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Licentiate Thesis

Off-site manufacturing systems development in timber house building

Towards mass customization-oriented manufacturing

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Jönköping University
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Abstract

The need for housing in Sweden has been showing a constant increase over the past couple of years. However, this situation might change in 2018 since there are indications that the increase in demand will reach its peak. On the other hand, the use of timber as a load bearing structure has become more popular in the multi-family house building sector. It is competing with concrete and steel frames, and its market share might even reach 50% by the year of 2025. Adding the involvement of customers in house design decisions and a high level of customization, the conclusion is that timber house building must continue the development towards mass customization. There is a lack of knowledge on how mass customization is developed and implemented regarding off-site manufacturing systems. In this thesis, a contribution is made to manufacturing system development in timber house building by proposing a novel approach to aligning off-site manufacturing systems to the requirements of production strategy, market needs, product design, and manufacturing processes. The proposed conceptual framework is a synthesis of the knowledge gained from three empirical studies and different methods found in theories of changeable manufacturing systems, mass customization, and manufacturing system development. The research purpose addressed by the presented work, is to increase the knowledge on how the development potential of off-site manufacturing systems can be identified in mass customization-oriented timber house building. Case study research was applied to gather the empirical data. The data collection and analysis methods used in the empirical studies can be useful when discussing the potential improvements. However, these data are not comprehensive enough in terms of presenting a holistic view of off-site manufacturing and consideration of the market as well as variation in product and processes. Therefore, a comprehensive set of requirements is proposed in the conceptual framework together with a step by step description of how the development potential of off-site manufacturing systems can be identified.

Sammanfattning

Behovet av bostäder i Sverige har ständigt ökat under de senaste åren. Denna situation kan dock förändras 2018, eftersom det finns tecken på att ökningen av efterfrågan kommer att nå sin topp. Å andra sidan har användningen av trä som lastbärande konstruktion blivit mer populär i flerfamiljshusbyggnaden. Det konkurrerar med betong- och stålstomme och dess marknadsandel kan till och med nå 50% år 2025. Att lägga kundernas medverkan i husdesignbeslut och en hög anpassningsnivå är slutsatsen att trähusbyggnaden måste fortsätta utveckling mot mass customization (MC). Det finns brist på kunskap om hur MC utvecklas och implementeras när det gäller off-site tillverkningssystem. I denna avhandling görs ett bidrag till tillverkningssystemutveckling i trähusbyggnad genom att föreslå ett nytt tillvägagångssätt för att anpassa tillverkningssystem till de olika kraven av produktionsstrategier, marknaden, produktdesign och tillverkningsprocesser. Den föreslagna konceptuella ramen är en sammansättning av kunskapen från tre empiriska studier och olika metoder som finns i teorier om förändringsbara tillverkningssystem, MC och tillverkningssystemutveckling. Forskningssyftet med det presenterade arbetet är att öka kunskapen om hur utvecklingspotentialen av off-site tillverkningssystem utanför anläggningen kan identifieras i MC-orienterad trähusbyggnad. Fallstudier användes för att samla empiriska data. Datainsamlings- och analysmetoderna som används i de empiriska studierna kan vara användbara när man diskuterar potentiella förbättringar. Men denna information är inte tillräckligt komplett när det gäller att presentera en helhetsbild av off-site tillverkning, utan en bedömning av marknaden samt kunskap om variationer i produkt- och processer behövs även. Därför presenteras det konceptuella ramverket, inklusive en kravlista samt en stegvis beskrivning av hur utvecklingspotentialen för off-site tillverkningssystem kan identifieras.

Acknowledgements

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Djordje Popovic
Jönköping, January 2018

List of appended papers

Paper 1
Popovic, D., and Winroth, M. (2016). Industrial timber house building – levels of automation. *Proceedings of the 33rd International Symposium on Automation and Robotics in Construction (ISARC).* Auburn, Alabama, USA. 18-21 July 2016.

Paper 2
Popovic, D., Fast-Berglund, Å., and Winroth, M. (2016). Production of customized and standardized single-family timber houses – A comparative study on levels of automation. *7th Swedish Production Symposium (SPS).* Lund, Sweden. 25-27 October 2016.

Paper 3
Popovic, D., Schauerte, T., and Johansson, J. (2017). Prefabrication of single-family timber houses – problem areas and wastes. *Proceedings of the 25th Annual Conference of the International Group for Lean Construction (IGLC).* Heraklion, Crete, Greece. 9-12 July 2017.

Additional publications, not included in the thesis

Popovic, D., Meinlschmidt, P., Plinke, B., Dobic, J., & Hagman, O. (2015). Crack Detection and Classification of Oak Lamellas Using Online and Ultrasound Excited Thermography. *Pro Ligno*, 11(4), 464-470.

Pahlberg, T., Thurley, M., Popovic, D., and Hagman, O. (2018). Crack detection in oak flooring lamellae using ultrasound-excited thermography. *Infrared Physics & Technology.* 88, 57-69. https://doi.org/10.1016/j.infrared.2017.11.007.

Abbreviations

MC - mass customization
DMS – dedicated manufacturing system
FMS – flexible manufacturing system
RMS – reconfigurable manufacturing system
CAD – computer aided design
CAM – computer aided manufacturing
DES – discrete event simulation
CODP – customer order decoupling point
ETO – engineer-to-order
SV – select-a-variant
EWE – exterior wall element

Contents

List of figures

List of tables

1. Introduction

At the outset of this chapter, off-site manufacturing will be described as a concept. After this, a description of the problem area and Swedish house building will be given. Then the research purpose and scope are presented. The chapter will conclude with an outline of the thesis.

1.1. Off-site manufacturing in house building

In industrialized house building some of the house building activities that are performed on-site in traditional settings, are shifted into the factory environment where elements, components, and modules are manufactured off-site, i.e., prefabricated (Finnimore, 1989). Implementing off-site manufacturing (OSM) brings potential benefits, such as lower costs, shorter lead times due to concurrent off-site and on-site schedules, better quality of houses, higher efficiency, automation possibilities, improved production control, and better working conditions (Blismas et al., 2006; Friedman & Cammalleri, 1997; Gibb & Isack, 2003; Huang et al., 2006; Sacks et al., 2004). OSM can be characterized by its degree regarding the proportion of work performed, which is further related to the level of product customization and production strategies.

The degrees of OSM relate to the share of work that is done in the factory environment. Gibb (2001) defines two degrees of OSM: volumetric preassembly (VPA) and non-volumetric preassembly (NVPA). Jonsson and Rudberg (2015) develop this classification further by introducing the following degrees of OSM, starting from the lowest: component manufacturing and sub-assembly (CM&SA), pre-fabrication and sub-assembly (PF&SA), pre-fabrication and pre-assembly (PF&PA), and modular building (MB). Gibb's VPA and NVPA are replaced by PF&SA and PF&PA, respectively. Salama et al. (2016), on the other hand, distinguish between different off-site prefabricated systems: modular, panelized, prefabricated, and processed materials construction. The off-site construction systems are most commonly hybrids of those mentioned above (ibid.). As modules can be defined at many levels of house structure, the highest-level modules will be referred to as volume elements (Höök, 2005) in this thesis.

The degree of OSM and level of product customization is often correlated (Jonsson & Rudberg, 2015). Unique construction projects where highly customized houses/buildings are built mainly using traditional construction methods have small or no share of parts built off-site. On the other side, there are highly standardized houses/buildings that are prefabricated in modular fashion using the volume technique in the factory environment and as such are transported and assembled on-site. Product standardization is the result of the need to produce and build affordable homes, and it led to the mass production of houses (Barlow et al., 2003). The implementation of such prefabrication strategy alone is very beneficial in cutting costs and achieving economies of scale, but this is with standardized or, in the best case, a limited number of product variants. On the other hand, the implementation of a full customization strategy results in very high production costs (Brege, 2008; Marchesi & Matt, 2017). However, there are examples in the industry where customized buildings are prefabricated in volume elements (Jonsson & Rudberg, 2015). Accordingly, the trade-off between productivity and flexibility is reduced, therefore enabling the implementation of mass customization (MC).

