounding terminology and content. The terms can be mixed and sometimes used interchangeably without fully describing all the parts. There is still no consensus on the terminology and the content of these initiatives (Lu, 2017). To provide an overview of these initiatives, the most common components used to describe the content of these initiatives are presented and compiled in Table 3 below. Henceforth, Industry 4.0 will be used to refer to various initiatives related to the fourth industrial revolution.

## Components of Industry 4.0

Table 3 presents the components of Industry 4.0 and gives a brief description of each one. For more detailed information about these components, see Paper IV.

**Table 3. Components of Industry 4.0.**

| Components of Industry 4.0 | References |
|---|---|
| *Additive manufacturing*<br>A manufacturing technique that simplifies and speeds up the processes of new product design and manufacturing. | (Ghobakhloo, 2018, Kang et al., 2016, Kusiak, 2018, Mittal et al., 2017, Mittal et al., 2019, Saucedo-Martínez et al., 2018) |
| *Augmented reality (AR)*<br>Computer graphics that are placed in a real environment for a more efficient and safe execution of operations or training. | (Ghobakhloo, 2018, Kusiak, 2018, Kang et al., 2016, Lasi et al., 2014, Mittal et al., 2017, Mittal et al., 2019, Pereira and Romero, 2017, Oztemel and Gursev, 2018, Saucedo-Martínez et al., 2018) |
| *Automation and industrial robotics*<br>Achieving a process or procedure performed with minimal human assistance with support from software, machines, and robots. | (Ghobakhloo, 2018, Kang et al., 2016, Kusiak, 2018, Lasi et al., 2014, Mittal et al., 2017, Mittal et al., 2019, Pereira and Romero, 2017, Saucedo-Martínez et al., 2018, Thoben et al., 2017) |
| *Big data*<br>Discovering, capturing, and analyzing a large volume of a wide variety data; action must be taken for optimal results. | (Ghobakhloo, 2018, Kang et al., 2016, Kusiak, 2018, Lu, 2017, Mittal et al., 2017, Mittal et al., 2019, Oztemel and Gursev, 2018, Pereira and Romero, 2017, Saucedo-Martínez et al., 2018, Thoben et al., 2017, Wang et al., 2016) |

| Components of Industry 4.0 | References |
| --- | --- |
| *Cloud computing*<br>The on-demand availability of computer system resources, manufacturing, and services. | (Ghobakhloo, 2018, Kang et al., 2016, Kusiak, 2018, Lu, 2017, Mittal et al., 2017, Mittal et al., 2019, Oztemel and Gursev, 2018, Saucedo-Martínez et al., 2018, Thoben et al., 2017, Wang et al., 2016) |
| *Cyber physical systems (CPS)*<br>CPS enables the fusion of the physical and the virtual world by integrating computing and physical processes. | (Ghobakhloo, 2018, Hermann et al., 2016, Oztemel and Gursev, 2018, Kang et al., 2016, Kusiak, 2018, Lasi et al., 2014, Lu, 2017, Mittal et al., 2017, Mittal et al., 2019, Pereira and Romero, 2017, Thoben et al., 2017, Wang et al., 2016) |
| *Cybersecurity*<br>Incorporates security mechanisms that provide confidentiality, authenticity, integrity, access control, etc. These mechanisms can be used to prevent computer and network intrusions and attacks. | (Ghobakhloo, 2018, Kang et al., 2016, Mittal et al., 2017, Mittal et al., 2019, Saucedo-Martínez et al., 2018) |
| *Decentralization*<br>To work independently and make decisions autonomously (e.g., machines do not depend on human interference). | (Ghobakhloo, 2018, Hermann et al., 2016, Lasi et al., 2014, Lu, 2017, Mittal et al., 2019, Mittal et al., 2017) |
| *Internet of services (IoS)*<br>Information about product usage and condition is transferred to the manufacturer to act upon through sensor-based products. | (Ghobakhloo, 2018, Lasi et al., 2014, Lu, 2017, Pereira and Romero, 2017, Oztemel and Gursev, 2018, Kang et al., 2016, Mittal et al., 2017, Mittal et al., 2019, Thoben et al., 2017, Wang et al., 2016) |
| *Internet of things (IoT)*<br>The inter-networking of physical devices, vehicles, buildings, and other items embedded with electronics, software, sensors, actuators, and network connectivity that enable these objects to collect and exchange data. | (Ghobakhloo, 2018, Hermann et al., 2016, Kusiak, 2018, Kang et al., 2016, Lu, 2017, Mittal et al., 2017, Mittal et al., 2019, Oztemel and Gursev, 2018, Pereira and Romero, 2017, Saucedo-Martínez et al., 2018, Thoben et al., 2017, Wang et al., 2016) |
| *Interoperability*<br>Systems that can work together, exchange data, and share information and knowledge. | (Ghobakhloo, 2018, Kang et al., 2016, Lu, 2017, Mittal et al., 2017, Mittal et al., 2019, Oztemel and Gursev, 2018) |

| Components of Industry 4.0 | References |
| --- | --- |
| *Modularity*<br>Agile manufacturing systems that can adapt to ever-changing circumstances and requirements. | (Ghobakhloo, 2018, Hermann et al., 2016, Lu, 2017, Mittal et al., 2017, Mittal et al., 2019, Oztemel and Gursev, 2018) |
| *Real-time capability*<br>Collecting real-time and real-world data from factories, products, and business partners through a range of dimensions. | (Ghobakhloo, 2018, Hermann et al., 2016, Kang et al., 2016, Lu, 2017, Mittal et al., 2017, Mittal et al., 2019, Oztemel and Gursev, 2018) |
| *Sensor*<br>Device to collect and control data in real time. | (Kang et al., 2016, Kusiak, 2018, Lasi et al., 2014, Mittal et al., 2017, Pereira and Romero, 2017, Thoben et al., 2017) |
| *Service orientation*<br>The emergence of new technologies in Industry 4.0 has changed the way that products and services are sold and provided; this affects traditional business models and creates new business opportunities. | (Ghobakhloo, 2018, Kang et al., 2016, Lasi et al., 2014, Lu, 2017, Mittal et al., 2019, Oztemel and Gursev, 2018, Pereira and Romero, 2017, Saucedo-Martínez et al., 2018, Thoben et al., 2017, Wang et al., 2016) |
| *Simulation and modeling techniques*<br>Evaluate changes and behaviors before realizing them, preventing error at an early stage. | (Ghobakhloo, 2018, Lasi et al., 2014, Kang et al., 2016, Kusiak, 2018, Mittal et al., 2017, Mittal et al., 2019, Saucedo-Martínez et al., 2018) |
| *Skills development*<br>Industry 4.0 will demand new skills. Society and organizations must create opportunities to educate workers in these required skills. | (Ghobakhloo, 2018, Kang et al., 2016, Lasi et al., 2014, Oztemel and Gursev, 2018, Pereira and Romero, 2017, Thoben et al., 2017) |
| *Smart factory*<br>A smart factory consists of integrative real-time intercommunication between every manufacturing resource, sensor, machine, robot, human, product, etc. | (Ghobakhloo, 2018, Hermann et al., 2016, Kang et al., 2016, Lasi et al., 2014, Lu, 2017, Mittal et al., 2017, Mittal et al., 2019, Oztemel and Gursev, 2018, Pereira and Romero, 2017, Thoben et al., 2017, Wang et al., 2016) |
| *Smart product*<br>A new generation of physical products that can use different types of sensors embedded within them to communicate with the environment to collect, store, and transfer data during their life cycles. | (Ghobakhloo, 2018, Lu, 2017, Mittal et al., 2017, Mittal et al., 2019, Pereira and Romero, 2017) |

| Components of Industry 4.0 | References |
|---|---|
| *Sustainability and resource efficiency* Realizing sustainability and resource efficiency enables the efficient coordination of products, materials, and energy throughout products' life cycles. | (Ghobakhloo, 2018, Kang et al., 2016, Kusiak, 2018, Lasi et al., 2014, Mittal et al., 2017, Mittal et al., 2019, Oztemel and Gursev, 2018, Thoben et al., 2017, Wang et al., 2016) |
| *System integration* Refers to the process of bringing together the component sub-systems into one system to ensure that the system is able to deliver the intended functionality. | (Ghobakhloo, 2018, Pereira and Romero, 2017, Saucedo-Martínez et al., 2018, Wang et al., 2016) |
| *Virtual reality (VR)* Simulated experience that can be similar to or completely different from the real world. | (Kang et al., 2016, Kusiak, 2018, Lasi et al., 2014, Mittal et al., 2017, Mittal et al., 2019) |
| *Virtualization* A replication of a digital twin of the entire value chain by merging sensor data acquired from the physical world into virtual or simulation-based models. | (Ghobakhloo, 2018, Hermann et al., 2016, Lu, 2017, Mittal et al., 2017, Mittal et al., 2019, Oztemel and Gursev, 2018) |

### *2.4.2 Industry 4.0 in the construction industry*

The concepts of Industry 4.0 have not gained much attention in the construction industry despite the possible benefits and are still in their formative years (Dallasega et al., 2018, Love and Matthews, 2019, Oesterreich and Schimanski et al., 2019, Pasetti Monizza et al., 2018, Woodhead et al., 2018, Teuteberg, 2016).

Oesterreich and Teuteberg (2016) came up with an industry-specific definition for the concept of Industry 4.0 in the construction industry:

> *"Interdisciplinary technologies to enable the digitization, automation and integration of the construction process at all stages of the construction value chain" (Oesterreich and Teuteberg, 2016, p. 137).*

There are several types of central technologies, such as building information modelling (BIM), parametric design techniques, cloud computing, and IoT, to name a few. In some cases, Industry 4.0 is used as a synonym to describe the increasing use of ICT and other manufacturing technologies. However, BIM is considered to be the central technology for the digitization of the construction industry (Oesterreich and Teuteberg, 2016, Pasetti Monizza et al., 2018).

These technologies are at different levels of maturity. On the one hand, several technologies have reached market maturity and thus are currently available (e.g., BIM, parametric design techniques, modularization). On the other hand, a few technologies are still at the formative stage, as their prototypes and applications are being developed for mainstream use (e.g., additive manufacturing, AR, and VR) (Oesterreich and Teuteberg, 2016, Pasetti Monizza et al., 2018).

According to Oesterreich and Teuteberg (2016), adopting Industry 4.0 components would have implications for the whole construction industry, the involved companies, the environment, and employees. Beside the economic benefits of improving productivity, efficiency, quality, and collaboration, adopting these components can help to enhance safety and sustainability, thus improving the construction industry.

# 3. Research methodology

*This chapter begins by clarifying the research context, process, and design presented in this thesis. This is followed by a description of the three research studies. The chapter concludes by delineating the quality of the research and the ethical considerations.*

## 3.1 Research context

I am part of the ProWOOD Industrial Graduate School, which means that as a doctoral student, I am closely connected to a company (referred to as "Company Theta"). The aim of ProWOOD is to support innovation and improve competitiveness in the Swedish wood industry. The research project in this thesis is a joint formulation by the industry and academia. Company Theta joined ProWOOD with a vision to create a smart wooden house factory with a focus on improved competitiveness and automation; this vision is the foundation of this research. As a doctoral student, my time is divided into 80% research and 20% departmental duties. The latter have involved both teaching responsibilities and working on projects at the company.

Company Theta was located in Sweden and had 260 employees. The company produced wooden single-family houses with a building system featuring prefabricated wall elements. The company offered two brands—one more standardized, and one more customizable. Both brands were usually sold under turnkey contracts, the customer was usually the end-user, and Sweden was the main market. The annual volume was around 300 wooden single-family houses per year. The off-site manufacture of building parts took place at two factories, Factory A and Factory B, where wall elements, trusses, and load-bearing inner walls were built from raw material in a manual production system. The wall elements were completed and equipped with windows, prepared for electrical installation and ventilation, and fitted with the outer panel/wainscot to create a complete wall element. The finished wall elements and trusses were loaded onto a covered truck together with the required installation materials and transported to the building site for on-site production/assembly.

## 3.2 Research process

This thesis is the first step in to develop the concept of smart wooden house manufacturing, which, when realized, is expected to contribute to improved competitiveness for the wooden single-family house industry. The thesis aims to increase the knowledge about what smart manufacturing means for the wooden single-family house industry with the aid of three research questions (see Section 1.4). In order to meet the aim and answer the research questions, three research studies were executed. The timeline of the three research studies and the resulting papers are schematically illustrated in Figure 5.

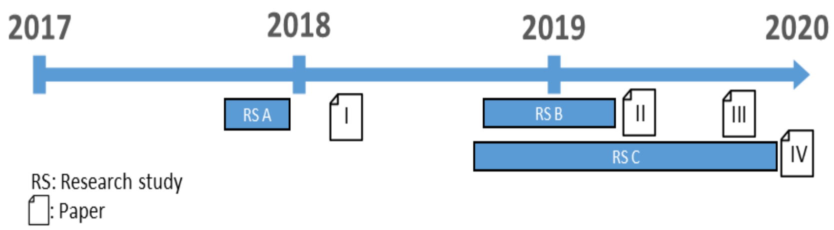


**Figure 2. The timeline of the three research studies and resulting papers.**

Research Study A was carried out between October 2017 and December 2017. The results from the study are presented in Paper I, which was published in May 2018. Research Study B was conducted between September 2018 and April 2019. The results from this study are presented in two papers: Paper II, published in May 2019, and Paper III, submitted to a journal in October 2019. Research Study C began in August 2018 and was finished in December 2019. Part of the study contributed to Paper III; the full results are presented in Paper IV.

## 3.3 Research design

At the core of this thesis is the conceptualization of a smart wooden single-family house factory. A concept is defined as

> *…[ ] cognitive symbols (or abstract terms) that specify the features, attributes, or characteristics of the phenomenon in the real or phenomenological world that they are meant to represent and that distinguish them from other related phenomena (Podsakoff et al., 2016 p.161).*

When developing a concept, it is essential to identify its potential attributes. This can be done through literature reviews, case studies, and interviews with practitioners (Podsakoff, 2016). Beside these recommendations to create a foundation for a concept, the research design for this thesis used workshops. The rationale for the selected research design is presented next (i.e., the selection of research methods and techniques for data collection).

A literature review can be helpful to identify the various ways in which the concept has been defined previously and the attributes or characteristics that other researchers consider are critical to its definition (Podsakoff et al., 2016). A literature search is also helpful because it provides the researcher with critical information about the concepts that the focal concept should be distinguished from (Gerring, 2011). For this thesis, a literature review was conducted to identify, evaluate, and interpret the existing body of knowledge (Jesson et al., 2011) as well as to identify patterns, themes, and issues in the literature (Seuring and Müller, 2008).

Case studies may prove useful in helping to identify a concept's attributes (Podsakoff et al., 2016). Here, case studies were conducted because the concept of smart manufacturing in the wooden single-family house industry is in need of an exploratory investigation, as the variables are still unknown and the phenomenon is not well understood (Yin, 2018). A case study is particularly suitable for answering the questions "why" and "how," it is even suitable to answer "what" questions (Yin, 2018).

Interviews with practitioners can help the researcher to identify the concept's definitions and attributes (Podsakoff et al., 2016). Interviews are a technique for data collection, and here, they were conducted to gather information in the form of perceptions and experiences of and with the phenomenon smart wooden house manufacturing from practitioners in the wooden single-family house industry (Säfsten and Gustavsson, 2019). This research used semi-structured interviews with a standard list of questions. However, it did allow the interviewers to follow up on leads that the participants provided (Williamson, 2002).

Workshops are used for data collection and to validate the collected data (Säfsten and Gustavsson, 2019). Workshops allow researchers and practitioners to jointly work out new ideas, find solutions to various problems, and identify critical factors in a project focused on change and development. Researchers can collect data on the studied phenomenon at the same time (Ørngreen and Levinsen, 2017).

An overview of the research design is presented in Table 4. Research Study A, aimed at answering RQ1, RQ2, and RQ3, was carried out as a single case study; a literature review, interviews, and a workshop were included. The results from this study are presented in Paper I. Research Study B, aimed at answering RQ1, RQ2, and RQ3, was carried out as a multiple case study using interviews and workshops as techniques for data collection. The results from this study are presented in Papers II and III. Research Study C, focused on RQ3, was carried out as a traditional literature review. The study contributed to the results presented in Paper III and Paper IV.

**Table 4. Research studies, papers, and research questions.**

| **Research Study** | **Research Study A** | **Research Study B** | **Research Study C** |
|---|---|---|---|
| **Targeted RQ** | RQ1, RQ2, & RQ3 | RQ1, RQ2, & RQ3 | RQ3 |
| **Research method** | Case study | Multiple case study | Literature review |
| **Data collection techniques** | Literature review, interviews, and a workshop | Interviews, workshops | Traditional literature review |
| **Paper/s** | Paper I | Paper II and Paper III | Paper III and Paper IV |

Each of the research studies are described in detail in the following Sections, 3.4, 3.5 and 3.6. Additional details can also be found in the corresponding papers (see Table 4).

## 3.4 Research Study A

The purpose of Research Study A was to investigate whether IHB characteristics might be a step toward a smart wooden house factory. The study was carried out as a deep single-case study (Yin, 2018), with a wooden single-family house company as the unit of analysis. Company Theta was selected based on convenience and interest from the company. For a description of Company Theta, see Section 3.1. The data were collected through a literature review, semi-structured interviews, and a workshop (Williamson, 2002). An interview guide was developed prior to the interviews. The interview guide was designed based on the eight characteristics of the IHB framework (Lessing, 2006) (see Appendix 1). The interviewees were chosen based on their assumed knowledge of the characteristics included in the IHB framework. The interviewees held the following positions: sales support manager, calculation manager, shop floor worker, logistics manager, production manager (Factory A), business developer, architect and construction manager, purchasing manager, contract coordinator, production manager (Factory B), and sales manager.

A total of 11 interviews were performed; they ranged from 15 min to 1.5 hours, depending on the interviewees' knowledge of the certain area. For the 15 min interview, the interviewee only had knowledge about one area of the IHB framework. The interviews were recorded, and the recordings were transcribed. The transcribed interviews were analyzed using the IHB framework to assess the implementation level of the eight characteristic areas. A workshop was conducted to confirm the estimated level of industrialization in Company Theta (i.e., the level of implementation of the eight characteristics of IHB). The workshop had two purposes: (1) to verify the results of the estimated level of industrialization, and (2) to collect data about the company's vision of a smart wooden house factory to increase understanding. The goal of the workshop was to gain a unified understanding of Company Theta's level of industrialization and to discus and specify the characteristics of a smart wooden house factory and the challenges regarding adopting characteristics related to the smart wooden house factory.

The workshop was conducted with seven members of the operation management team. The reason for involving them was twofold: (1) they were assumed to have an overall knowledge of the characteristic areas included in the IHB framework, and (2) Company Theta explicitly wanted this group to participate. The company thought it could trigger interesting discussions for future work. The participating team members held the following positions: architect and construction manager, business developer, sales support manager, calculation manager, production developer, production manager/developer, and chief operating officer. Two researchers attended the workshop: (1) the author of this thesis, who ran the workshop; and (2) another researcher, who documented the workshop (one of the authors of Paper I). The workshop was held from 9–12 and 13–16 on a single day.

During the first part of the workshop, the operation management team were split into smaller groups and asked to assess the level of implementation as per the IHB framework. The groups presented their assessment for each category, which was compared to the researchers' assessment. This was followed by a discussion aimed at finding mutual understanding about the company's level of implementation.

The workshop proceeded to discuss the characteristics of a smart wooden house factory and the challenges regarding the possibility of adopting these characteristics; this was also done in smaller groups. The discussion continued until three characteristics and two challenges were identified. For this part of the workshop, the second researcher documented the data regarding the smart wooden house factory. Furthermore, the small groups used Post-It notes to jot down ideas, which were collected after the workshop. The documented data from the workshop were used to establish the characteristics of the smart wooden house factory and the challenges involved in reaching these characteristics.

## 3.5 Research Study B

The purpose of Research Study B was to investigate what a smart factory would mean for the wooden single-family house industry. The study was carried out as a multiple case study, with wooden single-family house-building companies as the unit of analysis. Replication logic was applied to select suitable cases, which means that each case was expected to predict similar results (Eisenhardt, 1989, Yin, 2018). The case inclusion criteria included off-site manufacturing of wooden single-family houses, similar building systems, and business-to-end-user models in order to ensure that the customer process was similar between the cases. These criteria were chosen to ensure that building part production took place at an off-site factory and that the building systems to produce the parts were similar. Based on these criteria, two companies, Company Theta and Company Omega, were selected (see Table 5). The names Company Theta and Company Omega were used in the kappa to facilitate the reader. In the appended papers, the names Company A and Company B were used, however not consistently. The companies were classified with the same code according to the Swedish Standard Industrial Classification (manufacturing of prefabricated wooden houses). For more information about Company Omega, see Paper III.

**Table 5. Overviews of the companies involved.**

| | **Company Theta** | **Company Omega** |
|---|---|---|
| **Appears in** | Paper I (as Company A)<br>Paper II (as Company B)<br>Paper III | Paper II (as Company A)<br>Paper III |
| **Employees** | 260 | 1,000 |
| **Annual volume** | 300 | 1,500 |
| **Building system** | Wall elements | Wall elements and modules |

This was a joint study involving three researchers with slightly different purposes. Each researcher developed an individual interview guide with open-ended questions. My interview guide, which focused on the smart factory, is presented in Appendix 2. The interviewees were chosen in order to gain a holistic representation of the companies. Furthermore, the researchers chose interviewees with similar positions and knowledge. A total of 14 interviews were conducted, with each interview session lasting 1–3 hours. The interviewees held the following positions in Company Theta (six interviewees): architect and construction manager, technical manager, marketing director, system developer, production engineer, and production manager. There were eight interviewees from Company Omega: chief architect, reclaims manager, product manager, building permit drawer, head of design department, computer-aided design (CAD) developer, technical manager, and business area manager of production. All of the researchers were present during the interviews and took turns performing their own interviews based on their interview guides. All the interviews were recorded; the parts connected to my interview guide were transcribed. The data were used in Paper II (see Section 3.5.1 for the data analysis). Additional data collection was carried out for Paper III (see Section 3.5.2).

### *3.5.1 Data analysis for Paper II*

Several times during the interviews, questions from the other researchers would trigger the interviewees to refer components as a part of a smart factory for the wooden single-family house industry. For Paper II, the answers from all three researchers' interview questions were analyzed to learn about smart manufacturing technologies (the change in terminology is explained in Section 4.1) in the wooden single-family house industry. The results from this joint analysis were reported in Paper II.

### *3.5.2 Additional data collection and analysis for Paper III*

The data used in Paper III were solely based on the transcribed interviews related to my own interview guide. The data analysis followed the procedure for qualitative data analysis that Miles et al. (2020) described. Initially, within-case analysis was carried out (i.e., the data from Company Theta and Company Omega were analyzed seperately). Transcribed interviews were coded into different themes based on the practitioners' views about smart manufacturing in the wooden single-family house industry (Miles et al., 2020). A pattern emerged from the inductively identified themes, and the components of a smart wooden house factory for each company could be delineated. Two researchers conducted these delineations (two of the authors of Paper III).

NVivo software was used to develop the interviewees' definitions of a smart wooden house factory. The transcribed interviews from each company were run through the word frequency function of NVivo. This was done to ensure that words that were frequently used to describe a smart wooden house factory formed part of the resulting definitions.

Additional data were collected for Paper III. In both companies, workshops were organized to elaborate upon and confirm the results from the analysis (Säfsten and Gustavsson, 2019). At Company Theta, the workshop involved four of the six interviewees; at Company Omega, the workshop involved three of the eight interviewees. Two researchers attended the workshop, and the author of this thesis ran the workshops.

During the first part of the workshop, the identified components of a smart wooden house factory were presented and discussed. Thereafter, the proposed definition of a smart single-family wooden house factory was introduced and discussed. During the workshop, the participants ranked the components according to perceived importance, discussed whether any components were missing, and talked about whether the suggested definition should be reformulated. Eventually, the workshop concluded, having produced a set of components comprising a smart single-family wooden house factory and a definition that everyone agreed upon.

## 3.6 Research Study C

The purpose of Research Study C was to investigate different initiatives that denoted the fourth industrial revolution (e.g., Industry 4.0, smart manufacturing, smart factory). This study was based on a traditional literature review (Jesson et al., 2011). The search was limited to document type (review), language (English), and publication year (2015–2019). The first search yielded 154 papers. The next step was to screen the titles and abstracts for eligibility, ensuring that the papers focused on several components of the initiative, not just on a certain component. During this process, snowballing techniques were also used on papers that seemed interesting (Wohlin, 2014). In total, 13 relevant papers were identified.

### *3.6.1 Data analysis for Paper III*

The 13 papers underwent a content analysis to fulfill the data analysis requirements of Paper III (Seuring and Gold, 2012). The content analysis focused on what components were used to describe the content of Industry 4.0.

### *3.6.2 Data analysis for Paper IV*

Based on the data analysis from Paper III, the researchers established that Industry 4.0 was considered to be an unclear term (Ghobakhloo, 2018, Hermann et al., 2016), and there was no consistent classification of the content components of Industry 4.0.

For Paper IV I wanted to go deeper into the content analysis and use triangulation to ensure validity of the components. Another content analysis was performed on the 13 papers to inform Paper IV. Here, source triangulation was used to ensure the validity of the components (Säfsten and Gustavsson, 2019). The component had to be represented in more than one paper in order to be included; 23 components emerged. Some components resembled one other, and these were gathered into one component (e.g., cloud computing, cloud manufacturing, and the cloud; service orientation and new business models; etc.).

It is worth noting that the original references for each of the 23 components found in the 13 papers were traced in order to elaborate further on the components as needed.

All 23 components were structured based on a framework featuring two categories: technologies and design principles. The number of times the technologies and design principles occurred in the 13 reviewed papers was also analyzed to give an indication of the most frequently occurring technologies and design principles. For the components that resembled each other and that were gathered into one component, duplicate references were excluded. The technologies or design principles with the same number of occurrences were sorted based on alphabetical order.

## 3.7 Quality of the research

The traditional quality criteria of validity and reliability were used to evaluate the quality of the research (Yin, 2018). Validity is the extent to which the measured/observed elements correspond to what the researchers intended to investigate (internal validity) and the context in which the results are valid (external validity). Reliability is the ability to repeat an observation/study and get the same results (Yin, 2018). For all three research studies (A, B and C), measures were taken to secure and strengthen both validity and reliability.

In Research Study A, triangulation was used in the form of data triangulation (Leedy and Ormrod, 2014). Here, interviews were combined with a workshop. Using several data sources yields a more rigorous foundation. Researcher triangulation (Säfsten and Gustavsson, 2019) was used because two researchers conducted the workshop (two of the authors of Paper I). This reduces the risk of bias based on a single researcher’s perceptions (Karlsson, 2016). Respondent validation was also conducted with all of the interviewees (Säfsten and Gustavsson, 2019). At the end of each interview, the researcher and interviewee agreed upon the company’s achieved level of industrialization within the characteristic areas that they had discussed within the IHB framework. A case study database was set up containing the interview guide, audio recordings of the interviews, transcribed documents, notes from the workshop, and clarification on the research procedures (Yin, 2018). This could allow other researchers to access the data and repeat the analysis, if measures to secure anonymity were taken. This is a common procedure when data are collected through interviews, as it is not possible to repeat these same interviews (Säfsten and Gustavsson, 2019).

In Research Study B, measures were taken to secure and strengthen validity and reliability. Replication logic (Eisenhardt, 1989, Yin, 2018) was used in the sampling process of the cases, and literal replication was used when similar results were anticipated through a comparable type of participant. Triangulation was used in the form of data triangulation (Leedy and Ormrod, 2014)—interviews were combined with a workshop, as several data sources create a more thorough foundation (Säfsten and Gustavsson, 2019). Researcher triangulation was also used, as three researchers took part in the interviews (the authors of Paper II). Two researchers took part in the data analysis for my interviews (two of the authors of Paper III). Two researchers took part in the workshop at Company Theta (two of the authors of Paper III). Three researchers took part in the workshop at Company Omega (two of the authors of Paper III). Researcher triangulation reduces the risk of bias based on using just one researcher's perceptions (Karlsson, 2016). The workshops functioned as a type of respondent validation to ensure that there were no misunderstandings (Säfsten and Gustavsson, 2019). Finally, a case study database was set up containing the interview guide, audio recordings of the interviews, transcribed documents, notes from the workshops, and clarification of the research procedures (Yin, 2018).

Research Study C followed a traditional literature review process to ensure transparency (Jesson et al., 2011). Snowballing techniques were also used (Wohlin, 2014).

## 3.8 Ethical considerations

In terms of ethical considerations, it is important to ensure that no harm is done to the participants via the confidentiality of records and respondent anonymity (Bryman and Bell, 2015). This was done for Research Studies A and B. The participants were informed about the research and told that it was up to them to decide if they wanted to partake or not. Additionally, the interviewees were informed that the information shared about the study would be done in a safe and secure manner (Williamson, 2002).

Co-authorship statement is an ethical consideration, the ambition at School of Engineering, Jönköping University is to follow the Vancouver rules for co-author statement (http://www.codex.vr.se/en/etik2.shtml). The papers that this licentiate thesis is based on have the ambition to follow the Vancouver rules for co-author statement. See the authors' contributions in the list of appended papers.