The degree to which a house can be customized is usually defined by the production strategy that the firm follows. Production strategy defines when, in the design, engineering, and manufacturing phases, customer involvement is allowed in the specification process (Winch, 2003). There are two slightly different ways of classifying production strategies in the house building context found in the literature. On one side, according to the classification by Hvam et al. (2008), there are engineer-to-order (ETO), modify-to-order (MTO), configure-to-order (CTO), and select-a-variant (SV) strategies. When the ETO strategy is applied, the possibilities for customization are the highest since customer involvement is allowed very early in the engineering phase of the specification process (Hicks et al., 2000). The MTO strategy is related to open building systems with a partly defined platform but project-specific product differentiation is still possible (Lidelöw et al., 2015). The CTO production strategy relates to closed building systems with a fully modularized platform and standard parts, and customization is realized through configuration (ibid.). Finally, the SV strategy is employed when a customer is allowed to choose between a number of fully developed and predefined products (Hvam et al., 2008). On the other hand, some authors (Bonev et al., 2015; Jansson, 2013; Johnsson, 2013; Lidelöw et al., 2015) claim that the production strategies found in construction are all variations of the ETO strategy. Here, the production strategy is divided into engineering and manufacturing dimensions, where in the engineering dimension these are design-to-order, adapt-to-order, configure-to-order and engineer-to-stock strategies. This terminology is slightly different from but corresponds to the four production strategies described previously. Furthermore, the strategies in the manufacturing dimension are classified as make-to-order, assemble-to-order, and make-to-stock. This particular classification was established by Wikner and Rudberg (2005). To provide consistency, the classification by Hvam et al. (2008) will be used in the thesis.

1.2. Problem area

In MC the firm might offer high customization possibilities for the final product yet not the whole product in terms of its parts would be customized and unique. For example, Schoenwitz et al. (2017) analyze the alignment of customer order decoupling points within house structure levels against customer preference. Commonality and distinctiveness can be utilized across the whole product structure, combining product platform and uniqueness. In consequence, the manufacturing systems used to produce different product parts face different requirements in terms of functionality and capacity.

Although there are studies that report the successful implementation of MC, for example in Germany (Thuesen & Hvam, 2011), Japan (Bowden, 2008), and Sweden (Johnsson, 2013), according to Huang (2008) and Tabet Aoul et al. (2016) the house building industry, overall, is not there yet. Orientation and further development efforts towards achieving MC within the house building industry are needed (Lidelöw et al., 2015; Marchesi & Matt, 2017; Said et al., 2017).

Nowadays, customer involvement in the specification process of a house is inevitable, causing high levels of product customization and need for design variety and flexibility (Hofman et al., 2006; Nahmens & Bindroo, 2011; Zabihi et al., 2013). At the same time, remaining competitive by decreasing costs and achieving a high quality production of houses poses a challenge (Isaac et al., 2016). Balancing between product commonality and distinctiveness, where the latter directly corresponds to customer value and the former to standard parts, is of crucial importance (Marchesi & Matt, 2017). Well defined product platforms based on modular architectures where customer needs are met through configuration lead to product differentiation, while at the same time high levels of commonality are achieved (Robertson & Ulrich, 1998). However, achieving both economies of scale and scope, i.e., establishing internal and external efficiency (Pine, 1993), requires robust production processes and the reuse of resources as well (Jiao et al., 2007). Therefore, MC can be further realized through innovations in off-site production needed to achieve internal efficiency (Barlow, 1999; Barlow & Ozaki, 2003).

The development of flexible and efficient design and OSM systems and processes that are shared among different product variants is essential in achieving economies of scale (Gibb, 2001; Kazi et al., 2007; Sawyer, 2006; Shewchuk & Guo, 2012). Thus far, research efforts regarding design processes and systems in MC-oriented house building are to a large extent found in the literature compared to the research regarding OSM systems analysis and development.

The construction industry and in particular the house building industry (Said et al., 2017) has been developed for decades through knowledge transfer in the form of methods, technologies, and concepts from the manufacturing industries, such as car manufacturing (Azzi et al., 2011; Barlow & Ozaki, 2003; Persson et al., 2010; Piroozfar, 2013; Winch, 2003; Yu et al., 2013). The development of flexible and reconfigurable manufacturing systems is seen as a solution to the problem of achieving the manufacturing efficiency needed in the presence of product variety and changing market demands (ElMaraghy et al., 2013). However, apart from the absence of available literature about the frameworks for manufacturing system design in timber house building, there is also a lack of consideration for comprehensive product analysis when formulating requirements for manufacturing system design in the existing frameworks (Andersen, ElMaraghy, et al., 2017).

1.3. House building market in Sweden

The demand for housing in Sweden has been constantly rising over the last decade. The total number of built housing in 2016 shows a 34% increase compared to 2015 (TMF, 2016). However, in 2017 the increase was 7%, while the expected increase in 2018 is 3% (Palmgren et al., 2017). Given the uncertainty in future demand and current capacity there is a possibility of a decline in the house building industry (ibid.).

So far, timber frames are the dominating type of load bearing structure for single-family houses, with 80% market share (Nord & Widmark, 2010; TMF, 2017b). The number of completed single-family timber houses per year is increasing, where according to a TMF (2017b) report there was a 7% increase in 2017 compared to 2016. Despite the increase, there are factors that can hinder the development, such as a long administration process for building permits, a lack of detail planned land, and sharpened financial requirements for customers (TMF, 2017b).

In the multi-family sector, the market share is the opposite, where concrete and steel are mostly used for load bearing structures. According to TMF (2017a) the market share for multi-family timber houses has during the last 10 years been varying around 10%. However, due to the increased interest in timber frames and existing socio-economic challenges related to demography, climate, employment, and resource efficiency, there is a potential for this share to grow in the future through an expansion in capacity and may constitute around 50% by 2025 (Brege et al., 2017).

Regarding the level of prefabrication, 73% of all timber frame housing is completely prefabricated, while 25% is prefabricated to a certain extent. Only 2% is currently built traditionally on-site (TMF, 2017a). Manually performed work with handheld tools and machines is dominant in OSM (Persson et al., 2009).

1.4. Research purpose and scope

The challenges that the industry faces in terms of demand volatility and increased customer involvement, combined with high levels of off-site completion dominated by manual work, lead to the need for a greater orientation of house building companies towards MC. The existing research that addresses these challenges reveals a knowledge gap within the OSM systems area. Therefore, the research purpose is to increase the knowledge on how the development potential of OSM systems can be identified in mass customization-oriented timber house building.

The context in which the empirical studies were conducted and for which the conceptual framework is proposed is the OSM of single-family timber houses. However, the framework can be applicable in the context of the OSM of multi-family timber houses. Therefore, in the conceptual framework it is referred to as timber house building. Furthermore, product design analysis is also taken into consideration within the conceptual framework. Considering the context from a top-down perspective, the research is conducted within the construction industry. Figure 1 is given to clarify how the research is positioned with regard to the construction industry. The blue fields are used to describe the path from the construction industry down to the focus area.

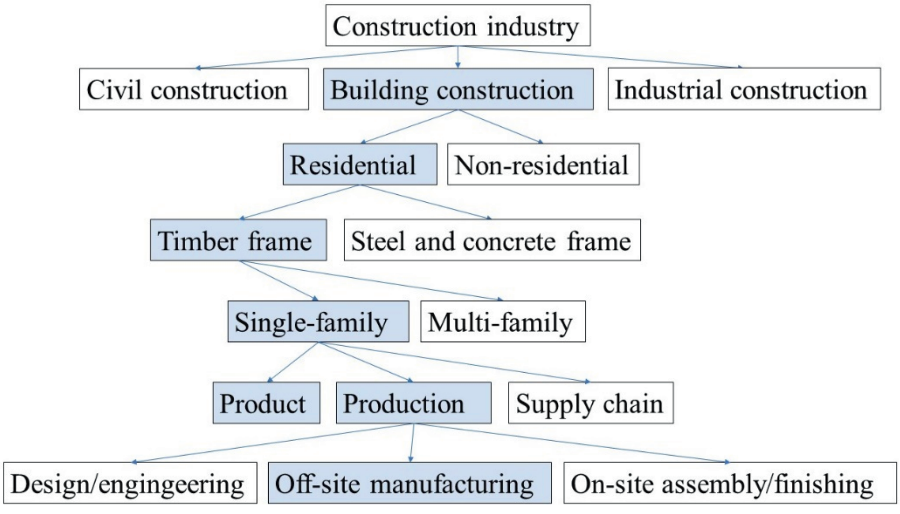

Figure 1 Scope of the thesis.

1.5. Thesis outline

The thesis is composed of two parts: a frame and three appended conference papers. The frame of the thesis consists of five chapters. It connects the three papers, summarizes their main points, and also provides additional contributions that have not yet been published.

The introduction chapter (1) of the thesis frame provided the description of OSM in house building, introduced the need for MC development and implementation in house building, described the current housing market in Sweden, and finally gave the research purpose and scope. A brief description of the thesis frame's remainder is given below.

The frame of reference is presented in the next chapter (2). It includes theory descriptions of MC, changeable manufacturing systems, and manufacturing system development. The chapter concludes with a literature review.

The research design chapter (3) gives a description of the research methods used and the data collection and analysis applied in the empirical studies. The research strategy shows how the empirical studies, papers, conceptual framework, frame of reference, and research purpose are connected. Comments in regard to research quality are given afterwards. The chapter concludes with a description of the case company and exterior wall element assembly.

A summary of the results and a discussion are given in the fourth chapter (4). The results from the empirical studies are given at the outset of chapter. An analysis of the empirical studies in relation to product variety and manufacturing system flexibility follows. The conceptual framework and a discussion are given afterwards, and the chapter concludes with the limitations of the research.

Conclusions are provided in the last chapter (5). General conclusions, research contributions, and future research are given.

2. Frame of reference

In this chapter theories of mass customization, changeable manufacturing systems, and manufacturing system development are introduced. After this, a literature review on mass customization development and implementation in house building is presented.

2.1. Mass customization

To address the volatility of market demand, high competitiveness, and the need for product differentiation, mass customization (MC) has become an established manufacturing paradigm in many industries nowadays (Fogliatto et al., 2012). MC is related to the capability of designing products and services tailored to the needs of each customer and using flexible and efficient processes to produce and deliver these products and services (Da Silveira et al., 2001). In other words, the flexibility to meet customer needs found in craft production was combined with the production efficiency found in mass production (Pine, 1993). Companies that successfully employ MC achieve economies of scale through the standardization of components that can be combined in many ways, creating end-product variety, therefore achieving economies of scope (Jianxin Jiao & Zhang, 2005). Salvador et al. (2009) list three fundamental capabilities of a company to successfully implement MC: solution space development, robust process design, and choice navigation. Solution space development relates to the (1) translation of customer needs into differentiating product attributes, (2) standardization of everything that gives little or no value to customers, (3) development of a product platform, and (4) constant monitoring of customer needs (Piller & Tseng, 2009). Robust process design refers to the delivery of customized solutions at near mass production efficiency and the reuse of value chain resources for the fulfillment of differentiated customer needs (ibid.). Choice navigation is the capability to simplify the navigation through product assortment by employing efficient and effective configuration systems (ibid.). The research presented in the thesis is positioned within the robust process design area of MC.

Enabling methodologies and technologies of MC are as follows: lean and agile methodologies, postponement, product platforms and families, product modularization and configuration, flexible manufacturing, and information and communications technologies (ElMaraghy et al., 2013; Fogliatto et al., 2012; Jiao et al., 2007; Kull, 2015).

2.1.1. Lean and agile management

Lean and agile management principles enable the development and implementation of MC by making production processes of predefined standard and common parts efficient and customization processes more effective, in other words, better delivery of what the customer wants (Ben Naylor et al., 1999). In lean management the focus is on reducing waste, improving flow and quality, and reducing costs of production. Ohno (1988) formulated seven types of waste: overproduction, waiting, transport, over-processing, excess inventory, unnecessary motions, and defects. Womack and Jones (2010) added unused human potential as another type of waste. According to the Toyota Production System, all types of waste should be eliminated, or at least reduced as much as possible, to improve production efficiency (Liker, 2004). On the other hand, agile management is oriented towards delivering value to customers through increased levels of services via product flexibility and variety (ibid.). The combined use of lean and agile management can be beneficial when a customized product is required at lower cost, i.e., MC. According to Romme and Hoekstra (1992), separation between the two is realized by the customer order decoupling point (CODP). Upstream, the CODP the supply chain is based on planning and forecast, while downstream the CODP supply chain is based on orders and demand (ibid.). Delaying the product differentiation, a quite common MC strategy, causes the CODP to be positioned further downstream, which is also called postponement (Ernst & Kamrad, 2000).

2.1.2. Product platforms and product family design

Product family is defined as a set of similar products that share a certain number of common parts, components, and/or modules, meaning the platform they are derived from. Therefore, the product platform can be regarded as a part of product commonality. Unique parts or components of products from the same family address specific customer needs (Meyer & Lehnerd, 1997). Product distinctiveness is achieved through the configuration of product platform and design and the engineering of unique parts and components. Each individual product of a product family is a product variant. If a product family is targeting a certain market segment, a product variant satisfies a subset of customer needs within that segment.

Robertson and Ulrich (1998) define platforms as a collection of four assets that are shared by set of products, with these assets being components, processes, knowledge, and relationships. Meyer and Lehnerd (1997) introduced process platforms as a complement to product platforms (what the company offers to the customers), where process platforms represent how products should be designed, produced, and delivered. Product platform thinking is becoming increasingly more important for companies to adopt as markets continue to pose more challenges in terms of providing products of higher variety and quality, lower cost, and faster delivery. The successful utilization of product platform strategy enables companies to constantly improve their internal (cost, quality, and delivery) and external (product variety) efficiency (Krause & Eilmus, 2011).

2.1.3. Product modularity and product configuration

The concepts of modularity and configuration are closely related to product platforms (Hvam et al., 2008). The most common way of addressing modularity in the MC literature is that of the product architecture, although modularity has also been addressed in production processes and in supply chains (Fine, 1998). However, modular product architecture and standardized interfaces are prerequisites to configuration systems that are developed with the aim of making customization processes more efficient and effective (Hvam et al., 2008). Configuration systems are developed in the form of the automation of both sales and engineering processes, where predefined product parts, components, and modules, i.e., product platform, can be combined according to a customer need using information technology (ibid.). A configurator is a software package composed of a knowledge base that stores a generic model of a product and a set of assistance tools that helps the user find a solution (Aldanondo et al., 2003).

2.1.4. Flexible manufacturing and information technologies

ElMaraghy et al. (2013) review the literature on variety-oriented manufacturing and report changeable manufacturing systems as an umbrella concept covering both flexible and reconfigurable manufacturing systems that can support variety in platform design. This field of theory is explained further in sections 2.2 and 2.3.

Information technologies enable the development and implementation of MC by providing fast and automated operations, access, and exchange of information. Correct order fulfillment is enabled through the integration of information flows, and the demands and preferences of customers are stored in databases through the monitoring of configuration processes (Dietrich et al., 2007). Customer involvement in the production process is enabled through product specification and configuration as well as co-designing (Piller et al., 2004).

2.2. Changeable manufacturing systems

Changeable manufacturing systems were introduced as a joint term that envelops flexible and reconfigurable manufacturing systems as, nowadays, depending on the context, manufacturing systems combine both flexible and reconfigurable solutions (Wiendahl et al., 2007). In this section, manufacturing systems and changeability are first described as concepts separately. Afterward, flexible, reconfigurable, and changeable manufacturing systems are introduced.

2.2.1. Manufacturing systems

There are two opposing ways of defining and distinguishing between production and manufacturing, and production and manufacturing systems, found in the literature. On one side, there are authors (Bellgran & Säfsten, 2010; Rösiö, 2012) who consider manufacturing as a superior term to production. Production is a process in the function of manufacturing, where goods and/or services are created by combining material, work, and capital. Manufacturing is an overarching term for a group of activities and operations, namely marketing, design, production planning, production, production control, management, and product quality inspection (Chisholm, 1990). Processes are distinguished from systems as the manufacturing system refers to the actual system or a plant where product realization takes place from the design to the release. Production system refers to the production facilities, machines, and equipment to physically produce the product (Figure 2a).

On the other side, there are authors who define these terms in the opposite way. For example, Groover (2016) defines a production system as a collection of people, factory facilities, and manufacturing support systems organized to perform the manufacturing operations of a company. Here, manufacturing systems are a part of factory facilities. Therefore, the term production system is seen as superior to manufacturing system (Figure 2b).

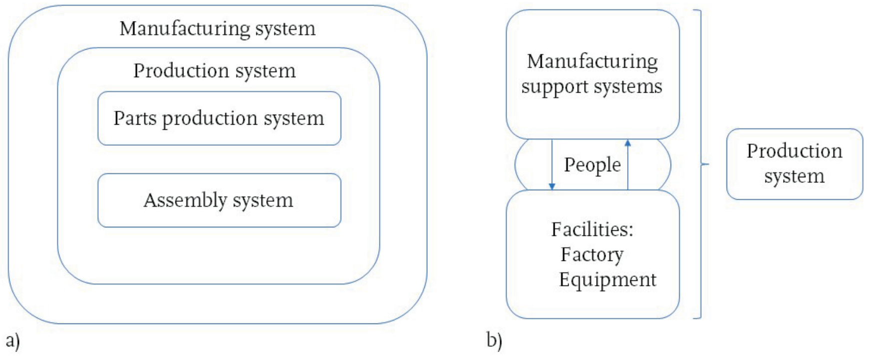

Figure 2 Two contradictory ways of differentiating between production systems and manufacturing systems according to a) Bellgran and Säfsten (2009), manufacturing superior to production, and b) Groover (2007), production superior to manufacturing.