# 4. Findings from the appended papers

*This chapter gives a brief summary of the appended papers. Findings are extracted from the papers to answer the three research questions of this thesis.*

## 4.1 Terminology and relationships between the papers and research questions

In this thesis, smart wooden house manufacturing in the wooden single-family house industry is partly described with empirically derived components (from Papers I, II, and III). A component refers to themes and patterns that the industry practitioners used when explaining their views on smart manufacturing in the wooden single-family house industry. A component serves as an element of something larger (i.e., smart wooden house manufacturing). However, the term "component" has not been used throughout all of the papers. In Paper I, components are referred to as "characteristics of a smart wooden house factory." In Paper II, components are referred to as "smart manufacturing technologies."

Another term that has changed throughout the research is the name of the sought concept—the term used in this thesis—is "smart wooden house manufacturing." In Paper I and Paper III, smart wooden house manufacturing was referred to as "smart wooden house factory/smart single-family wooden house factory." However, the research matured over time, and the aspect of the building site needed to be considered, the term factory indicated a limitation to the off-site activities, hence the change.

For an overview of the relationships between the appended papers, research questions, and research studies, see Table 6. Paper I contributed to answering RQ1, RQ2, and RQ3; the reported results in Paper I are from Research Study A. Paper II contributed to answering RQ1 and RQ2; its results are based on Research Study B. Paper III contributed to answering RQ1, RQ2, and RQ3; its results are based on Research Study B and partly on Research Study C. Paper IV contributed to answering RQ3; its results are based on Research Study C.

**Table 6. Relationships between the appended papers, research questions, and research studies.**

| Paper | RQ1 | RQ2 | RQ3 | Research study |
|---|---|---|---|---|
| **Paper I** | X | X | X | A |
| **Paper II** | X | X | | B |
| **Paper III** | X | X | X | B, C |
| **Paper IV** | | | X | C |

In the next Sections (4.2, 4.3, 4.4 and 4.5) findings are extracted from the papers to answer the research questions of this thesis.

## 4.2 Paper I

The aim of this paper was to investigate whether IHB characteristics might be a step toward a smart wooden house factory. The research questions for this paper were as follows:

- What are the characteristics of a smart wooden house factory for the single-family wooden house-building sector?
- What are the challenges for the single-family wooden house-building sector regarding the possibility to adopt the characteristics related to a smart wooden house factory?
- What is the relationship between industrialized house-building and a smart wooden house factory for the single-family wooden house-building sector?

The current situation concerning level of IHB in company Theta was assessed as a starting point for the analysis. Lessing's (Lessing, 2006) established framework for assessment of level of industrialized house building was used. The assessment gave an overview of the current situation and gave a foundation for the elaboration on challenges for the smart wooden house factory. In this paper, the main ideas of a smart wooden house factory were synthesized, and challenges on the way toward the smart wooden house factory were identified.

The following sections present the empirical findings from Paper I that helped to answer RQ1, RQ2, and RQ3 in this thesis.

RQ1: What is smart manufacturing in the wooden single-family house industry?

In this paper, three characteristics of a smart wooden house factory were identified:

- The holistic responsibility from seed to occupancy (including off-site and on-site assembly)
- Digitalization and automation
- Standardization in combination with flexibility

The first characteristic of a smart wooden house factory was identified as holistic responsibility from seed to occupancy. A smart wooden house factory is more than just prefabricated houses and on-site assembly. It must assist the client throughout the entire process, from the design phase to selecting materials, and finished house on-site, to name a few, to ensure a satisfied customer. This implies that the responsibility is not only internal to the company, but that it must also ensure that the whole chain is optimized to reduce waste and deliver value to the customer from forest to finished house.

The second characteristic was identified as digitalization and automation. A smart wooden house factory should have a level of digitization enabling it to automate production if wanted or needed. Digitization must first be improved, as it is a prerequisite for automation—the two are interrelated. Currently, parts of the production process could easily be automated, but the level of digitization is too low.

The third characteristic was identified as standardization in combination with flexibility. A smart wooden house factory should utilize standardization without sacrificing flexibility. Company Theta has two product concepts, one that is more standardized, and one that is more customized. A smart wooden house factory should make it possible to use one standardization for both concepts without affecting flexibility, especially for customized houses. One example could be standardization regarding the wainscot within the building system. However, it is imperative that the standardization does not affect flexibility so that the company can build the customized house the customer wants.

### RQ2: What are the challenges related to smart manufacturing in the wooden single-family house industry?

Two challenges were found regarding the possibility of adopting the characteristics related to a smart wooden house factory:

- Culture
- Competence

The first challenge identified was culture. The industry is known for being slow in taking action to increase efficiency. Even if Company Theta wanted to improve, the culture of the industry would hold it back. The maturity level in the culture and organization in terms of adopting modern technology and modern working methods is low. Desire within the culture to change, improve, and utilize modern technology is a challenge.

The second challenge identified was competence. There is a lack of knowledge, and it is hard to find people with the appropriate skills. Even if Company Theta wants to change, the knowledge of how to do so does not exist. For example, it is a challenge to obtain the level of digitalization, standardization, and knowledge that is required to build an automated house production line without losing the flexibility to provide a fully customized house.

### RQ3: What are the enablers for realization of smart wooden house manufacturing?

In this paper, IHB was investigated as a potential first step toward a smart wooden house factory. The IHB framework (Lessing, 2006) could be a way for the housing industry to reach a smart wooden house factory, since an increase in the level of implementation of IHB will move Company Theta closer to the characteristics necessary for a smart wooden house factory. The IHB framework can also be used as a measurement tool. Company Theta knows the current situation and the future challenges that lie ahead—it can structure its planned improvement activities according to how they will affect the IHB framework, the desired impacts, and what level the company is aiming for.

The IHB framework has some weaknesses, which was raised during the workshop, in relation to the empirical principles involved with a smart wooden house factory. The IHB framework does not consider the production system per se—for the smart wooden house factory, the conundrum of utilizing automation and standardization without sacrificing flexibility lies beyond the IHB framework. The IHB framework also does not clearly define the production system. Another issue raised during the workshop was that the IHB framework does not consider the knowledge and competence level of the housing industry.

## 4.3 Paper II

The aim of this paper was to explore the potential of smart manufacturing to complement and support product platforms in theory and practice in the context of IHB.

This paper was not originally planned in my research proposal. The idea for this paper came in connection with a Product platform course I took together with two of the authors of this paper (also a doctoral student within ProWOOD). The final assignment for the course was to write a paper with a product platform theme and we had just finished the data collection for research study B. It was a great opportunity for us (the authors of Paper II) to write something together and at the same time look at the data from a product platform perspective. Furthermore, through the collaboration we got the opportunity to expand the focus of the study to include the perspective from all three of us. As mentioned in Section 3.5.1, during the interviews, questions from the other researchers triggered the interviewees to refer components related to smart manufacturing. In this section, these components are extracted i.e. components that was brought up during the two other researchers interviews.

It is important to note that even though product platform aspects might be interesting for smart wooden house manufacturing, this has not been the focus for this findings extraction. The rational for this was my ambition to have an inductive approach for what smart manufacturing means in the wooden single-family house industry.

One note about Paper II is that Company Omega is called Company A, and Company Theta is called Company B (see Table 6 for overviews of the companies involved). For more information about company Omega, see Papers II and III.

Company Theta and Company Omega in this thesis targeted two customer segments. Segment 1: end-users buying houses for the first time, generally younger in age. Segment 2: end-users that are financially strong and have built houses before, generally older. Company Theta and Company Omega offer different products to each segment.

For segment 1, Company Theta and Omega offers customized houses built with prefabricated wall element with a standardized exterior and interior assortment under a turnkey contract.

For segment 2, the Company Theta offers a restricted number of standardized catalogue-house built with prefabricated wall element on a narrower standardized interior and exterior assortment under a turnkey contract.

For segment 2, Company Omega offers a restricted number of standardized catalogue-house built with modules on a narrower standardized interior and exterior assortment under a turnkey contract.

For the customized houses built with prefabricated wall elements the house can remain in the engineering phase for a long time, depending on the customer's wishes. The house does not go into production until an approved building permit and a signed contract are secured. The actual time spent in the factory is roughly 1–3 weeks. On-site production/assembly at the building site can take 4–6 months before the house is finished.

For the standardized catalogue-houses built with prefabricated wall elements, the design of the houses is based on market demands and trends. The interior and exterior assortment is standardized based on market demands and trends. The customer can only choose from a certain set of options. The houses are engineered to stock—depending on what options are offered and what the customer chooses, the house can be adapted-to-order. The house does not go into production until an approved building permit and a signed contract are secured. The actual time spent in the factory is roughly 1–3 weeks. On-site production at the building site can take 4–6 months before the house is finished.

For the standardized catalogue-house built with modules, the design is based on market demands and trends. The interior and exterior assortment is standardized based on market demands and trends. The customer can only choose from a certain set of options. Creating catalogue houses takes a lot of time and planning. The houses are engineered to stock and depending on what options are offered and what the customer chooses, the house can be adapted-to-order. The house does not go into production until an approved building permit and a signed contract are secured. The actual time spent in the factory is roughly 2–3 weeks. On-site production at the building site can take up to one month before the house is finished.

The building site is where companies usually lose control of the product. Normally, there is a building site manager who is responsible for making sure that the entrepreneurs can perform on-site production/assembly, are following the schedule and deliveries, etc. The companies try to build long-term relationships with entrepreneurs who know their products and have done good work in the past.

The next sections present the empirical findings from Paper II, which helped to answer RQ1 and RQ2 in this thesis.

### RQ1: What is smart manufacturing in the wooden single-family house industry?

Companies Theta and Omega mentioned several smart manufacturing technologies and challenges related to them. These technologies and challenges are explained below (for an overview, see Table 7).

*Flexible digital building system*

Both companies saw the development of flexible and digitalized building systems as a means to achieve higher efficiency in generating product variants for different product families.

*Flexible manufacturing system/flexible manufacturing system with higher automation level*

The necessity of alignment between manufacturing systems and building systems calls for the development of flexible manufacturing systems. The current challenge for Company Omega is to develop a flexible building system, as it is constrained by the capabilities of dedicated manufacturing systems (i.e., wall and floor assembly lines that were designed for a niche product that were bought and implemented in the 1980s). Meanwhile, Company Theta is not willing to invest in a high level of automation, as no production system suppliers have solutions that match the flexibility of Company Theta´s current building system.

*Sales configuration*

Creating flexible sales configurators that enable the configuration of not only the product assortment, but also the floor layouts and geometries is in line with developing flexible and digitalized building systems. Both companies encounter challenges with process efficiency due to salespeople who accept customer requirements that are outside their building system and assortment offerings. Sales personnel are often ignorant regarding the building system, causing them to promise the customer something outside the building system boundary, particularly when the market is down. Causing additional work in the design phase to fit the requirements as much as possible within the boundaries of the building and manufacturing systems. The challenge for both companies is that the existing configurators are not vertically integrated with their CAD and enterprise resource-planning (ERP) systems. Moreover, ERP, CAD, and other IT systems are currently not vertically integrated. This has a negative impact on the efficiency of their internal processes because error-prone and tedious manual information transfer is needed.

*Vertical IT integration*

The aim of both companies is to optimize the product realization process so that information is only entered into the system once to ensure vertical IT integration.

*Parametric modelling*

Both companies have started realizing the advantages of parametric CAD modelling tools and have developed custom libraries with predefined components to avoid reworking detailed designs. The development of parametric modelling tools and the digitalization of building systems are seen as means of addressing the three main challenges of (1) long lead times in the design phase, (2) quicker employee turnover in relation to long education time for newly employed personnel, and (3) the automatic generation of digital information for manufacturing automation.

*Virtual reality and augmented reality*

Both companies view the use of virtual reality (VR) and augmented reality (AR) technologies as a means to improve product representation to customers and to enable more efficient manual assembly of special elements.

*Digitizing knowledge*

Both companies have a digital database with documented descriptions regarding processes and products to support personnel. As the design phase creates a bottleneck, knowledge of how to use CAD software is transformed into parametric modelling tools. So far, Company Theta has such an application in its CAD software regarding exterior walls. Both companies want to digitize explicit knowledge in the form of parametric modelling tools to actively support their employees.

*Horizontal IT integration*

In Company Theta, the consultants working with electrical installations can add information directly into the CAD model, thereby enabling horizontal IT integration. Both companies are facing challenges with outsourcing their engineering of installations to consultancy firms. These firms use different software that are inoperable with the companies' CAD software. Therefore, their aim is to further improve internal efficiency by utilizing the benefits of horizontal IT integration.

**Table 7. Overview of the smart manufacturing technologies.**

| Company Omega | Company Theta |
|---|---|
| *Flexible digital building system* | *Flexible digital building system* |
| *Flexible manufacturing system with a higher automation level* | *Flexible manufacturing system* |
| *Sales configuration* | *Sales configuration* |
| *Vertical IT integration* | *Vertical IT integration* |
| *Parametric modelling* | *Parametric modelling* |
| *Virtual reality and augmented reality* | *Virtual reality and augmented reality* |
| *Digitizing knowledge* | *Digitizing knowledge* |
| | *Horizontal IT integration* |

## RQ2: What are the challenges related to smart manufacturing in the wooden single-family house industry?

In the section above several challenges are mentioned related to the smart manufacturing technologies, the challenges are summarized below:

- Constrained by the capabilities of existing dedicated manufacturing systems
- Suppliers of automation solutions
- Orders outside the building system
- Manual transfer of information between systems
- Long lead times in the design phase
- Employee turnover vs. long education time
- Interoperability with consultancy software

## 4.4 Paper III

The purpose of this paper was to expand the understanding of what the fourth industrial revolution implies for the wooden single-family house industry. The paper took a practitioner's perspective on the content and meaning of smart single-family wooden house factory based on current views and practices. The content of a smart single-family wooden house factory was related to state of-the-art research concerning Industry 4.0, with differences and similarities between the two highlighted. The paper contributed with potential areas for further development in the wooden single-family house industry.

The paper applied the term “smart factory” to denote the application of principles associated with the fourth industrial revolution at the plant level, which is in line with Thoben et al. (2017). Furthermore, Industry 4.0 was used as a common term for various initiatives related to the fourth industrial revolution.

In the next sections, the empirical findings from Paper III that have helped to answer RQ1, RQ2, and RQ3 in this thesis are presented.

### RQ1: What is smart manufacturing in the wooden single-family house industry?

Several components of a smart single-family wooden house factory were derived from Companies Theta and Omega. One definition of a smart single-family wooden house factory from each company was also found. For an overview of the components, see Table 8.

**Table 8. Components of a smart single-family wooden house factory.**

| Company Theta | Company Omega |
|---|---|
| *Automation** | *Automation** |
| *Building site* | |
| *Building system for automation* | |
| *CAD program** | *CAD program** |
| *Competitive products** | *Competitive products** |
| *Configurator** | *Configurator** |
| *Flow management* | |
| *Generation of digital information* | |
| *Production monitoring* | |
| *Product model simulation* | *Product model simulation** |
| | *Product platform* |
| *Sustainable products** | *Sustainable products* |
| *Systems integration** | *Systems integration** |
| | *Training and education* |
| *Virtual reality** | *Virtual reality** |

In Company Theta, 13 components of a smart single-family wooden house factory were identified, as described below. The components marked with an * were perceived to be the most important. Company Theta's definition of a smart single-family wooden house factory is given at the end.

*Automation**. A potential way to automate was described, which used the digital information in the product model to make tasks easier or completely automated in production (e.g., machines, Computer Numerical Control (CNC) machines, laser projections, robots). *Augmented reality* was considered to be a part of automation and a potential tool in production that was not in use.

Both factories had manual production lines, as the company did not perceive any existing automated solutions to be flexible enough. Automation solution suppliers for wooden house industry did not offer up-to-date solutions, compared to the suppliers of the mechanical industry. Company Theta used software automation in its CAD program.

*Building site*. This was added as a component of a smart single-family wooden house factory during the workshop. The participants mentioned efficient material flow to and on the building site as a component of a smart single-family wooden house factory. Currently, Company Theta feels the building site has the potential to improve. The company admitted that there was a lack of control when the product reached the building site.

*Building system for automation*. Currently, the company has manual production lines with benches at its off-site factories and a building system based on craftmanship solutions. Company Theta wanted to invest in automation and realized that its building system needed adjustment if it were to begin using an automated solution.

*CAD program*.* This would function as the main information aggregator of a 3D product model containing all the necessary information, such as installations (electricity, plumbing, heating, ventilation, and air conditioning). Company Theta had all the electricity installations included in its product model. The company emphasized an open application programming interface (API) in its CAD program to facilitate software development.

*Competitive products*.* The focus of any development project must result in competitive products, be it a product development, systems development, or production development project.

A *configurator** makes it easier to order complex products, as the information about the product is efficiently presented and collected. Company Theta was considering two types of configurators. Already in use was a configurator for the standardized products with a restricted number of house models and a standardized interior and exterior assortment. The company's vision was to achieve a more advanced configurator that was able to handle customized products. In a smart single-family wooden house factory, the customer could change the design of the house and feel that a unique house had been achieved.

*Flow management*. Company Theta strived to have takt time in the factory with kitting and optimized material flows, the company assumed this would improve off-site manufacturing efficiency.

*Generation of digital information for automation in production* was emphasized as being important to ensure that the entire process became more efficient, design and off-site manufacturing. To avoid simply shifting time from the production phase to the design phase, a holistic perspective on information flows was required.

*Production monitoring.* Company Theta wanted to implement a production monitoring tool in which each station logged stops and causes. This would allow the company to identify and eliminate root causes for stops as well as make decisions based on facts.

In a similar vein, *product model simulation* was expected to prevent errors in the early stages of product realization. Simulation could be used for quality control and clash tests in the product model.

*Sustainable products**. The importance of using sustainable materials and surface treatments was mentioned. Currently, the company can offer products with certified sustainable labelling.

*Systems integration**. The company needs to manually transfer information between systems. Company Theta felt that there was potential to get systems to work together—to communicate and to exchange data and information. Integration between the configurator, the ERP system, the CAD program, and the manufacturing execution system was specifically pointed out as being important. The vision was that information should be added once, then only refined.

*Virtual reality** was perceived as a useful tool for customer communication, as it ensures that the company and customer have a unified picture of product expectations. It also helps the customer in his or her decision-making process. Currently, VR is used in the configurator for standardized products. The ambition is to further develop this VR.

Company Theta defined a smart single-family wooden house factory as follows: competitive products developed with efficient information flows throughout the whole process, from customer idea to finished off-site and on-site production, achieved through a defined process that everyone follows, configurator, CAD program, system integrations, automation, production monitoring, and flow management.

In Company Omega, 10 components of a smart single-family wooden house factory were identified, as described below. The components marked with an * were perceived to be the most important. Company Omega's definition of a smart single-family wooden house factory is given at the end.

*Automation** was considered a key component. A potential to automate was described, with the digital information in the product model, to make tasks easier or completely automated in production e.g. machines, CNC machines, laser projections, robots. *Augmented reality* was considered as a part of automation and a promising tool in production. Augmented reality was perceived as interesting for installations but was not in use. Currently the company has an automated line for wall-elements with limited flexibility. Software automation was also considered, especially in the CAD-program.

*CAD-program** was mentioned as a critical component. One CAD-program was aimed at, with the function as the main information aggregator of a 3D product model that can contain all the necessary information, e.g. installations (electricity, plumbing, heating, ventilation, and air conditioning).

Currently, the company has several CAD programs with different information and features; this makes the process less effective.

*Competitive products**. The product development department needs to fulfil customer and market requirements.

A *configurator** to support salespeople during dialogues with customers was mentioned as one component of a smart factory. The product should be presented in such a way that customers feel that they can change anything and perceive the product as completely unique—nonetheless, it consists of standardized components. The configurator should have a standardized interior and exterior assortment. Company Omega also mentioned its vision for a more advanced configurator, where the customer could design the house through playing a "video game"—the product would still consist of the standardized components.

*Product model simulation** can prevent errors in the early stages that might otherwise result in substantial costs. Company Omega mentioned that simulation can be used for quality control and clash tests in the product model.

*Product platform* with a set of standardized components that are shared across a range of the company products to achieve repetition was mentioned as a component of smart single-family wooden house factory. Currently, the company is working to develop its product platform.

*Sustainable products* were considered as a component of a smart single-family wooden house factory. The importance of using sustainable materials and surface treatments was mentioned. Currently, the company cannot offer products with certified sustainable labelling.

*Systems integration**. Currently, manual transfer of information between systems is needed, but the company felt there was potential to get systems to work together—to communicate and to exchange data and information. Integration between the configurator, the ERP system, the CAD program, and the manufacturing execution system was specifically pointed out as being important.

*Training and education*. The company wanted to have consistent training in how to add information to the product model to ensure that all the functions of the modern CAD program were utilized and could be utilized later in the process. Current problems had resulted in manual work to attain information. Digital information in the product model was perceived as beneficial for production. More knowledge was required concerning how the digital information in the product model could be utilized and transferred to production.

*Virtual reality** was perceived as a useful tool for customer communication, as it ensures that the company and customer have a unified picture of product expectations. It also helps the customer in his or her decision-making process. Company Omega recently hired a person with experience in developing VR.

Company Omega defined smart single-family wooden house factory as follows: Competitive products efficiently developed that goes through the design phase and the automated wall-line efficiently. Competitive products that goes through the design phase and the automated wall-line efficiently. This is achieved through an established product platform, configurator, CAD-program, training and education, systems integration and automation.

### RQ2: What are the challenges related to smart manufacturing in the wooden single-family house industry?

Challenges related to the components of a smart single-family wooden house factory were empirically derived, see Table 9 for an overview.

*Supplier of automation solutions*

Company Theta had manual production lines because it did not perceive any of the available automated solutions to be flexible enough. The suppliers of automation solutions did not offer up-to-date solutions compared to the supplies of automation solutions for the mechanical industry.

*Loss of control at building site*

*C*ompany Theta admitted that there was a lack of control when the product reached the building site, a reason given for this was the coordination of entrepreneurs working at the building site.

*Building system for craftmanship*

Currently, Company Theta has manual production lines with benches in the off-site factories and a building system based on craftmanship solutions. It wanted to invest in automation and realized that the building system needed adjustment if it was to accommodate an automated solution. There is a lack of experience within the company in terms of changing the building system to fit automated solutions.

*Manual transfer of information between systems*

There is a vast amount of information that needs to be handled at every step in order to efficiently build a house. The companies use different systems and conducts a lot of manual transfers of information. Indeed, this is a challenge for both companies.

*Lack of experience in generating digital information*

This has to do with what type of information and how much more information needs to be added to a product model for the machine/automation to work.

*Information added in the wrong way in CAD program*

When information is added incorrectly into the product model, functions of the modern CAD program cannot be utilized later in the process. The company's current problems with this, results in manual intervention to obtain the correct information.

**Table 9. Overview of the challenges related to the components of a smart single-family wooden house factory.**

| Company Theta | Company Omega |
|---|---|
| *Supplier of automation solutions* | |
| *Loss of control at building site* | |
| *Building system for craftmanship* | |
| *Manual transfer of information between systems* | *Manual transfer of information between systems* |
| *Lack of experience in generating digital information* | *Lack of experience in generating digital information* |
| | *Information added in the wrong way in CAD program* |

### RQ3: What are the enablers for realization of smart wooden house manufacturing?

Some of the empirically derived components of a smart single-family wooden house factory from Company Theta and Company Omega could be related to the components of Industry 4.0 mentioned in the literature. Eight of the 15 empirically derived components of a smart single-family wooden house factory were found to correspond to components commonly mentioned in the literature. An overview of the result is presented in Table 10.

**Table 10. Components of a smart single-family wooden house factory related to the literature.**

| Company Theta | Company Omega | Corresponding components in Industry 4.0 |
|---|---|---|
| *Automation* | *Automation* | *Automation and augmented reality* |
| *Building site* | | |
| *Building system for automation* | | |
| *CAD program* | *CAD program* | *End-To-End engineering integration* |
| *Competitive products* | *Competitive products* | |
| *Configurator* | *Configurator* | |
| *Flow management* | | |
| *Generation of digital information* | | |
| *Production monitoring* | | *Technical assistance* |
| *Product model simulation* | *Product model simulation* | *Simulation and modeling* |
| | *Product platform* | |
| *Sustainable products* | *Sustainable products* | *Sustainability* |
| *Systems integration* | *Systems integration* | *Interoperability* |
| | *Training and education* | *Personnel training* |
| *Virtual reality* | *Virtual reality* | *Virtual reality* |

However, several of the components related to Industry 4.0 that were commonly mentioned in the literature were not mentioned by the two companies studied here: vertical integration and networked manufacturing systems, horizontal integration through value networks, IoT, cyber physical systems, sensors, cloud computing, big data technologies, and modularity. These could be potential areas for the further development of a smart wooden house factory.

## 4.5 Paper IV

The purpose of this paper was to present the content about initiatives related to the fourth industrial revolution in a structured manner. This was expected to support understanding of the fourth industrial revolution and thereby facilitate the transformation. To fulfil the purpose, two research questions were formulated:

RQ1: What are the components of Industry 4.0?

RQ2: How can the components of Industry 4.0 be structured to support the transformation?

For this paper, Industry 4.0 was applied as a common term for various initiatives related to the fourth industrial revolution.

The next sections present the findings from Paper IV that help answer RQ3 in this thesis.

### RQ3: What are the enablers for realization of smart wooden house manufacturing?

Several of the reviewed articles (Ghobakhloo, 2018, Gilchrist, 2016, Hermann et al., 2016, Mittal et al., 2019, Oztemel and Gursev, 2018, Pereira and Romero, 2017) described the components of Industry 4.0 in terms of technologies and/or design principles. A framework was developed based on these two components to reveal the content of Industry 4.0. Technologies describe the advanced digital technological innovations that, if used, can ascent new digital industrial technology (Gilchrist, 2016, Liao et al., 2017). Design principles address the issue of fuzziness in Industry 4.0 by systematizing knowledge and describing the components of this phenomenon (Ghobakhloo, 2018, Gregor, 2002, Hermann et al., 2016). The design principles allow manufacturers to anticipate the adaptation progress of Industry 4.0. The principles also give them the “how-to” knowledge about developing suitable methods and solutions required for the Industry 4.0 transition (Ghobakhloo, 2018). The design principles and technologies can be seen in Table 11.

**Table 11. The content of Industry 4.0 categorized into technologies and design principles organized in descending number of occurrences in the reviewed articles.**

| Technologies | Occurrences in reviewed articles | Design principles | Occurrences in reviewed articles |
|---|---|---|---|
| *Cyber physical systems* | 12 | *Smart factory* | 11 |
| *Internet of things* | 12 | *Service orientation* | 10 |
| *Big data* | 11 | *Sustainability and resource efficiency* | 9 |
| *Cloud* | 10 | | |
| *Internet of services* | 10 | *Real-time capability* | 7 |
| *Augmented reality* | 9 | *Decentralization* | 6 |
| *Automation and industrial robotics* | 9 | *Interoperability* | 6 |
| | | *Modularity* | 6 |
| *Simulation and modeling* | 7 | *Skills development* | 6 |
| | | *Virtualization* | 6 |
| *Additive manufacturing* | 6 | *Cybersecurity* | 5 |
| *Sensor* | 6 | *Smart product* | 5 |
| *Virtual reality* | 5 | *System integration* | 4 |

The 11 technologies and 12 design principles identified in this paper were also analyzed based on number of occurrences. The most frequently occurring technologies were CPS, IoT, and big data. The most frequently occurring design principles were smart factory, service orientation, and sustainability and resource efficiency.

The findings of this paper indicate that a digital transition is required to implement Industry 4.0. This transition featuring all the technologies and design principles identified can seem overwhelming for companies. However, it is important to note that it is not necessary for companies to have every design principle and technology in place before embarking on a digitalization journey. Specific areas of companies' operations can be digitalized first—to do this, Ghobakhloo (2018) recommends establishing a transition strategy.

# 5. Discussion

*This chapter discusses the main findings from the research. The empirically derived definitions are related to the literature and constitute the foundation for the conceptualization of smart wooden house manufacturing. The empirically derived components and challenges related to smart wooden house manufacturing are sorted into the identified parts of smart wooden house manufacturing and related to the literature. The identified enablers are also discussed. The chapter ends with a discussion of the research methods used.*

## 5.1 What is smart manufacturing in the wooden single-family house industry?

This licentiate thesis is a first step toward conceptualizing smart wooden house manufacturing. In this section, the results related to RQ1 (What is smart manufacturing in the wooden single-family house industry?) are discussed.

To answer RQ1, two research studies, A and B, were performed. They resulted in Papers I, II, and III. Their results are examined in depth, as each paper contributes with fragments to answering RQ1. Based on the empirically derived components and definitions of smart wooden house manufacturing from these papers, a first step to synthesize the conceptualization of smart wooden house manufacturing is taken. The empirically derived components and definitions of smart wooden house manufacturing are also discussed and related to the frame of reference to identify any uniqueness or similarities.

The concept of smart wooden house manufacturing for the wooden single-family house industry has not yet been elaborated upon in the literature. Even in a broader search that included the construction industry, the concepts of smart manufacturing and other synonyms, like Industry 4.0, smart production, or smart factory, have not gained much attention (Dallasega et al., 2018, Love and Matthews, 2019, Monizza et al., 2018, Oesterreich and Teuteberg, 2016, Pasetti Monizza et al., 2018, Schimanski et al., 2019, Woodhead et al., 2018). In order to conceptualize smart wooden house manufacturing, a broader set of literature was required that included industry sectors where the literature on smart manufacturing and synonyms like Industry 4.0 were more established (Ghobakhloo, 2018, Mittal et al., 2017, Oztemel and Gursev, 2018).