In the collected literature, both ways of referring to production and manufacturing are found. However, in this thesis, the term production is regarded as superior to manufacturing. Therefore, off-site production includes design, engineering, and OSM.

Manufacturing processes can be divided into processing operations and assembly operations (Groover, 2016). In processing operations, raw materials' physical and/or mechanical properties are altered. On the other hand, in assembly operations raw materials, components, or elements are joined to create a final product or its modules. In timber house building, assembly operations are mostly used and are commonly referred to as prefabrication or preassembly.

A manufacturing system can be divided into constituent systems, which are, according to Hubka and Eder (2012), technical, human, material handling, computer and information, and building and premises.

2.2.2. Changeability

Changeability is in this thesis regarded as an umbrella term for different types of flexibility that characterize different production levels of a company. These include agility, transformability, general flexibility, and reconfigurability (ElMaraghy & Wiendahl, 2009). Production can, according to Wiendahl et al. (2007), be divided into network, factory, segment, system, cell, and station/machine. Figure 3 depicts how different changeability levels correspond to different production and product levels.

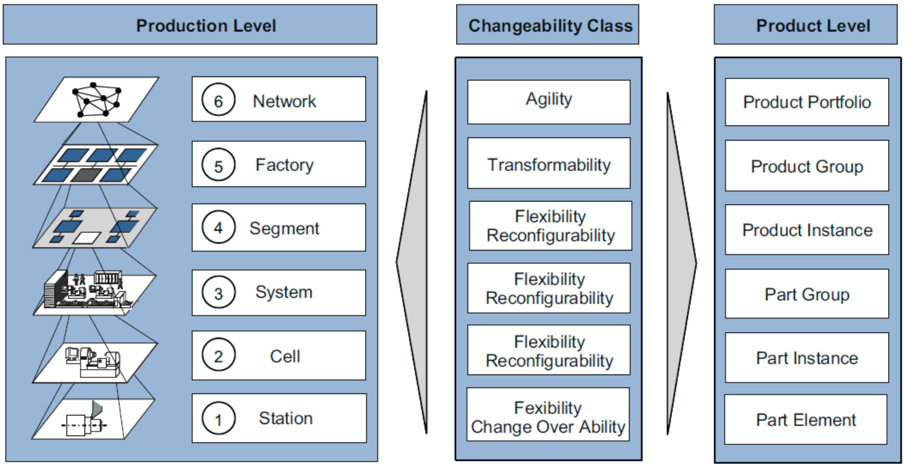

Figure 3 Hierarchies of production, changeability, and product levels (ElMaraghy & Wiendahl, 2009).

Although this classification is a good way of describing the connection between changeability classes, production, and product levels, it is derived based on the manufacturing industry and is not fully valid for describing the off-site production of all house building companies. Furthermore, as development potential on the level of network and factory are outside the scope of this thesis, the changeability classes of transformability and agility are not considered. However, flexibility and reconfigurability are changeability classes applicable on the segment level and the levels below it.

Changeability can be defined as the ability of a manufacturing system to change its functionality and/or capacity while not affecting quality and with little penalty in terms of time and cost (ElMaraghy & Wiendahl, 2009). However, a change can happen either within the boundaries of the system or through physical reconfiguration. To describe how changeability is seen in relation to the types of flexibility and manufacturing systems, Table 1 is given.

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

	Changeability		*Dedication*
Type of flexibility	General flexibility	Customized flexibility or reconfigurability	Focused flexibility
Type of MS	FMS	RMS	DMS

Focused flexibility refers to the ability of manufacturing system to handle a very narrow range of functionality and predefined fixed capacity. It is related to dedicated manufacturing systems (DMSs). On the other side, there are flexible manufacturing systems (FMSs) that have wide range of functionalities and scalable capacity. These manufacturing systems are considered to have a priory built-in general flexibility. Finally, reconfigurability is the ability of a system to quickly adapt in terms of changeable functionality and scalable capacity to cope with product, process, and/or production variety. These reconfigurable manufacturing systems (RMSs) achieve so-called customized flexibility through the rearrangement of structural components.

2.2.3. Dedicated, flexible, and reconfigurable manufacturing systems

DMSs are commonly used for mass produced products. These manufacturing systems have limited and predefined functionality and capacity, where changes come at great cost. Nevertheless, these highly automated systems have very high throughput rates (Koren et al., 1999).

FMSs, on the other hand, are less productive than DMSs but have the ability to tackle large product variety through built-in general flexibility (Zhang et al., 2006). They evolved with the emergence of lean manufacturing and MC (Figure 4).

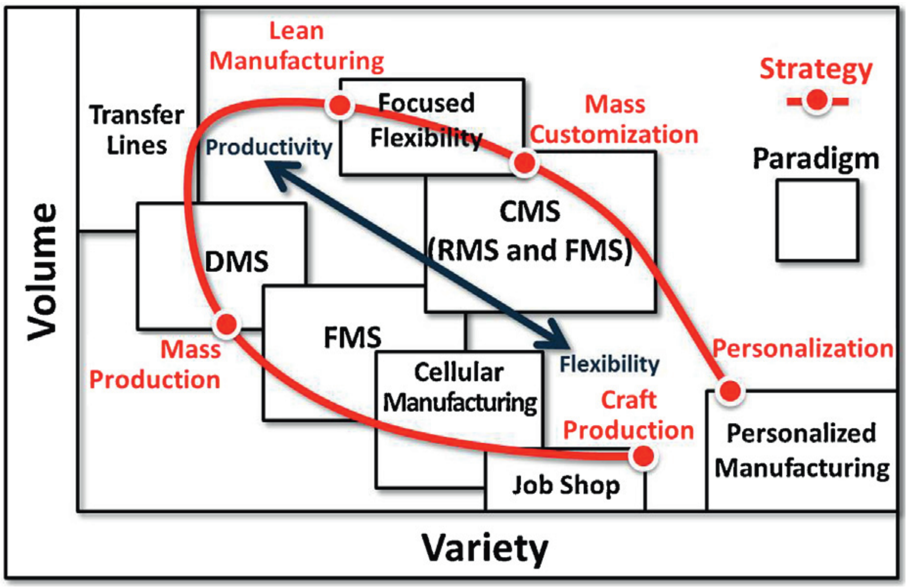

Figure 4 Variety and evolution of manufacturing systems paradigms (ElMaraghy et al., 2013).

RMSs were first coined and conceptually introduced at the end of the 1990s (Koren et al., 1999). The development of the RMS concept was a response to the need for high customization in product offering, high production volumes, the frequent introduction of new product variants, and high-quality products (ibid.). Neither of the two main manufacturing system paradigms existing at that time, namely DMSs and FMSs, could meet these requirements at a reasonable cost (Koren & Shpitalni, 2010). The thinking was to create a manufacturing system that would embody the productivity of DMSs and the flexibility of the FMSs by meeting different demand situations through repeated rapid capacity and functionality adjustments (ibid.). Different part families are manufactured on the same RMS through reconfiguration. Depending on the context, reconfiguration can happen in any of the system's constituents and can therefore be divided into physical, logical, and human reconfiguration (Rösiö, 2012)

Unlike the general flexibility of FMSs, which in many cases is not utilized fully, RMSs have customized flexibility, referring to providing only the necessary flexibility degree needed for a given part family. By reducing the flexibility degree from general to customized, the trade-off between flexibility and productivity is reduced. Moreover, while DMSs and FMSs are static against demand and have an integral design, RMSs are dynamic (Figure 5), can adjust to the demand, and are modular (ibid.).

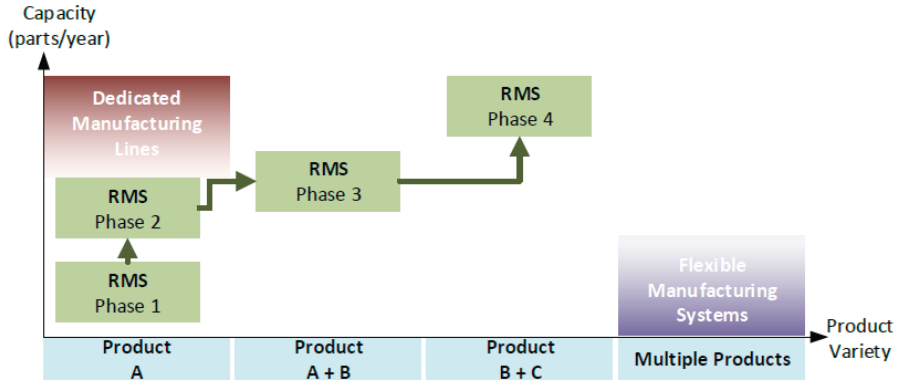

Figure 5 Manufacturing system paradigms (Koren & Shpitalni, 2010).