Literature on IHB was also part of the foundation for conceptualization as it dealt with improved competitiveness in the house-building industry (Lessing, 2006). However, the IHB literature focuses more on the business-to-business industry (Lessing, 2006), whereas the companies in this thesis focus on business-to-end-users.

Furthermore, the traditional operations management literature (Hayes and Wheelwright, 1984, Hill and Hill, 2009) serves as an important foundation for development of manufacturing systems and manufacturing strategies that are at the core of the concept of smart wooden house manufacturing.

### *5.1.1 Defining smart wooden house manufacturing*

The first step to synthesize the concept smart wooden house manufacturing is taken in this section. Here, the empirically derived definitions of smart wooden house manufacturing are discussed and related to the frame of reference.

A well-described concept is one that establishes the features, attributes, or characteristics of the phenomenon in the real word that it is meant to represent; it also distinguishes the concept from other related phenomena (Harter and Schmidt, 2008, Podsakoff et al., 2016, Shaffer et al., 2016).

Concepts can be explained and delimited in relation to other concepts, which can be done through definitions (Säfsten and Gustavsson, 2019). A definition is a conceptual definition or a delimitation of the meaning or use of a linguistic expression (Hansson, 2007). The empirically derived definitions of smart wooden house manufacturing are stipulative. According to Hansson (2007), a stipulative definition refers to how you define the term yourself (i.e., the definitions are based on the company’s own perceptions of what smart wooden house manufacturing is).

As per the results of Research Study B, presented in Paper III, the two participating companies defined smart wooden house manufacturing as follows in Table 12.

**Table 12. Empirical definitions of smart wooden house manufacturing in the wooden single-family house industry.**

| Company Theta | Company Omega |
|---|---|
| *Competitive products developed with efficient information flows throughout the whole process – from customer idea to finished offsite and onsite production, achieved through a defined process that everyone follows, configurator, CAD-program, system integrations, automation, production monitoring and flow management.* | *Competitive products that goes through the design phase and the automated wall-line efficiently. This is achieved through an established product platform, configurator, CAD-program, training and education, systems integration and automation.* |

These definitions emphasize that the product goes through a process/phases from the customer's ideas to a finished house (i.e., a holistic process). The definitions also accentuate information flow and integration between different parts of the process/phases. The definitions contain different components that are used throughout the holistic process. Finally, they stress that if the products follow the holistic process, with integration throughout the process/phases, and utilize the components, the products will be competitive.

Similar aspects can be found in the literature on Industry 4.0. The need for a holistic process, integration within the process/phases, and the use of certain components is also highlighted when Industry 4.0 is defined for the construction industry:

> *...[ ] "Interdisciplinary technologies to enable the digitization, automation and integration of the construction process at all stages of the construction value chain" (Oesterreich and Teuteberg, 2016, p. 137).*

These empirically derived definitions can also be related to Lessing's (2006) definition of industrialized house-building:

> *"A thoroughly developed building process with a well-suited organization for efficient management, preparation, and control of the included activities, flows, resources and results for which highly developed components are used in order to create maximum customer value"* (Lessing, 2006, p. 93)

This definition accentuates that a product follows a holistic process, with integration throughout the process/phases. Furthermore, an expected positive result is included as an argument for using this kind of process (maximum customer value).

Based on this, as a first step to synthesizing the concept of smart wooden house manufacturing was made. As foundation, a holistic product realization process containing three main phases is visualized: engineering design, off-site production, and on-site production/assembly. From the empirical definitions, it is clear that the different phases need to be integrated. Another part mentioned in the definitions is the expected result. To sum up, the frame of the concept smart wooden house manufacturing is visualized in Figure 6.

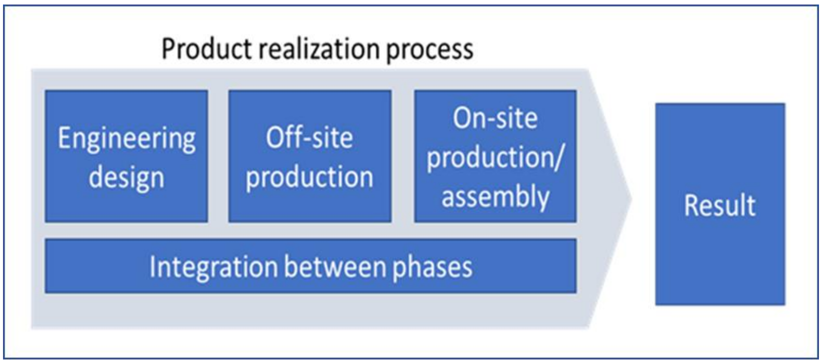


**Figure 3. Holistic process of smart wooden house manufacturing.**

The next step of the conceptualization was to add the components into the different parts of the frame of smart wooden house manufacturing. In this thesis, the focus is on off-site manufacturing and on-site production/assembly (see Section 1.4 delimitations). In the following section, the components of smart wooden house manufacturing derived from Research Study A and B, and presented in Papers I, II, and III, are sorted based on the product realization process.

### *5.1.2 Components of smart wooden house manufacturing*

The empirically derived components of smart manufacturing in the wooden single-family house industry are sorted into Table 13. The components marked with an * were perceived as being the most important component of smart wooden house manufacturing (according to Research Study B, presented in Paper III).

**Table 13. Components of smart wooden house manufacturing.**

| **Smart wooden house manufacturing** | | | |
|---|---|---|---|
| **Engineering phase** | **Off-site production phase** | **On-site production/ assembly phase** | **Result** |
| *Flexible digital building system*<br>*Standardization in combination with flexibility*<br>*Product platform*<br>*Configurator**<br>*Sales configurator*<br>*Virtual reality**<br>*Product model simulation**<br>*Software automation**<br>*Parametric modelling*<br>*Digitizing knowledge*<br>*Training and education* | *Automation**<br>*Augmented reality*<br>*Digitalization and automation*<br>*Flexible manufacturing system with higher automation level*<br>*Flexible manufacturing system*<br>*Flow management*<br>*Production monitoring* | *Building site (not investigated further)* | *Competitive products**<br>*Sustainable products** |
| **Integration between phases** | | | |
| *Systems integration**<br>*Horizontal IT integration*<br>*Vertical IT integration*<br>*CAD program**<br>*Generating digital information for automation*<br>*Building system for automation* | | | |

In the following sections, the empirically derived components of smart wooden house manufacturing from Table 13 are discussed and related to the frame of reference to identify any uniqueness or similarities.

### Components of the engineering phase

The components *Flexible digital building system, Standardization in combination with flexibility* and *Product platform* are means of generating product variants for different product families. This sort of logic is also utilized in IHB (Jansson, 2013). Furthermore, such aspects can be found in Lessing's (2006) framework for IHB in developed technical systems. Here, technical systems include frame solutions, electrical and sanitary installations, façade systems, etc. with different levels of flexibility. This indicates that these empirically derived components are not unique to the wooden single-family house industry.

The components *Configurator,* and the similar *Sales configurator,* were perceived as valuable means to present products to the customer and handle the information about the customer's choices more efficiently. According to the results presented in Paper III, a configurator was perceived as one of the most important components of smart manufacturing in the wooden single-family house industry. The use of a configurator can also be found in Eid Mohamed et al. (2017), whose research demonstrates the application of cutting-edge technologies in modes of integrating homebuyers into a participatory dialogue to achieve sustainable outcomes. In other industries, such as the automotive industry, configurators have been used for a long period of time. This indicates that the components are not unique to the wooden single-family house industry.

*Virtual reality (VR)* was also perceived as one of the most important components of smart manufacturing in the wooden single-family house industry. VR is used as a means to simulate an experience of the final product for the customer. VR is associated with the component configurator described above. VR is a frequently mentioned component of Industry 4.0 (Kang et al., 2016). The general idea of VR is to create a simulated environment that can be similar to or completely different from the real world (Earnshaw, 2014). However, this is not a unique component to the wooden single-family house industry, as this technology is used in many different industries, such as automotive and gaming.

The component *Product model simulation* concerns simulation in the CAD program. Product model simulations can be made to prevent error at an early stage. Such aspects are included in the *simulation and modeling techniques* component in Industry 4.0 (Saucedo-Martínez et al., 2018). Where simulation and modeling enable manufacturers to prevent errors at an early stage that might otherwise result in substantial costs, they can also be used to optimize a manufacturing plant during ongoing daily operations, for example (Gilchrist, 2016). *Product model simulation* was perceived as a crucial component for smart wooden house manufacturing.

The components *Software automation*, *Parametric modelling*, and *Digitizing knowledge* concern engineering in the CAD program. The companies want to support the staff with built-in solutions to make it easier to work in the CAD program. These components are related to the literature on IHB (Singh et al., 2015). Furthermore, parametric design techniques are one of the central technologies of Industry 4.0 in the construction industry (Oesterreich and Teuteberg, 2016). Paper III cited component *Software automation* as one of the most important components of smart wooden house manufacturing.

The *Training and education* component of smart wooden house manufacturing concerns the work performed in the CAD program. This component ensures that information is correctly added so that users can take advantage of the built-in functions of the CAD program. The empirically derived component indicated that the working environment is changing alongside modern CAD programs, and the possibilities for using digital information in the product model are manifold. In order for employees to manage these changes, training and education was mentioned as a component of smart wooden house manufacturing. The organization need to train the personnel to be qualified. Such aspects can also be found in the *skills development* component of Industry 4.0 (Oztemel and Gursev, 2018). Industry 4.0 will demand new competences; society and organizations must create opportunities for workers to be trained in these required skills (Erol et al., 2016).

All the empirically derived components in the engineering phase could be related to the literature, indicating that the engineering phase components of smart wooden house manufacturing are not unique per se. However, the industry-specific conditions (see Section 2.1) and products (see Section 4.3) need to be considered when developing the components for smart wooden house manufacturing.

### Components of the off-site production phase

The components of *Automation and Digitalization*, *Automation* and *Augmented reality* are all connected to production and an urge to make tasks easier or completely automated. Such aspects can also be found in the *Automation and industrial robotics*, a component of Industry 4.0 (Ghobakhloo, 2018). Automation focuses on achieving a process or procedure that is performed with minimal human assistance using support from software, machines, and robots (Kolberg and Zühlke, 2015). The empirically derived component *Augmented reality* was perceived as being interesting for making installations more efficient. AR is also a component of Industry 4.0 (Ghobakhloo, 2018); it is an enhanced version of reality where live, direct, or indirect views of physical real-world environments are enhanced with overlaid computer-generated images (Oztemel and Gursev, 2018). The *Automation* component was perceived as one of the most important components of smart manufacturing in the wooden single-family house industry.

*Flexible manufacturing system with higher automation level* and *Flexible manufacturing system* concern the necessity for alignment between the production system and building system. This should be done to be able to produce the products that can be developed from the building system. Although automation is a component of smart wooden house manufacturing, according to the companies, it is important that the automation is flexible. This can be related to Andersson et al. (2007), who argued that companies producing single-family houses should focus on a higher degree of automation, and at the same time, be able to use a flexible production system. These sorts of aspects can also be found in the component *Modularity* in Industry 4.0. Whereas modularity concerns the shift from linear manufacturing and planning, rigid systems and inflexible production models must be pushed toward an agile system that can adapt to ever-changing circumstances and requirements (Gilchrist, 2016).

The components of *Flow management* and *Production monitoring* concern the development of stations and takt flow with optimized logistics and tracking the status in the production of the different stations. Such aspects can be found in the *Real-time capability* component of Industry 4.0 (Hermann et al., 2016). Real-time capability is about collecting real-time, and real-world, data through a range of different dimensions, such as factory, product, business partners, etc. To help make the right decision, this is facilitated by IoT (Lee et al., 2015). However, the *Production monitoring* component of smart wooden house manufacturing is not as holistic. Furthermore, takt flow and production monitoring are not unique for this industry—both of these have existed in other industries for a long time (Ohno, 1988).

All the components in the off-site production phase could be related to the literature, which indicates that the off-site production phase components of smart wooden house manufacturing are not unique per se. However, the industry-specific conditions (see Section 2.1) and products (see Section 4.3) need to be considered when developing these components. Furthermore, the categorization of off-site production, and some aspects of the components, can be found in the characteristics of the off-site manufacturing of building parts in Lessing's (2006) framework for IHB. However, this framework is more suited for the business-to-business sector and not specifically for the wooden single-family house industry (Vestin et al., 2018).

### Components of the on-site production/assembly

The last phase of the product realization process is on-site production/assembly (see Figure 6 and Table 13). The research studies did not focus on on-site production, but the efficient flow of material to and on the building site was mentioned as a component of smart wooden house manufacturing, denoted as *Building site.* According to Company Theta, the building site has the potential to improve, as there was a lack of control when the product reached the building site. Such aspects can be found in the area of *Logistics integrated in the construction process*, which is one of the characteristics areas of IHB (Lessing, 2006). The activities on the building site include final assembly and complementing work. The deliveries of material must be thoroughly planned and work according to the Just In Time (JIT) principle and implemented in close collaboration with material suppliers.

Issues related to the building site could not be related to any components of Industry 4.0. The means of producing products is unique to the house-building industry. Other sectors feature final assembly phases that are separate from component manufacturing and sub-assembling, but these are still carried out in a manufacturing plant under controlled conditions. On-site production/assembly is usually a more uncontrolled situation featuring shifting weather conditions and a high number of external project participants (Lidelöw et al., 2015). For smart wooden house manufacturing, the building site needs to be considered. The empirical results suggest that smart wooden house manufacturing is a holistic responsibility for the organization and the participants. They must assist the client throughout the entire process to ensure customer satisfaction, including on-site assembly, logistics, etc.

### Components of the integration between phases

The components *Horizontal IT integration*, *Vertical IT integration*, and *Systems integration* concern the information flow within different systems/programs and departments. Information is added both internally within the companies and externally by consultants. The intention with various forms of systems integration is to remove the unnecessary manual transfer of information between programs and systems, and to get systems/programs to work together to communicate and exchange data and information. *Systems integration* was perceived as one of the most important components of smart manufacturing in the wooden single-family house industry. Similar components are frequently mentioned in the Industry 4.0 literature, including *interoperability* and *systems integration* (Ghobakhloo, 2018, Oztemel and Gursev, 2018, Wang et al., 2016). Interoperability is about the ability of two systems to exchange data and to share information—to understand each other and to use each other's functionality (Chen et al., 2008). System integration refers to the process of bringing together the component sub-systems into one system to ensure that the system is able to deliver the intended functionality (Ghobakhloo, 2018). In the Industry 4.0 literature, three different types of integration are mentioned: end-to-end, horizontal, and vertical. An empirically derived component that is related to the component of *End-To-End Engineering* in Industry 4.0 is the component *CAD program* in smart wooden house manufacturing. The CAD program component was perceived as one of the most important components. The CAD program is the main information aggregator of the 3D product model. The product model is enriched with information from different departments throughout the engineering phase and carries a vast amount of different information. This empirically derived component is similar to *End-To-End Engineering Integration* in Industry 4.0, as it refers to the integration of a continuous and consistent product model that can be used in every stage (Wang et al., 2016). In a product-centric value creation process, a chain of activities is performed: customer requirement expression, product design and development, production engineering, etc. It should be possible to use the product model in every stage (Wang et al., 2016).