The characteristics of RMSs include customization, convertibility, scalability, modularity, integrability, mobility, automation ability, and diagnosability (Andersen, Brunoe, et al., 2017; Rösiö, 2012). Customization refers to the flexibility of the system being tailored for the part family requirements. It is achieved through convertibility and scalability, which refer to a system's ability to change functionality and capacity. The enablers of convertibility and scalability are modularity, integrability, mobility, and automation ability. The system has a modular architecture and standardized interfaces with modules that can be moved easily and adjustable levels of automation. The last characteristic is diagnosability, which refers to the ability to detect the state of the system and create the corrections needed to be carried out to reach the performance level planned (ibid.).

While it is good for the description purpose to refer to DMS, RMS, and FMS, in practice, systems are, taking into consideration all constituents, rarely purely dedicated, reconfigurable, or flexible. More often they are compound or hybrid systems where different types of flexibility are combined. For example, there can be a reconfigurable fixture or tool, but the material handling can be dedicated (Terkaj et al., 2009). Lotter and Wiendahl (2009) also use hybrid systems as a term when human labor and machinery are combined. In manufacturing systems flexibility is achieved either through flexible automation or human labor. Operators still remain the most flexible resource (Benkamoun, 2016). Depending on how the operations within the flexible system are allocated between the two, systems can have different automation levels and can be classified according to Lotter and Wiendahl (2009) as manual, hybrid, and automated. Furthermore, based on their study they conclude that hybrid systems are a better solution than flexible automated systems in terms of assembly costs, capital expenditures, and capital risk.

2.3. Manufacturing system development in mass customization

Since the purpose of this research is to propose a way of discovering the development potential of off-site manufacturing systems in timber house building, previous work related to manufacturing system development in MC customization is presented below.

2.3.1. Platform-based development

Initially coined by Harlou (2006), product variant master (PVM) is a tool based on object-oriented modeling for the analysis of product range and its suitability for the development of configuration systems. It enables modularity and interface definition and is a powerful tool for product range visualization. However, PVM consists of three views: customer view, engineering view, and part (production) view. In this way the integration of all relevant information for configuration system formulation, such as product functions and properties and the life-cycle properties of production assembly and installation, can be integrated in the model (Hvam et al., 2008). The obvious drawback of the PVM is the connection to the manufacturing systems in use.

Michaelis et al. (2015) suggested an integrated platform model where function-means trees are used to capture the conceptual considerations of the product and manufacturing system. Manufacturing processes are mapped to link the product and production models. Component trees are used to clarify how design solutions are realized in physical components. The proposed framework supports platform-based development in the conceptual design phase of products and manufacturing systems. This approach is quite comprehensive in the sense that the process analysis is included in the product and manufacturing system co-development model. Also, a platform approach is taken throughout the analysis. However, the flexibility requirements for manufacturing system solutions are omitted, and it is unclear what kind of manufacturing system paradigms are considered for a solution.

2.3.2. Reconfigurable manufacturing system design methods

Andersen, Brunoe, et al. (2017) have recently done a review of the methods and frameworks for RMS design. They reviewed and divided 13 methods into two groups: cyclic and phased methods. A generic method for the reconfigurable manufacturing system design is proposed based on the reviewed methods since the common underlying pattern of the reviewed design methods was identified in terms of common structure. The generic RMS design method consists of several steps in which the deliverables are development plan, requirement specification, design concept, design specification, and operating system.

Jefferson et al. (2015) presented a unique reconfigurable assembly system (RAS) design method developed for the specific context of the aerospace industry. The approach was formulated based on a set of requirements derived from the context, and it involves a combination of the existing methods as follows: axiomatic design, design structure matrix, knowledge capture, product-process-system framework, and design for changeability. The design methodology was validated in the rib assembly case study, and the results show that the reconfigurable cell has a higher investment cost compared to the non-reconfigurable cell, but, due to its scalable structure, the ramp-up period is shortened, and the rate matches the demand.

Manzini et al. (2004) proposed a flexible cellular assembly system design framework, which is an approach integrating design for assembly, group technologies, cellular manufacturing, and production flow analysis. A holistic approach is suggested through the analysis and optimization of products, manufacturing systems, and processes.

Andersen, ElMaraghy, et al. (2017) developed a participatory systems design method for changeable manufacturing systems. The requirements for the manufacturing system design are obtained through the responses to the questions that are formulated and posed in the stakeholder domain. These responses contain information that translates into statements that describe the required properties and behavior of the manufacturing system. Once a company-specific set of requirements is identified, a hybrid solution combining dedication, flexibility, and/or reconfigurability is likely to be obtained in the functional domain. Finally, changeability enablers with respect to their structure, nature, and type are obtained, therefore resulting in a manufacturing system solution.

Apart from the design method proposed by Andersen, ElMaraghy, et al. (2017), where all three manufacturing system paradigms are considered, the other frameworks have a focus on RMS design. Keeping in mind that in MC, platform thinking and a balance between product commonality and distinctiveness are applied, dedication, reconfigurability, and flexibility should be considered for corresponding manufacturing systems. However, not only systems but the manufacturing process has to be considered as well.

2.3.3. Levels of automation and Dynamo ++ framework

Research on levels of automation (LoA), i.e., the allocation of functions or tasks between humans and technology, has been going on for more than half a century (Fitts, 1951). Sheridan (1980) defined 10 LoA, ranging from one, human makes all the decisions and does all physical tasks, to 10, the computer makes the decisions and the equipment carries out the tasks without humans being involved at all. The Dynamo project (Frohm, Lindström, Stahre, et al.,

2008) reduced the number of LoA to 7. Frohm (2008) has defined LoA as *the allocation of physical and cognitive tasks between humans and technology, described as a continuum ranging from totally manual to totally automatic.* This reference scale is on a task level, and so far there is no methodology dealing with LoA on a production systems level. Fasth-Berglund and Stahre (2013) discuss the importance of considering both physical and cognitive automation when aiming for FMSs or RMSs.

Table 2 Dynamo ++ method.

Num.	Step	Phase
1.	Choose the system	Pre-study
2.	Walk the process	
3.	Conduct a time study	
4.	Identify the main operations and subtasks	Measurement
5.	Measure LoA (both physical and cognitive)	
6.	Document the result	
7.	Conduct a workshop	Analysis
8.	Design the square of possible improvements (SoPI)	
9.	Analyze the SoPI	
10.	Write and visualize suggestions of improvements based on 9.	Implementation
11.	Implement the chosen suggestions	
12.	Follow-up	

The Dynamo++ method was developed to be easy to use in the industry environment (Fasth, 2012) as a continuation of the original Dynamo project. The method aims at measuring and presenting the accurate current state of information flow and level of automation present in an observed assembly system (Fasth et al., 2008). Moreover, it aims at establishing the accessible LoA present in the factory in order to create a range of possible LoA. This would further enable a flexible task allocation by which production disturbances could be avoided and productivity increased when a high product variety is assembled at the factory (Frohm, 2008). The framework focuses on the task level of assembly processes on the shop floor, not considering the automation present in assembly support systems (Fasth, 2012). The method consists of 12 steps divided into four 3-step phases: pre-study, measurement, analysis, and implementation (Fasth, 2012). The steps in each phase are shown in Table 2. In this thesis, the first seven steps of the Dynamo ++ framework were performed in empirical studies 1 and 2. The measurement phase was covered in study 1, and the time studies and workshops were covered in study 2.

2.4. Literature review

2.4.1. Systematic approach

As MC is regarded in this thesis as an overarching theory that encompasses other theories presented in the frame of reference, a literature review on the development and implementation of MC in house building is presented. The scope of the review is broader than that of the thesis (section 1.4). Not only the OSM step, but also other steps of the product realization process in house building, i.e., product development, design-engineering, on-site, and supply chain were included. The product development step refers to the descriptions and development processes of the building systems. The design step refers to the systems and processes performed during conceptual design, sales, and engineering. OSM refers to manufacturing processes and systems in the factory environment as well as planning and control. On-site assembly refers to the final assembly of house parts, components, and modules at the building site and the control of these activities. Supply chain refers to the activities between all the actors, including purchasing, logistics, and relationships with suppliers and subcontractors. Furthermore, not only residential building construction and timber construction but also non-residential building construction and concrete and steel frame construction were included in the sample. This approach to the review was chosen to both establish the knowledge gap and to demonstrate why further research in the OSM area is needed from a theoretical perspective.