The components *Horizontal IT integration*, *Vertical IT integration*, *Systems integration*, and *CAD program* of smart wooden house manufacturing can be related to Industry 4.0 in terms of the construction industry. Industry 4.0 in the construction industry is used as a synonym to describe the increasing use of ICT (Oesterreich and Teuteberg, 2016). The use of ICT is also one of the eight areas in Lessing's (2006) IHB framework. Lessing argues that industrialized processes require accurate and reliable information, and that modern ICT can provide tools that effectively handle, update, and change digital material and provide solutions for information exchange and data storage.

The component *Generating digital information for automation in production* concerns integration between the engineering phase and the off-site manufacturing phase. The component is linked to the empirically derived components *CAD program*, *Vertical IT integration*, and *Systems integration*. According to the companies studied in this thesis, the potential to automate production comes from the digital information in the product model. It is important to make sure that the equipment in production can get the right type of information from the engineering phase to function. The information in the product model must be added in the engineering phase in such a way that the equipment in production can perform its tasks. Furthermore, as the component emphasizes, the entire process needs to become more efficient to ensure that not only time is moved from the off-site manufacturing phase to the engineering phase. This aspect is also found in the literature on Industry 4.0, it is important to establish the generation of actions and information from the information management systems for the machine or robot (Kang et al., 2016, Oztemel and Gursev, 2018).

Another component that is sorted into the integration between phases is *Building system for automation*. This component was specific to Company Theta, which had manual production lines with benches and a building system based on craftmanship solutions. To achieve automated production, Company Theta found that the building system needed to be adjusted, which might also affect the engineering of products. This component is in line with techniques such as design for manufacturing (DFM) and design for automation (DFA). DFM and DFA are established techniques in other industries and are important parts of concurrent engineering and integrated product development (Bellgran and Säfsten, 2009).

All the components related to the integration between phases could be related to the literature, which indicates that the integration between phases in product realization in smart wooden house manufacturing is not unique per se. However, the industry-specific conditions (see Section 2.1) and products (see Section 4.3) need to be considered when developing these components. The two companies have embarked on their digital transformation, with a strong focus on how to add and share digital information between systems/programs.

### Result components

The components *competitive products* and *sustainable products* concern the expected results of smart wooden house manufacturing. As per the findings from Research Study B, presented in Paper III, these two components were perceived as two of the most important components of smart wooden house manufacturing. It is crucial for the companies, considering the competitiveness of the market, to offer different products to different customers (end-users) in order to cover certain well-selected parts of the market, as described in Section 4.3. Having a customer focus is also emphasized in the IHB framework (Lessing, 2006).

The empirically derived component *Sustainable products* indicates that it is important to have a sustainable label attached to products. Such aspects are included in the *Sustainability and resource efficiency* component of Industry 4.0 (Lasi et al., 2014, Mittal et al., 2019, Thoben et al., 2017). Sustainability and resource-efficiency should be the focus of the design of industrial manufacturing processes, as they enable efficient coordination of the product, material, and energy throughout the product life cycle (Stock and Seliger, 2016). However, the sustainable life cycle perspective described in the literature was not found in any of the empirically derived definitions or components of smart wooden house manufacturing.

The components mentioned here could be related to the literature, indicating that the expectations from smart wooden house manufacturing are not unique. In their highly competitive market (Schauerte et al., 2014), the companies have focused on the customers (end-users) when developing products. From a manufacturing strategy perspective, it is important to focus on the order qualifiers and order winners of the market (i.e. cost, quality etc.) (Hayes and Wheelwright, 1984, Hill and Hill, 2009). However, the specific order qualifiers and order winners for the companies and smart wooden house manufacturing were not included in the scope of this thesis.

## 5.2 What are the challenges related to smart manufacturing in the wooden single-family house industry?

In this section, the results related to RQ2 are discussed (What are the challenges related to smart manufacturing in the wooden single-family house industry?) The challenges related to the components associated with smart wooden house manufacturing have been empirically derived from Research Studies A and B, presented in Papers I, II, and III. The challenges were sorted according to the preliminary parts of the concept of smart wooden house manufacturing (see Figure 6). An additional category was added: general challenges. The companies described a challenge as an underlying feature that complicated a situation.

Several empirically derived challenges related to the components associated with smart wooden house manufacturing were found (see Table 14 for an overview).

**Table 14. Challenges related to the components associated with smart wooden house manufacturing.**

<table>
<tr><th colspan="3">Smart wooden house manufacturing challenges</th></tr>
<tr><th colspan="3">General challenges</th></tr>
<tr><td colspan="3">Culture<br>Competence</td></tr>
<tr><th>Engineering phase challenges</th><th>Off-site production phase challenges</th><th>On-site production/assembly phase challenges</th></tr>
<tr><td>Orders outside the building system<br>Information added in the wrong way in CAD program<br>Employee turnover vs. long education time<br>Long lead time in design phase<br>Interoperability with consultancy software</td><td>Constrained by the capabilities of an existing dedicated manufacturing systems<br>Suppliers of automation solutions</td><td>Loss of control at building site</td></tr>
<tr><th colspan="3">Challenges of integration between phases</th></tr>
<tr><td colspan="3">Manual transfer of information between systems<br>Lack of experience in generating digital information for automation<br>Building system for craftmanship</td></tr>
</table>

Some of the challenges were directly connected to the empirically derived components of smart wooden house manufacturing (Table 13). Components mentioned as being essential for smart wooden house manufacturing were sometimes an immediate response to the perceived challenges and vice versa. This will be further discussed below. In the following sections, the empirically derived challenges for smart wooden house manufacturing are discussed and related to the frame of reference.

### General challenges

The *Culture* challenge concerns a resistance to change and to improving and utilizing modern technology. It takes a long time to adapt to new technology and new working methods. This challenge is well known within the house-building industry. The industry is slow in activities to increase efficiency (Eliasson, 2011). Höök and Stehn (2008) argue that there is a need for a change in organizational culture in construction companies in order to better utilize the advantages of industrialized housing production. Knowledge on how to approach and implement such production methods needs to be created and spread amongst employees (Stehn and Höök, 2008).

The *Competence* challenge concerns the lack of appropriate knowledge and competences in the industry—in other words, finding people with the appropriate skills is a challenge. Stendahl (2009) found that well-educated employees have a positive impact on innovative activities. This challenge can also be related to the challenges found in the action plan for the smart industry (Näringsdepartementet, 2016). The challenges of modern technology, digitalization, and automation as well as a lack of competence are known in the Swedish industry not only in the small sector of wooden single-family house builders. It seems that wooden single-family house industry are facing the same or at least similar changes as, other industrial sectors (Näringsdepartementet, 2016).

### Challenges in the engineering phase

*Orders outside the building system* was described as a challenge concerning the situation when sales staff accept customer requirements that are outside the building system and/or interior/exterior assortment. This entails additional work that the company has a hard time charging for. The components *configurator* and *sales configurator* of smart wooden house manufacturing are responses to these challenges, as they make it harder to accept orders outside the building systems. Here, the orders must follow a certain process starting from the configurator. Furthermore, the configurator can guide the customer to ensure that the customer makes the choices presented in the configurator.

The challenge of *Information added in the wrong way in CAD program* concerns staff working in the CAD program and how information is incorrectly added. This can mean functions of the program cannot be utilized properly. The component of *training and education* of smart wooden house manufacturing is a response to this challenge by educating the staff on how to correctly add information to ensure that all features can be used. As per Stendahl (2009), well-educated employees have a positive impact on innovative activities.

*Long lead time in design phase* and *Employee turnover vs. long education time* were described as challenges. The products spend a long time in the engineering phase. For Company Omega, it is important to have employees that can work efficiently and independently in the CAD program. This takes time and effort from both the employees and company to achieve. However, the industry tends to resign employees when the market goes down (Eliasson, 2014). Thus, employees in training are let go, and their competences are lost. The components of *parametric modelling*, *digitizing knowledge*, and *software automation* for smart wooden house manufacturing are responses to these challenges. These components can make it easier and faster for employees to learn and to work with less education in the CAD program and still be independent.

*Interoperability with consultancy software* was described as a challenge concerning the external consultancy work done in the product model. The consultancy uses different software that is inoperable with the CAD program, forcing the companies to use two versions of the product model containing different sets of information. This can lead to problems with clash testing, as one example. The component *horizontal IT integration* for smart wooden house manufacturing is a response to this challenge. It could ensure that the programs can exchange data and share information, and as a result, have only one product model with all the information.

## Challenges in the off-site production phase

*Constrained by the capabilities of an existing dedicated manufacturing systems* is a challenge, as existing production equipment can be old and inflexible. However, it is an investment and a risk to buy and implement new production equipment. Wooden house manufacturers may face profitability—and thus, financial problems—when converting to new production systems (Lindblad et al., 2016b).

The challenge *Suppliers of automation solutions* concerns the products offered for automation solutions in the wood industry. According to Company Theta, the product offering for automation in the wood industry is less innovative compared to the suppliers of automation solutions in the mechanical industry. This is similar to what Salim et al. (2020) found—limited involvement in the design of manufacturing automation appears to reflect the traditional culture of the companies operating in wood product industries. This could imply that in order to enable smart wooden house manufacturing, the suppliers of automation solutions to the wooden house industry need to innovate. The wooden house industry needs to put greater demand on these suppliers to do so.

## Challenges in the on-site production/assembly

*Loss of control at building site* was described as a challenge. When the product reaches the building site, there are a lot of different entrepreneurs who get involved. In other words, there is a high number of external project participants involved at different stages and locations for house building (Lidelöw et al., 2015). Hence, maintaining control over the building site is a challenge. The component of *building site* for smart wooden house manufacturing is a response to this challenge.

## Challenges of integration between phases

The challenge of *Manual transfer of information between systems* concerns the vast amount of information on a house that must be handled in the product realization process. The problem is that the information between the systems/programs used requires error-prone and tedious manual information transfer. The component *systems integration* for smart wooden house manufacturing is a reaction to this challenge.

*Lack of experience in generating digital information for automation* was described as a challenge. It concerns what type of information and how much more information that needs to be added to the product model for the machine/automation to function. The component g*enerating digital information for automation* for smart wooden house manufacturing is a response to this challenge.

The challenge *Building system for craftmanship* concerns the lack of experience/knowledge in changing the building system for automated solutions. The component b*uilding system for automation* for smart wooden house manufacturing is a reaction to this challenge.

## 5.3 What are the enablers for realization of smart wooden house manufacturing?

The conceptualization of smart wooden house manufacturing is at the core of this thesis. When developing a concept, it is essential to identify its potential attributes (Podsakoff et al., 2016). As presented before, this can be done by using case studies and interviews as well as through a review of the literature (Podsakoff et al., 2016). In this thesis, the literature on the IHB framework and Industry 4.0 was reviewed. Some attributes have been identified that could potentially enable the realization of smart wooden house manufacturing, discussed below.

### Industrialized house-building framework as an enabler

Research Study A in Paper I revealed that the IHB framework developed by Lessing (2006) could be a way for the wooden single-family house industry to enable smart wooden house manufacturing. This is because increasing the level of implementation of the eight characteristic areas of IHB will move companies closer to the components of smart wooden house manufacturing.

Established in the discussion of RQ1 in this thesis, five of the eight characteristics areas of Lessing's (2006) IHB framework were identified in the empirically derived components of smart wooden house manufacturing (Section 5.1.2): Developed technical systems, customer focus, use of information and communication technology, off-site manufacturing of building parts, and logistics integrated in the construction process. If companies worked with the IHB framework and increased the level of implementation and achievement in these specific categories, it could enable the realization of smart wooden house manufacturing. However, the framework focuses on the business-to-business sector and is not specifically developed for the wooden single-family house industry with business-to-end-users model. Additional weakness with the IHB framework were identified in Paper I. One example was the conundrum of utilizing automation and standardization without sacrificing flexibility, which is essential for smart wooden house manufacturing but is not included in the IHB framework. Another issue is that the IHB framework does not consider the knowledge and competence level of the housing industry.

### Industry 4.0 as an enabler

The concept of smart manufacturing, or synonyms like Industry 4.0, for the wooden single-family house industry is not yet elaborated upon in the literature. The literature for how to enable and realize the components of smart wooden house manufacturing does not exist. However, the literature on Industry 4.0, and synonyms like smart manufacturing and smart factory, are more established. Furthermore, the identified components of smart wooden house manufacturing in Research Studies A and B presented in Papers I, II, and III had similarities with the components of Industry 4.0. Theories about how to implement components of Industry 4.0 with road maps, guidelines, and maturity models exist (Ghobakhloo, 2018, Mittal et al., 2018). This knowledge could be used for the matching components of Industry 4.0 and smart wooden house manufacturing to enable the realization of smart wooden house manufacturing. These components were sustainability and resource efficiency, virtual reality, systems integration, simulation and modeling techniques, skills development, interoperability, automation and industrial robotics, augmented reality, modularity, and real-time capability. However, one question that remains to be answered is to what degree solutions found for other industrial sectors might be applicable in the wooden single-family house industry to achieve smart wooden house manufacturing. This will be further discussed in future research (Section 6.3).

## 5.4 Discussion of the method

The research process and method chosen in this thesis are closely related to ProWOOD and the aim of the industrial graduate school. As doctoral students at ProWOOD are attached to a company, this has affected the case selection. Company Theta is a part of ProWOOD. The company's visions of the future state of a factory was the initiation of this research, making the company a natural part of the research. The direction of my research has developed in collaboration with the company, based on their needs for the future. In this section, the discussion focuses on the consequences that the methodological choices for this thesis may have. It is important to acknowledge that each scientific method has certain limitations that can influence the findings and conclusions.

This research is based on case studies—which have been identified as an appropriate research method in relation to the purpose, aim and RQs of this thesis. One important reason for choosing case study was the focus on the context of the studied phenomenon. The case study approach provided very detailed and rich data concerning what smart manufacturing means in the companies, challenges related to smart manufacturing, and enablers for realization smart manufacturing in the wooden single-family house industry. However, one limitation is that the data collected in this thesis are entirely qualitative. Although the procedure for qualitative data analysis that Miles et al. (2020) described was followed, there is a risk that the data analysis are subjective and influenced by the researchers' interpretations (Williamson, 2002). Therefore, measures were taken when transcribing the data to maintain the traceability of the analysis and conclusions to the raw data supporting them (Miles et al., 2020, Yin, 2018).