A systematic literature review was conducted in several steps: defining keywords, formulating an appropriate search strategy through the iterative collection of sources, title and abstract screening, full-text screening, choosing the final sample, and content analysis. The first step was to define the keywords for the house building context. The context of house building is covered in the literature by many different keywords and their synonyms, as described by (Kamar et al., 2011). Initially in this study, the following were the keywords used to develop the final search strategy: off-site production, off-site manufacturing, off-site fabrication, off-site construction, pre-assembly, prefabrication, prefab, modern methods of construction, modern methods of house construction, modern methods of house building, building system building, non-traditional building, and industrialized building. However, after multiple iterations this list of keywords was refined with other keywords and synonyms, and their combinations, to provide the best possible coverage of the context. On the other hand, the keyword "mass customization" was found to be not comprehensive enough and so was consequently complemented with the keywords of MC enablers, as according to Fogliatto et al. (2012).

The formulated search strategy consisted of a total of 15 strings, as shown in Appendix A. Each string created for the house building context was narrowed down using the delimiting Boolean "AND" operator with the keywords related to MC and MC enablers. The collection of sources was performed in the Scopus database by applying search strings to article titles, abstracts, and keywords. Regarding the inclusion criteria, peer reviewed journal articles published in English were collected, and there was no limitation in terms of publishing year. In total, 1,714 articles were identified, and after the removal of duplicates there were 1,492 articles left. These journal articles were analyzed in the next step, abstract screening. In total, 1,339 articles were removed since these were either related to a different context or not related to MC, and the remaining 153 journal articles were retrieved for the full-text screening. After the full-text screening, 109 journal articles were removed as these were not possible to classify into the product realization process. Aside from the 44 remaining articles, an additional 14 relevant publications were identified through a backward citation search. Therefore, in total 58 peer reviewed journal articles were chosen for the content analysis. Furthermore, Scopus alerts were set for all search strings, and for the period between October and December of 2017, no additional relevant sources were identified.

2.4.2. *Sample of articles*

Product development is addressed by the development of platform-oriented building systems where the focus was on modular architecture and configurable design (Isaac et al., 2016; Marchesi & Ferrarato, 2015; Marchesi & Matt, 2017; Veenstra et al., 2006; Yu et al., 2008). Nijs et al. (2011) suggest a method for the development of standardized interfaces, while Hentschke et al. (2014) propose a method for the definition of value adding attributes of customized houses, therefore enabling the creation of relevant product distinctiveness. Said et al. (2017) developed a model for the optimization of existing platforms to adjust to customer requirements while maintaining fabrication efficiency. Regarding the implementation of MC in product development, an analysis of existing building systems, product ranges, and platforms was done through case studies (Jensen et al., 2015; Kudsk, Grønvold, et al., 2013; Kudsk, Hvam, Thuesen, et al., 2013; Malmgren et al., 2011; Persson et al., 2009).

By far the most elaborated in the literature is the design step where final product design is defined through customization processes. Different efforts were made in the development of information systems or frameworks for their development. These are the systems used for (1) the configuration of product platforms and customer involvement (Duarte, José P., 2005; Duarte, J. P., 2005; Duarte & Correia, 2006; Eid Mohamed et al., 2017; Friedman, Sprecher, & Mohamed, 2013; Herkommer & Bley, 1996; Jensen et al., 2012; Juan et al., 2006; Khalili-Araghi & Kolarevic, 2016; Khalili & Chua, 2014; Khalili & Chua, 2013; Kim & Jeon, 2012; Salama et al., 2015; Shin et al., 2008; Wikberg et al., 2014), (2) handling customer-specific information (Frutos & Borenstein, 2003; Khalili-Araghi & Kolarevic, 2016), and (3) design automation used in the detailed design phase (Benros & Duarte, 2009; Khalili-Araghi & Kolarevic, 2016; Knight & Sass, 2010; Said, 2016). Friedman, Sprecher, and Eid Mohamed (2013) proposed a framework for the development of design systems for MC in the housing industry. Implementation was explored in case studies through an analysis of product specification processes (Jensen et al., 2015; Persson et al., 2009), configuration systems (Da Rocha & Formoso, 2013; Kudsk, Hvam, & Thuesen, 2013; Malmgren et al., 2011; Sandberg et al., 2008), knowledge-based engineering (Sandberg et al., 2008), and the management of customization in the design processes (Da Rocha et al., 2016; Jansson et al., 2016). In this study, the process of customization indicates both the platform configuration and the specification of unique product parts.

Published research about the development and implementation of MC in off-site prefabrication is scarcer than that in the design step. Three groups of research directions were identified regarding MC development. Production control was addressed using simulation and an experimental design (Azimi et al., 2012; Lu et al., 2011; Mullens et al., 1995). The OSM system design was addressed by developing flexible systems that handle product variety. Azzi et al. (2011) used the group assembly method for the design of FMSs used to produce a variety of non-bearing curtain walls for multistory buildings. In terms of future work, they propose this type of development in the house building sector of construction. A method for the automation of precast concrete element production is proposed by Garg and Kamat (2014). Kasperzyk et al. (2017) address the late changes in product design by developing a robotic prefabrication system having both assembly and re-fabrication functions. On the other hand, the implementation of MC in OSM was investigated using lean production (Nahmens & Mullens, 2009) and production management principles (Bashford et al., 2005). Production planning was addressed through CAM implementation (Benjaoran & Dawood, 2006; Herkommer & Bley, 1996; Khalili & Chua, 2014; Knight & Sass, 2010).

On-site assembly is usually related to the traditional way of building houses. The industrialization and MC of house building implies moving as much work as possible into the controlled factory environment. This can be one reason why only two sources were related to MC development by developing an on-site prefabrication system design (Martínez et al., 2013) and addressing the implementation of MC management in construction (Andújar-Montoya et al., 2015).

MC in the house building supply chain was mainly addressed through the development (Da Rocha & Kemmer, 2013; Naim & Barlow, 2003) and implementation (Barlow et al., 2003; Gosling et al., 2010) of supply chain strategies. These strategies are related to delayed product differentiation, i.e., postponement, the positioning of COPD, and the combination of lean and agile management principles. Schoenwitz et al. (2017) investigate product, process, and customer preference alignment by positioning COPDs across product levels.

Finally, articles addressing the whole product realization process report on the development (Jansson et al., 2015) and implementation (Bonev et al., 2015; Jansson et al., 2014; Lennartsson & Björnfot, 2010; Thuesen & Hvam, 2011; Voordijk et al., 2006) of house building platforms, including product, production processes, and supply chain.

Overall, studies about the development and implementation of MC in house building by far mostly address the design step of the whole product realization process. Eliminating the wasteful use of resources and improving the flow is important regardless of the degree of product variety, but MC production systems require high flexibility in processes as well. On that note, very few sources from the sample address the development and implementation of FMSs capable of handling product and volume variety, which is considered a crucial capability for the successful implementation of MC in house building (Khalili-Araghi & Kolarevic, 2016; Naboni & Paoletti, 2015; Nahmens & Bindroo, 2011).

3. Research design

The purpose of this chapter is to introduce the research approach and method used and clarify the research strategy. The data collection and analysis are explained for the empirical studies, and comments about the research quality are made. The chapter concludes with a description of the case company and the exterior wall element assembly.

3.1. Research approach and method

To increase the knowledge on how to identify the development potential of off-site manufacturing (OSM) systems in mass customization-oriented timber house building, an understanding of OSM in MC settings was needed. Therefore, the suitable research method to address this research purpose was case study research. Through case study, an understanding of the contemporary phenomenon and its practices in their natural context is created (Yin, 2013). The research techniques used are open interviews, observations through video recordings, archival documents, and workshops (Williamson, 2002). The data collection and analysis techniques used in the empirical studies are described in the following sections. The type of data collected through case studies was mostly qualitative in nature (ibid.).

3.2. Research strategy

The research strategy in this thesis is used to describe how the studies, conducted work, papers, thesis, and research purpose were connected (Figure 6). The second study and conceptual framework were not published in paper form but are instead reported in the present thesis. The first study resulted in two papers. The data from the first study were afterward used for the workshops in the second study together with time studies. Some of the data from the first two studies were joined with the secondary data from four other case studies and were together used to conduct the third study, out of which paper 3 was written. The references to these four additional studies are given in section 3.3.3. The conceptual framework presented in this thesis was formulated based on these three empirical studies and the frame of reference presented in the second chapter. Finally, the data altogether aim at fulfilling the research purpose.