This thesis followed the recommendations of Podsakoff et al. (2016) when developing the concept of smart wooden house manufacturing. At first, only Company Theta was part of the study (Research Study A). However, to gain a deeper understanding of smart manufacturing in the wooden single-family house industry, another case company was chosen based on replication logic in Research Study B (Eisenhardt, 1989, Yin, 2018). When developing a concept, it can be hard to know when to stop—when enough data has been gathered. As a general rule, conceptualization can be synthesized when the definitions and the attributes associated with the concepts become redundant (Gerring, 2011). Although with only a sample of two companies, it was hard to know whether this was achieved. It is possible that the findings in this thesis do not represent the wooden single-family house industry and cannot be generalized; hence, more case studies might be needed.

When conducting case studies, there is always a risk that the participants of the interviews and of the workshops will be influenced by how the research study was set up. In retrospect, a possible limitation from Research Study A was that the characteristics of a smart wooden house factory were discussed after the assessment on level of IHB. There is a risk that the participants were influenced by the discussion about the level of IHB when little bit later elaborated on the characteristics of a smart wooden house factory.

Another possible limitation was from Research Study B. There is a risk that the questions asked by the other researchers affected the replies I got, both in a negative and a positive way—that the topics were not on the respondents' minds but were triggered by the other researchers' questions.

To conclude, strategies have been used to secure reliability and validity (as described in Section 3.7); however, as Research Studies A and B have certain limitations, this may have influenced the findings and conclusions.

# 6. Conclusion

*This chapter presents the conclusions from the research presented in this thesis, organized in relation to the RQs. It outlines the scientific contributions and industrial contributions and ends with recommendations for future research.*

## 6.1 Smart wooden house manufacturing

The purpose of the research presented in this thesis is to contribute to improve the competitiveness of the wooden single-family house industry. The idea is to develop the concept smart wooden house manufacturing to capture what a company in the house building sector need to consider in order to meet the expected future demands, and thereby allow them to be competitive on the market. This thesis is the first step in developing the concept of "smart wooden house manufacturing," which, when realized, is expected to contribute to improve the competitiveness of the wooden single-family house industry.

In order to achieve the purpose, given the above-mentioned idea, the thesis aims to increase the knowledge about what smart manufacturing means for the wooden single-family house industry. This requires investigating what smart wooden house manufacturing is, what challenges might be associated with it, and what enablers there might be for realization of smart wooden house manufacturing.

Following the purpose and aim, three research questions were formulated. The conclusions drawn are here presented in relation to these questions.

Firstly, the findings confirmed that the concept of smart manufacturing in the wooden single-family house industry was not yet elaborated in the literature. An inductive approach was used to answer RQ1 (What is smart manufacturing in the wooden single-family house industry?). In total, 26 components and two definitions for smart wooden house manufacturing were empirically derived from Research Studies A and B.

Based on the empirically derived definitions a first step to synthesizing the concept of smart wooden house manufacturing was made. A holistic product realization process containing three main phases was formed: engineering design, off-site production, and on-site production/assembly. From the empirical definitions, it was clear that the different phases need to be integrated. Another part mentioned in the definitions is the expected result. The empirically derived smart wooden house manufacturing components could be sorted into the different parts of the frame of smart wooden house manufacturing (see Table 15).

**Table 15. Smart wooden single-family house manufacturing.**

<table>
<tr><th colspan="4">Smart wooden house manufacturing</th></tr>
<tr><th>Engineering phase</th><th>Off-site production phase</th><th>On-site production/ assembly phase</th><th>Result</th></tr>
<tr><td>Flexible digital building system<br>Standardization in combination with flexibility<br>Product platform<br>Configurator<br>Sales configurator<br>Virtual reality<br>Product model simulation<br>Software automation<br>Parametric modelling<br>Digitizing knowledge<br>Training and education</td><td>Automation<br>Augmented reality<br>Digitalization and automation<br>Flexible manufacturing system with higher automation level<br>Flexible manufacturing system<br>Flow management<br>Production monitoring</td><td>Building site (not investigated further)</td><td rowspan="3">Competitive products<br>Sustainable products</td></tr>
<tr><th colspan="3">Integration between phases</th></tr>
<tr><td colspan="3">Systems integration<br>Horizontal IT integration<br>Vertical IT integration<br>CAD program<br>Generating digital information for automation<br>Building system for automation</td></tr>
</table>

This thesis can conclude that most of the empirically derived components emphasized a digital transformation with a focus on digital information flow, how to add information, information compilation, and information distribution between systems/programs and departments. The on-site production/assembly phase with a building site component is a unique part of house-building. For truly smart wooden house manufacturing, the building site need to be considered.

For RQ2 (What are the challenges related to smart manufacturing in the wooden single-family house industry?), challenges related to the components associate with smart wooden house manufacturing were empirically derived from Research Studies A and B. These challenges could be sorted into a similar table to that of smart wooden house manufacturing, although an additional category was added to include general challenges (see Table 16).

**Table 16. Challenges related to the components of smart wooden house manufacturing.**

<table>
<tr><th colspan="3">Smart wooden house manufacturing challenges</th></tr>
<tr><th colspan="3">General challenges</th></tr>
<tr><td colspan="3">Culture<br>Competence</td></tr>
<tr><th>Engineering phase challenges</th><th>Off-site production phase challenges</th><th>On-site production/assembly phase challenges</th></tr>
<tr><td>Orders outside the building system<br>Information added in the wrong way in CAD program<br>Employee turnover vs. long education time<br>Long lead time in design phase<br>Interoperability with consultancy software</td><td>Constrained by the capabilities of an existing dedicated manufacturing systems<br>Suppliers of automation solutions</td><td>Loss of control at building site</td></tr>
<tr><th colspan="3">Challenges of integration between phases</th></tr>
<tr><td colspan="3">Manual transfer of information between systems<br>Lack of experience in generating digital information for automation<br>Building system for craftmanship</td></tr>
</table>

It can be concluded that most of the challenges were directly connected to the empirically derived components of smart wooden house manufacturing (Table 15). Components mentioned as being essential for smart wooden house manufacturing were sometimes an immediate response to the perceived challenges, and vice versa.

For RQ3 (What are the enablers for realization of smart wooden house manufacturing?), it can be concluded that five of the eight characteristics areas of Lessing's (2006) framework for IHB had similar aspects in the empirically derived components of smart wooden house manufacturing. Working with the framework and increasing the level of implementation and achievement in these specific categories could enable the realization of smart wooden house manufacturing. However, the framework is more adapted for the business-to-business sector of house-building.

This thesis is a first step to developing the concept of smart wooden house manufacturing and based on its findings, it can be concluded that further research is needed.

## 6.2 Scientific and industrial contributions

This licentiate thesis contributes to increased knowledge of what smart manufacturing means for the wooden single-family house industry. It also offers insight into how (thus far) smart wooden house manufacturing relates to other concepts, such as IHB and Industry 4.0. This licentiate thesis is a first step to conceptualize smart wooden house manufacturing and it is possible for other researchers to build upon.

The wooden single-family house industry is very competitive, and the purpose of this research is to contribute to improved competitiveness in this industry. This licentiate thesis is a first attempt to understand the content and meaning of smart manufacturing in the wooden single-family house industry. It uses definitions and components to indicate what industrial practitioners should focus on and develop to be on the way to achieve smart wooden house manufacturing.

## 6.3 Future research

The conceptualization of smart wooden house manufacturing is only in the beginning, further studies are needed to expand the concept and later on, how it can be realized.

*Conceptualization of smart wooden house manufacturing*

To expand the concept of smart wooden house manufacturing more companies in the wooden single-family house industry could be studied to confirm and complement the current findings. An inductive approach was used for the current components, to expand the concept, a future study with a deductive approach could be conducted. Moreover, the identified components need to be further investigated in the industry specific literature.

This licentiate thesis focused on off-site manufacturing. In the future, the on-site production and logistics between off-site and on-site also need to be included for truly smart wooden house manufacturing.

*Realization of smart wooden house manufacturing*

The findings presented in this licentiate thesis revealed some challenges related to the components of smart wooden house manufacturing. For realization of the concept more knowledge is needed about what challenges that needs to be addressed and how they can be overcome.

The so far identified components of a smart wooden house manufacturing indicate that there are similarities to components in the Industry 4.0 concept. There exists literature about how to implement components of Industry 4.0 with road maps, guidelines and maturity models (Ghobakhloo, 2018, Mittal et al., 2018) . This could help in the process of realization of smart wooden house manufacturing. One question that remains to be answered is to what degree solutions found for other industrial sectors might be applicable in this industry to realize smart wooden house manufacturing.

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# Appendix 1

# Appendix 1

**Intervjuguide för industriellt husbyggande**

Tanken är att genomföra intervjuer om nuläget på Theta för att få en bild av hur pass industrialiserat företaget är. Efter intervjuerna sammanställer jag min uppfattning och presenterar detta i en workshop för att kunna diskutera resultatet. På workshopen diskuteras även önskat läge.

**Nuläge**

**Grupper att intervjua:**

- Ledning
- Operativ personal

Behöver prata med relevanta personer som kan svara på frågor angående de olika områdena för industriellt husbyggande. Kan vara personer som kan svara på delar av områdena eller alla områden.

**Önskat läge**

**Genomför en WS:** Presentera mitt resultat, diskutera om de håller med, diskutera eventuella skillnader från ledning och operativ personal. Nästa punkt är att diskutera vart de vill uppnå och diskutera framtida utmaningar.

**De olika områdena i industriellt husbyggande** (Lessing, 2006)

**Planering och kontroll av processen**

Projektering, tillverkning, montage och kompletterande byggplatsarbete kräver en tydlig struktur och styrning från början till slut, så att effektiva processer uppnås och att maximalt värde levereras till kunderna. Planering och kontroll är viktigt för att minimera fel och icke värdeskapande aktiviteter samt att skapa ett jämt arbetsflöde. Det är viktigt att det sker en noggrann planering i alla faser av processen från idé till färdig byggnad och att utformning är fastlagd innan produktionsarbeten startar. Genom att använda välutvecklade tekniska system som stöds av strukturerade planeringsmetoder blir genomförandet av processen smidig och fel och brister undviks. Tydliga roller för processledning och projektledning är avgörande för kontinuiteten i processerna.

Frågor

- Hur sker palneringen av ett projekt?
- Vilka deltar?
- Vilken samordning sker?
- Hur fördelas ansvar?
- Är ansvarsfördelning tydlig?
- Hur leds arbetet?
- Hur sprids information?
- Sätts det upp en tidsplan?
- Hur tydlig är den?
- Hur följs det upp att den håller, milstoplar, gateways?

0. Ingen eller måttlig samordning och struktur i tidsplaneringen. Oklara ansvarsområden och ledningen har dålig kontroll över byggprocessen.

1. En övergripande struktur på planering och processer, men låg detaljeringsnivå. Alla aktörer accepterar den övergripande tidplanen.

2. Utvecklad metod för planering och alla aktörer är delaktiga i ett tidigt skede av projektet. Det finns en utvecklad struktur för att sprida rätt och tydlig information om projektet och dess lösningar.

3. Det finns en detaljerad tidplan med tydliga milstolpar. Alla delprocesser har "gateways" som måste uppfyllas innan projektet kan fortskrida. Grundliga förberedelser för alla aktiviteter både vid förtillverkning som montering.

4. Planerings- och kontrollsystem stöds av avancerade ICT-verktyg som också är integrerade med övriga styrsystem som till exempel ekonomi- och logistiksystem. Mätning genom nyckeltal ger värdefull input till planering och processutveckling.

**Systematisk mätning och erfarenhetsåterföring**

Industriellt husbyggande handlar i stor utsträckning om att använda och förfina teknik, metoder och lösningar. För att skapa ett underlag för vidareutveckling krävs kontinuerliga uppföljningar och mätningar i processerna och i arbetet med specifika byggprojekt, för såväl hårda som mjuka parametrar. Erfarenheter och mätningar analyseras och resultatet blir viktig input till vidareutveckling av processer, tekniska lösningar, arbetsmetoder etc. Personal från olika delar av organisationen bör delta i uppföljningsarbetet och uppmanas att bidra med egna förslag till förbättringar och utveckling. Genom långsiktiga relationer mellan aktörerna och genom att använda byggsystem med standardiserade tekniska lösningar skapas en

”infrastruktur” för att fånga upp och ta emot kunskap och information som kan leda till förbättringar och vidareutveckling. Detta är centralt ifråga om industriellt byggande eftersom det då blir en process av ständiga förbättringar som hela tiden kan göra teknik, processer och samarbete bättre och effektivare.

Frågor:

- Finns några nyckeltal för er verksamhet?
- För produktionen?
- Vilka och varför dessa?
- Hur mäts det?
- Av vem?
- Hur används resultat?
- Vilka nyckeltal mäts i produktionen idag?
- Finns det statistik över nyckeltalen, hur följs det upp. Är alla inblandade medvetna?
- Tas det emot feedback från aktörerna exempelvis förbättringsförslag?
- Om ja, hur fångas det upp och behandlas?
- Hur tas förbättringsförslag från anställda emot? Hur dokumenteras det?

0. Det förekommer ingen form av strukturerad kunskapsåterföring eller mätning av nyckeltal.

1. Det sker ett visst utbyte av erfarenheter och kunskap vid till exempel produktionsmöten och projekteringsmöten. Viss dokumentation förekommer.
2. Företaget mäter vissa nyckelaktiviteter som till exempel inom produktionen, montering, erfarenheter från projekteringen. Dokumentation sköts individuellt av respektive aktör.
3. Mätning av nyckeltal för alla delar av processen, men med liten koordination mellan processens olika delar. Processägaren ansvarar för dokumentation.
4. Mätning av nyckeltal för alla delar av processen och informationen sprids med hjälp av avancerade ICT-verktyg. Mätningen fungerar som underlag för ökat kundfokus, framtida leverantörsavtal, förbättrad planering och produktion.

**Kund- och marknadsfokus**

Ett tydligt kundfokus är nödvändigt för att säkerställa att rätt produkter, med rätt kvalitet, till rätt kostnad byggs för kunderna som kan vara såväl hyresgäster, bostadsköpare och förvaltare. För att veta vad kundernas prioriteringar och krav är måste systematiska undersökningar och utredningar göras och sedan användas som krav på den industriella byggprocessen. Genom att dela upp marknaden i målgrupper och segment där olika behov och krav identifieras skapas förutsättningar för olika koncept och system för att möta dessa olika krav. Alla aktiviteter i processerna ska vara inriktade på att skapa värde för kunderna. Kort sagt kan man säga att kundernas krav är det som en industriell byggprocess ska kunna leverera – om ett företag inte klarar av detta är processen fel utformad.

Frågor:

- Vilka är era främsta kunder? Målgrupp?
- Hur säkerställer ni att ni har koll på kundens önskemål?
- Hur hanteras kunders önskemål?
- På vilket sätt påverkar kunden er verksamhet?
- Hur jobbar ni med framtidens kundönskemål? proaktivt.