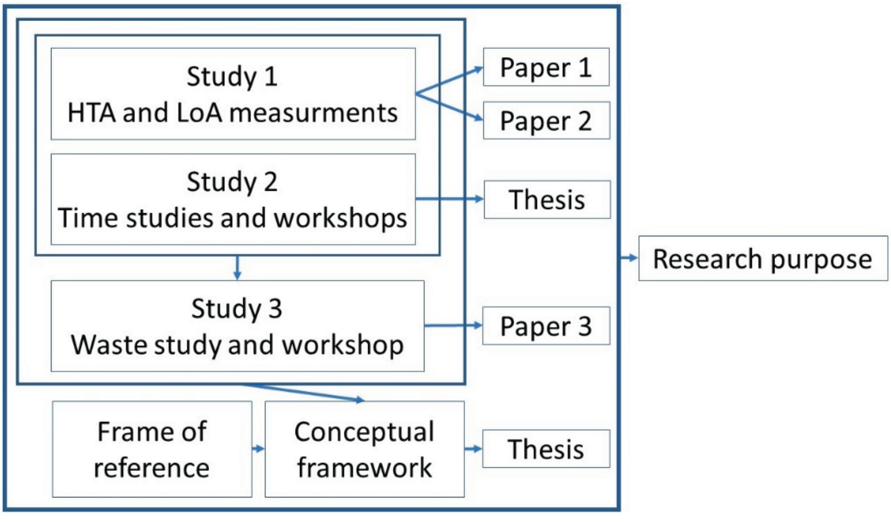

Figure 6 Research strategy.

3.3. Data collection and analysis

3.3.1. Study 1

The data collection technique used in study 1 included video recordings, informal interviews, observations, and documents. The documents, observations, and informal interviews were used to gather the data describing the assembly lines in the case company. The documents collected concerned the layout of the assembly line and the exterior wall element (EWE) shop-floor drawings. The observations were performed on the shop-floor along the assembly lines which complemented the information gained through the documents. Finally, the informal interviews were conducted to validate the data collected through the documents and observations and to gain new insights about the assembly process and products. The interviewees included managers from the technical department, middle management, and the operators working on the assembly line. The assembly process was recorded with several cameras positioned in such a way that they would not affect the process in any way but would ensure the activities at and around every station were captured in detail.

Table 3 Reference scale for seven levels of physical and cognitive automation. Adapted from Frohm, Lindström, Winroth, et al. (2008).

LoA	Mechanical and Equipment (Physical)	Information and Control (Cognitive)
1	Totally manual - Totally manual work, no tools are used	Totally manual - The user creates his/her own understanding for the situation and develops his/her course of action based on his/her earlier experience and knowledge
2	Static hand tool - Manual work with support of static tool, e.g., screwdriver	Decision giving - The user gets information on what to do or proposal on how the operation can be achieved, e.g., work order
3	Flexible hand tool - Manual work with support of flexible tool, e.g., adjustable spanner	Teaching - The user gets instruction on how the operation can be achieved, e.g., checklists, manuals
4	Automated hand tool - Manual work with support of automated tool, e.g., hydraulic bolt driver	Questioning - The technology questions the execution if the execution deviates from what the technology considers suitable, e.g., verification before action
5	Static machine/workstation - Automatic work by machine that is designed for a specific operation, e.g., lathe	Supervision - The technology calls for the user's attention and directs it to the present operation, e.g., alarms
6	Flexible machine/workstation - Automatic work by machine that can be reconfigured for different operations, e.g., CNC-machine	Intervene - The technology takes over and corrects the action if the executions deviate from what the technology considers suitable, e.g., thermostat
7	Totally automatic - Totally automatic work, the machine solves all deviations or problems that occur by itself, e.g., autonomous systems	Totally automatic - All information and control is handled by the technology. The user is never involved, e.g., autonomous systems

The collected data were first analyzed using the hierarchical task analysis (HTA) method. The whole assembly process was divided by its depth and width into working stations, operations, and tasks (Stanton et al., 2013). By analyzing the depth and the width of an HTA structure, indications about process characteristics such as efficiency, balancing, throughput time, complexity, and the need for automation can be obtained (Stanton, 2006). An efficient HTA structure should have a short depth and as short a width as possible. A deep HTA structure could be seen as an indicator of the high complexity of a station and also a need for cognitive automation to support the operator. A wide HTA structure could be an indicator of unbalanced lines and long through-put times. If the HTA is wide, physical automation could be a solution to achieve better balance between the stations and/or to reduce the number of stations (ibid.).

Afterwards, physical and cognitive components were identified for each operation. Physical and cognitive LoA were assigned to each operation using a LoA taxonomy (Table 3). The LoA taxonomy is composed of two reference scales for determining the LoA of every operation, both their physical and cognitive parts (Frohm, Lindström, Winroth, et al., 2008).

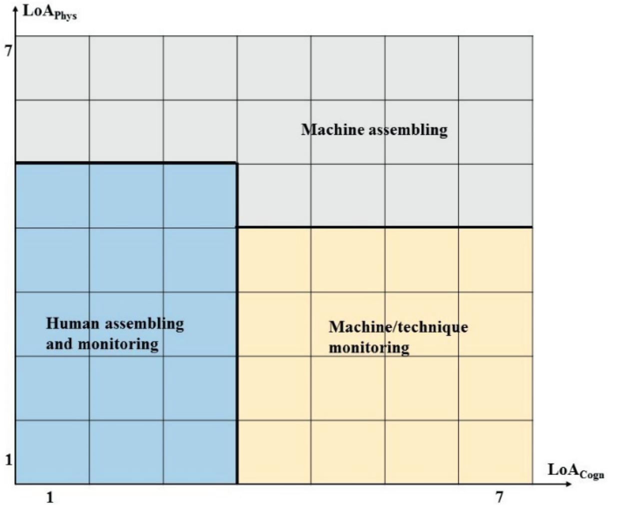

Figure 7 LoA matrix, adapted from Fasth and Stahre (2008).

Following the classification of operations according to their physical and cognitive LoA, an LoA matrix was used to visualize the cumulative result (Figure 7). It is a seven by seven matrix, which thus has 49 possible combinations. Furthermore, the matrix is divided into three general regions that can give the reader a quick overview of the assembly process and allocation of operations between human operators and machines. Finally, the average physical and cognitive level of automation was calculated and compared to the previous case studies where the same method was implemented (see Apendix B).

3.3.2. *Study 2*

Two more steps of Dynamo ++ were included in study 2: (1) conducting time studies based on the recorded assembly process and (2) identifying possible improvements using the workshop technique (Williamson, 2002) in the case company. Here, unlike study 1, the assembly of three different types of EWEs and two types of siding panels was analyzed with time studies. Therefore, the EWE variation was considered to some extent. The time studies were conducted using assembly process "avi" files in AviX software (AviX, 2017). The times of operations on each working station were measured and plotted for the EWE assembly processes described in section 3.5.

Two separate workshops were organized in the case company for each of the observed assembly lines. The participants in the workshops were company representatives from higher management and the manufacturing and design departments covering different levels in the organization. The presentation of the data obtained from the time studies together with the data about the HTA and LoA from the first study were the material used as an introduction to the workshops.

After the introduction the first goal in the workshops was to discuss and identify the critical work stations and assembly moments based on the abovementioned data. After that, the related recorded material was presented to the participants in order to identify the problems. Finally, the discussions about the possibilities for improvements were conducted.

3.3.3. *Study 3*

In the third study, secondary data from five case studies conducted during 2014–2016 (Andersson & Jönsson, 2016; Björk & Andersson, 2016; Tingström & Gunnarsson, 2014; Ulriksson et al., 2014) were used. The data for one of the case studies were from the research presented in the first and second studies. Common to all studies was the mapping of the OSM processes for the prefabrication of wall modules. The data collection technique in all studies comprised observations, semi-structured interviews with production management staff, and discussions with operative staff.

As the aim of the third study was to identify problem areas and to connect them with occurring types of waste, the collected secondary data were analyzed using the workshop technique (Williamson, 2002). Four academic researchers and two middle managers from one of the case companies attended workshop, which had two goals. The first goal of the workshop was to discuss each observation and reach a consensus on types of occurring types of waste. The second goal of the workshop was to categorize the observations into problem areas.

3.4. Research quality

The quality of the research can be commented on from the aspects of validity and reliability. Validity represents the extent to which the answers to the research purpose are correct (Kirk & Miller, 1986) and can be divided into internal and external validity. Internal validity is related to the extent to which the research measured what it was supposed to measure (Miles & Huberman, 1994), and external validity refers to the extent to which the findings of the research can be generalized (Meredith, 1998). Reliability refers to the accuracy of the research procedure descriptions (Kirk & Miller, 1986). It describes the extent to which the study can be replicated regardless of by whom or when it is carried out. Following are comments about how the validity and reliability were addressed in the empirical studies.