0. Företaget har liten eller ingen kunskap om kunden. Vet inte hur målgruppen ser ut.

1. Generell insikt om vad slutkunderna efterfrågar, vad gäller till exempel val av utrustning, lägenhetsstorlek etcetera. Företaget har en tydlig bild över vilken målgrupp de riktar sig emot.
2. Grundläggande utvärderingar över slutkundens behov och prioriteringar för olika kundsegment och kostnadsnivåer. Företaget undersöker bland annat val av utrustning, lägenhetsstorlek, layout, standard och kvalitet.
3. Det sker en kontinuerlig och systematisk analys över kundens önskemål och prioriteringar samt uppföljningar med inflyttade hyresgäster eller köpare. ICT-verktyg används för att samla in och utvärdera data.
4. Kundundersökningar och uppföljning är integrerade med andra områden som till exempel utveckling av tekniska system, produktions- och monteringsprocess samt projektplaneringen. ICT-verktyg gör informationen transparent genom hela processen.

**Långsiktiga relationer mellan aktörer**

Ett långsiktigt engagemang mellan aktörerna i byggprocessen är en förutsättning för att bygga upp gemensam kunskap och erfarenhet. Det är också viktigt för att få kompabilitet mellan företagens olika delsystem, vad gäller till exempel gränssnitt, standarder, kvalitet och ekonomi. Långsiktiga relationer innebär också att företagen kan odla en gemensam kultur och se till att utveckla varandras organisationer. Valet av samarbetspartners ska göras metodiskt och baseras på kriterier som tas fram för den aktuella verksamheten, för att uppnå gemensam styrka och kompetens. Långsiktiga relationer innebär att projekt kan påbörjas snabbare, i och med att det finns en struktur och organisation som direkt kan starta arbetet. En leverantör som används kontinuerligt behöver exempelvis inte utvärderas och upphandlas inför varje enskilt projekt. Genom att arbeta med långsiktiga relationer ökar nyttan av att återföra kunskap och erfarenheter eftersom det då finns mottagare av sådan information. Ständiga förbättringar av arbetsmetoder och tekniska lösningar blir möjligt eftersom det är samma aktörer som arbetar ihop över tiden.

Frågor:

- Hur ser ert försörjningsnätverk ut? Varför?
- Vilka delar görs av underleverantörer?
- De underleverantörerna ni använder hur ser relationen ut med dem?
- Genomförs det en utvärdering av leverantörer? Hur ofta?
- Vilket fokus har ni med leverantörerna? Projekt, process
- Är samarbetet med leverantörerna långsiktiga eller kortsiktiga?
- Vilka relationer är de viktigaste?
- Hur skulle du klassa relationen till dessa nyckelaktörer?
- Hur kommunicerar ni med alla aktörer?
- Tas det emot feedback från aktörerna exempelvis förbättringsförslag?
- Har ni långsiktigt skrivna kontrakt?

0. Det finns inga långsiktiga relationer, utan aktörer byts ut från projekt till projekt.

1. Företaget har identifierat vissa relationer som viktigare än andra, men utan att det finns en tydlig strategi.
2. Det finns tydliga etablerade relationer med nyckelaktörer. Partneringkoncept används sporadiskt.
3. Alla aktörer är involverade med ett långsiktigt perspektiv. Aktörerna arbetar tillsammans som ett team. Strategisk partnering sker med utvalda aktörer.

4. Ett strukturerat program finns för att aktivt jobba och utveckla sina samarbetspartners. Det sker en kontinuerlig utvärdering med stöd av ICTverktyg. Omfattande strategisk partnering.

**Logistik integrerat i byggprocessen**

Genom att flytta aktiviteter uppströms i värdekedjan, från byggarbetsplatsen, till fabriker där förtillverkning utförs, ställs höga krav på att materialflödet integreras i byggprocessen och anpassas till verksamheten. Flöden till och från tillverkningsenheterna ska koordineras med materialflöden till och från byggarbetsplatsen. Logistiken blir då en viktig faktor för att komponenter, material och arbete ska flöda genom produktionen. Vid ett industriellt byggande bör leveranser ske enligt JIT-principen Just In Time, det vill säga att byggnadsdelar levereras vid rätt tid och till rätt plats, i rätt kvalitet och med rätt utrustning. För detta krävs ett nära samarbete och effektivt informationsflöde mellan projektörer, leverantörer, tillverkare och entreprenörer.

Frågor:

- Hur arbetar ni med materialhantering i olika skeden av byggprocessen? Vem gör vad? Hur? Varför?
- Hur ser materialhanteringen ut inom företaget? Vem gör vad? Hur? Varför?
- Hur kontrolleras det att det är gjort?
- Hur funkar leveransen av de prefabricerade produkterna? Anländer det i rätt tid, rätt ordning,
- Använd JIT-principer?

0. Logistikaktiviteter finns inte på företagets agenda.

1. Det finns vissa lösningar för bättre materialhantering som används. Lämplig lagring, leveransmönster och informationsutbyte med nyckelleverantörer är exempel på aktiviteter som företaget arbetar med.
2. JIT-principer används i produktionen. Man arbetar strategiskt med att optimera lagernivåer, konfektionering, emballering och transportlösninar. Utvecklade relationer med nyckelleverantörer.
3. Supply chain aktiviteter är integrerade i byggprocessen. Specialutvecklade leverantörstjänster och tydliga informationsflöden möjliggör avancerade tekniska lösningar.

4. Supply chain aktiviteter är fullt ut integrerade i byggprocessen. Det finns ICT-verktyg för planering, inköp, leveransprecision, lagernivåer etcetera.

**Utvecklade byggsystem**

Byggsystemet är en central och viktig del av ett industriellt byggande. Hur man väljer att utforma och kombinera de tekniska systemen beror på vilken strategi man har för sitt industriella koncept och vilka resurser man är beredd att satsa på utveckling av systemen. Att utveckla byggsystem innebär att tekniska lösningar samlas i system som används i olika kombinationer i olika byggprojekt. Byggsystem kan utvecklas för alla delar i en byggnad som exempelvis bärande stomme, fasad, trappor, installationer, inredning och så vidare. I ett sådant arbete är det viktigt att arbeta med gränssnitten mellan de olika systemen så att de går att kombinera med varandra. Det som är vanligast att utveckla till system är den bärande stommen, där tekniska lösningar för bjälklag, bärande väggar, pelare, balkar och kopplingar mellan dessa utvecklas och systematiseras. Detta kan sättas samman med tekniklösningar baserat på betong, stål, trä eller kombinationer mellan dessa material. Ett stomsystem utgör ofta en central del av satsningen hos företag som väljer att utvecklas inom industriellt byggande.

Frågor:

- Vilka begräsningar finns det i byggsystemet, vad är det som är förbestämt?
- Finns det några standard hus ni går efter?
- Vilka fasta mått finns det på trästommen?
- Vad görs i väggmodulen mer än att bygga själva väggmodulen? Delsystem
- Hur beräknas boverkets bygg- och konstruktionsregler. Finns det inlagt i systemet så det varnar när arkitekterna ritar upp huset?
- Görs det inom företaget eller måste det göras externt?
- Vad finns det för metoder och strategier i produktionen?
- Hur jobbar personalen ute i produktionen, följer de utstakade metoder eller har de sina egna sätt att jobba?
- Finns det förklarat/nedskrivet hur exempelvis olika fönster ska monteras?
- Vad görs i eran produktion?
- De delar som nämns vet alla inblandade hur de ska utföras (standardiserad metod/strategi)
- Följer alla det?
- Tar ni hänsyn till leverantörerna när ni bygger väggmodulerna?

- De har projekt med att börja bygga golv
- Hur är det med spännvidden, sätter bjälklag/takstolar gränser?

0. Minimal användning av utvecklade tekniska system. Hantverksmetoder dominerar i produktionen.

1. Utvecklade tekniska system finns och används sporadiskt, men utan en tydlig metod och strategi. Tekniska system kan här till exempel vara stom-, fasad- eller installationssystem.
2. Utvecklade tekniska system finns för vissa delar av byggnaden och följer en tydlig metod och strategi.
3. Komplexa tekniska system används för majoriteten av byggnadsdelarna. System är konstruerade med standardiserade gränssnitt och utvecklas genom ett nära samarbete med leverantörerna.
4. Komplexa tekniska system används och utvecklas i nära samarbete med andra aktörer, baserat på gemensamma erfarenheter. Utveckling stöds av avancerade ICT-verktyg.

**Prefabricering**

Byggnadsdelar tillverkas i en miljö som är anpassad för rationell produktion, där lämpliga hjälpmedel och rätt utrustning finns tillgängliga och där arbetsmiljön är god. För att minimera antalet arbetsmoment på byggarbetsplatsen bör förtillverkningsgraden av byggnadsdelar optimeras. Det innebär att kartlägga vilka moment som lämpar sig för tillverkning på annan plats än på byggarbetsplatsen, och ofta innebär en sådan analys att stora delar av byggarbetet kan och bör förläggas till fabriksmiljö eller annan plats som har bättre förutsättningar för rationell produktion och kvalitetssäkert arbete. I takt med att graden av förtillverkning ökar, ökar också kraven på måttnoggrannhet, toleranser samt att byggnadsdelarna hanteras på rätt sätt på byggplatsen så att de inte skadas och så att de är färdiga att montera. Även kraven på när, hur och i vilken ordning byggdelarna anländer till byggplatsen, ökar eftersom det är avgörande för produktionstakten på byggplatsen.

Frågor:

- Beskriv procentuellt vad som görs på huset i fabriken kontra byggplats
- Vad görs i fabriken? Terminologi- lastbärande väggar med bjälklag, väggmoduler,
- Vad görs på byggplatsen?
- Vad är det som skickas från Theta till byggplatsen?

- När är sista punkten som kunden kan påverka det som byggs i fabriken?
- Vad skulle kunna göras i fabriken?
- El, vvs, badrum etc underleverantör

0. Det sker ingen direkt förtillverkning av byggnadsdelar.

1. Enkla byggnadsdelar och komponenter tillverkas på fabrik. Exempelvis plattbärlag av betong eller takstolar.
2. Mer avancerad förtillverkning av byggnadsdelar och komponenter som till exempel fasadelement, hela väggsektioner och trappor färdiga för montering.
3. Förtillverkning av avancerade byggnadsdelar som ingår i ett byggsystem. Det kan till exempel vara volymelement med färdiga ytskikt, färdiga badrumsmoduler etcetera.
4. Förtillverkning av avancerade byggnadsdelar där konstruktion och produktion stöds av avancerade ICT-system, integrerade logistiklösningar och ett system för produktionsplanering.

**Användning av informations- och kommunikationsteknik**

Effektiva processer kräver tillförlitlig och snabb tillgång till information och moderna ICT-verktyg (Information and Communication Technology) möjliggör effektiv hantering av förändringar, uppdateringar och utbyte av information. Ett avancerat utnyttjande av moderna ICT-verktyg stöder processerna med tillförlitlig information och bidrar till förutsättningarna för effektiv produktion och minimering av fel och är en förutsättning för hantering av komponenter och delar i tekniska plattformar och byggsystem som kräver strukturerad och pålitlig hantering. Genom att arbeta med informationsmodeller kan byggnader skapas virtuellt och egenskaper utöver de geometriska kan kopplas till modellen, såsom ekonomiska kalkyler, energiberäkningar, tidplaner för produktionen etc. Detta är ett område som erbjuder extra stora möjligheter då ett byggsystem utgör den tekniska grunden för byggverksamheten, eftersom informationsmodellen kan bli mycket detaljerad och byggas upp av de tekniska lösningarna som byggsystemet består av.

Frågor:

- Vilka IT-system finns på företaget idag och hur används dem?
- Kommunicerar systemen med varandra?

- Har leverantörerna samma typsnitt/gränssnitt i sina IT-system, kan informationen delas på ett enkelt sätt?
- Hur använder du företagets informations- och kommunikationsteknik?
- Vad funkar bra med dagens informations- och kommunikationsteknik?
- Vilka problem upplever du med dagens informations- och kommunikationsteknik?
- Hur behandlas inköp av material?
- Går det att se lagersaldo i något system?
- Planera och följa upp företagets ekonomiska flöde (affärssystem)
- Stödja försäljning (säljsystem)
- Rita upp och beskriva produkter (CAD och BIM)
- Katalogisera och versionshantera data kring en produkt (PDM-product data mangement)
- Kontrollera inköp och lager samt beställningar av varor (MPS-material- och produktionsstyrning)
- Kombinera ekonomihanteringen med de fysiska resurserna (ERP – enterprise resource planning)

0. Inga ICT-verktyg används.

1. ICT-verktyg används av vissa aktörer i processen.
2. Alla aktörer använder sig av ICT-verktyg som stödjer deras egna aktiviteter. Det finns inga gemensamma strategier eller system.
3. Alla aktörer använder sig av ICT-verktyg som är integrerade sinsemellan. Det finns också en gemensam strategi för aktörerna.
4. Avancerade ICT-verktyg används av alla aktörer med ett gemensamt system och gränssnitt. ICT-verktygen stödjer projektering, produktion, planering, prestationsmätning och inköp.

# Appendix 2

# Appendix 2

**Interview guide for study at Company A and Company B**

**First step: Open questions (inductive)**

1. What is a smart factory?

a. Ask the respondent to give their picture of what a smart factory is in their opinion in general, as well as what it could be for the wooden house industry.
b. What could enable your image of smart factory for the wooden house industry?
c. What are the barriers for your image of smart factory for the wooden house industry?

2. **What is being done within the company right now that you consider is a part of a smart factory?**

a. Ask the respondent for examples and what it means for the company, as well as enablers and barriers for it.
b. Are there any obstacles for further development?
c. From where did the idea of this “smart part” come from?

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## Smart Manufacturing for the Wooden Single-Family House Industry


To meet the demand of future building requirements, and to improve productivity and competitiveness, there is a need to modernize and revise the current practices in the wooden single-family house industry. In several other sectors, intensive work is being done to adapt to the anticipated fourth industrial revolution. The manufacturing industry has already begun its transformation with concepts such as smart manufacturing and Industry 4.0. So far, smart manufacturing has not been discussed to any significant extent for the wooden single-family house industry, even though it might be a way for this industry to improve productivity and competitiveness.

The research presented in this thesis aims at increased knowledge about what smart manufacturing means for the wooden single-family house industry. This requires investigating what smart wooden house manufacturing is, what challenges that might be associated with it, and how smart wooden house manufacturing can be realized. At the core of this thesis is the conceptualization of smart wooden house manufacturing—when realized, it is expected to contribute to improve the competitiveness of the wooden single-family house industry.

The findings presented here are based on three Research Studies. Two studies were case studies within the wooden single-family house industry. The third study was a traditional literature review.

The findings revealed two definitions and 26 components of smart wooden house manufacturing. At large, smart wooden house manufacturing emphasizes digital transformation with a focus on digital information flow, how to add information, information compilation, and information distribution between systems/programs and departments. Some of the challenges associated with smart wooden house manufacturing are, e.g. culture, competence and manual transfer of information between systems.

The findings indicate similarities of smart wooden house manufacturing within certain components of industrialized house building and Industry 4.0, these components could enable the realization of smart wooden house manufacturing.



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