3.4.1. Internal and external validity

Regarding internal validity, research quality was achieved in the first study by organizing an informative meeting for the operators working on the assembly lines about the video recordings. The operators were informed about the purpose of the study and in what way the recorded material would be exclusively used. Thereby, it was expected that the operators would work in a regular manner at a normal pace. Internal validity is also important from the data analysis perspective. The HTA and LoA analysis were performed by a sole researcher, which is prone to subjective judgment. Therefore, the workshops were a good way to validate the data.

Unless performed on a statistically significant number of cases, the external validity in case study research is often limited due to the inability to generalize (Yin, 2013). This issue is usually addressed and compensated by providing an in-depth analysis of the case, where it is left to the readers judgment whether or not the findings are applicable in another context.

3.4.2. *Reliability*

The reliability of the empirical studies is ensured through video recordings of the assembly processes of external wall elements, detailed documentation of the analysis, datasets, AviX project files, recordings of workshops, and the data collection and analysis presented in the thesis. Video recordings as a data collection technique require significantly more time and resources to implement compared to regular observations. However, it is possibly the best technique for ensuring reliability. As the production and manufacturing systems evolve over time, the video recordings represent crucial documentation for the replicability of the study. Furthermore, if only regular observations were made, replication more than one year after the initial study would be difficult. The video recordings enable anyone to repeat the study at any time. The reliability of the third empirical study is ensured through the research reports from which secondary data were obtained.

3.5. Case company description

The company where empirical studies 1 and 2 took place is Myresjöhus. Myresjöhus is owned by OBOS, which is the leading Nordic real estate company. Some of the OBOS-owned trademarks also include Smålandsvillan, Block watne, and Kärnhem. As of July 2017, OBOS, with all the trademarks combined, held second market position in sales after Skanska. Myresjöhus offers customized single-family timber houses and also has a special line of standardized products called Start Living. Myresjöhus houses are prefabricated in elements, while Start Living houses are prefabricated in volumes.

3.6. Exterior wall element assembly

Descriptions of the EWE assembly lines that were analyzed in the empirical studies are given. The assembly lines are referred to as engineer-to-order (ETO) and select-a-variant (SV) assembly lines. The assembly lines were named according to the end product for which the EWEs are assembled. Therefore, the EWEs for the customized houses are assembled on the ETO assembly line, while those for the standardized houses are assembled on the SV assembly line.

The assembly process on the ETO assembly line is divided into 13 work stations (Figure 8). The assembly process for the EWE shown in Figure 9 begins with the assembly of the basic wall structure. Work stations 1–7 are for the assembly of the outer side of the wall. Thereafter, the assembly process continues on the inner side through work stations 8–13. Important to note is that Figure 8 is taken from appended paper 1 but compared to the on-line version of the paper differs by having 13 stations instead of 14.

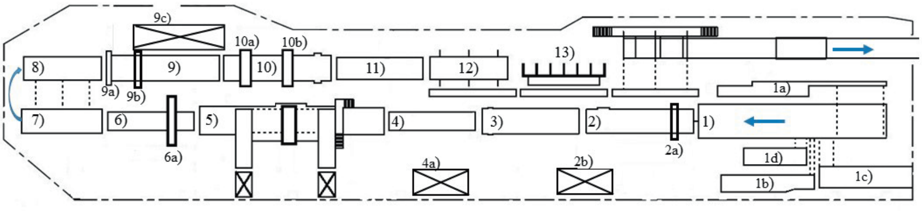

Figure 8 ETO assembly line layout.

The assembly process (Figure 8) is performed at 13 stations in the following sequence: (1) basic wall frame assembly, (1a) horizontal stud feed, (1b) vertical stud feed, (1c) sub-element unit magazine and feed, (1d) rock-wool insulation feed, (2) wind protection sheet and air studs assembly, (2a) nailing and air studs inventory, (3) nailing studs assembly, (4) manual positioning of the horizontal siding wood panels and mounting mice protection net, (4a) horizontal siding panels inventory, (5) nailing operation for the vertical siding panels, (6) nailing operation for the horizontal siding panels, (6a) nailing machine, (7) finalizing the outer side of the wall, (8) lifting belts assembly, (9) positioning of humidity protection plastic and gypsum/plywood boards, (9a) gypsum/plywood board positioner, (9b) gypsum/plywood board inventory, (10) nailing and routing operations for gypsum/plywood boards, (10a) nailing machine, (10b) CNC router, and (11, 12, 13) final operations on the interior side of the wall and quality control.

However, not all the work stations are used for every type of wall. Work station 5 (Figure 8) was not considered in the first study as the assembly of the EWE with horizontal siding panels was followed and filmed through the process. This station is dedicated for the nailing of vertical siding panels. Likewise, in study 2, where the assembly of two types of EWEs with vertical siding panels was analyzed via time studies, station 6 (Figure 8) was not considered.

Regarding the machinery used for the assembly, siding wood panels, gypsum, and plywood panels are assembled onto the basic wall structure by nailing machines. Besides automatic nailing, there are additional automated processes. The basic wall structure assembly is a collaborative human-machine operation, where parts (stations 1a, b, c, and d, in Figure 8) are machine-driven, positioned, and nailed automatically. Rock-wool insulation is automatically cut into correct lengths required for a particular EWE. The gypsum boards with standard dimensions are automatically transported and positioned (station 9 in Figure 8) prior to the nailing operation, and they are thereafter CNC routed at positions above the windows. All these automated operations are steered by machine codes. The nailing machine for the horizontal siding panels (station 6 in Figure 8) is not controlled by a machine code but instead uses sensors to detect the nailing positions.

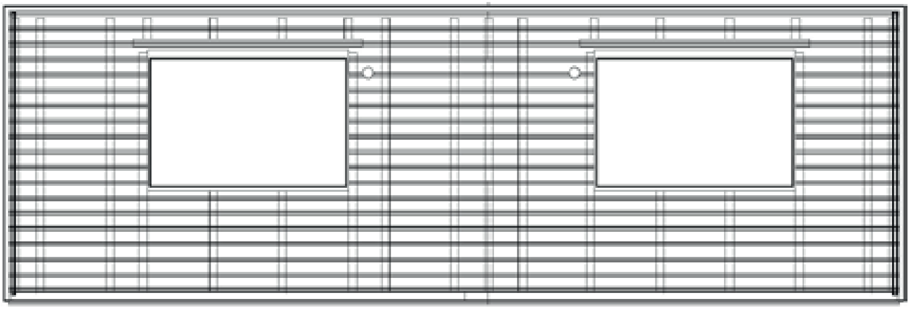

Figure 9 Type of EWE assembled on the ETO assembly line.

The assembly process on the SV assembly line is divided into eight stations. The process begins with the assembly of the inner side of the wall (Figure 11) at stations 1–4. After turning, the work on the outer side follows, at stations 5–8. (Figure 10).

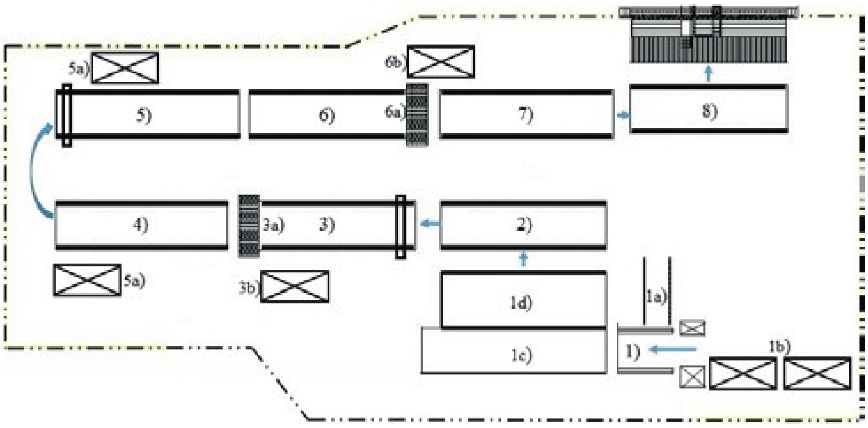

Figure 10 SV assembly line layout.

The assembly process is performed in the following sequence: (1) basic wall frame assembly; (1a) part units; (1b) vertical studs and horizontal studs; (1c) rock-wool insulation; (1d) transfer station; (2) attaching of lifting belts and electricity tubes; (3) positioning of humidity protection plastic and gypsum boards; (3a) nailing machine; (3b) gypsum board inventory; (4) final operations on the interior side of the wall; (5) wind protection sheet, nailing, and air studs assembly; (5a) nailing and air studs inventory; (6) manual positioning of the horizontal siding wood panels; (6a) nailing machine for vertical siding panels; (6b) siding panels inventory; (7) finalizing the outer side of the wall and manual nailing of horizontal siding panels; and (8) finalizing the outer side of the wall and quality control. Station number 6 was not considered in the first study since the EWE with horizontal panels was followed through.

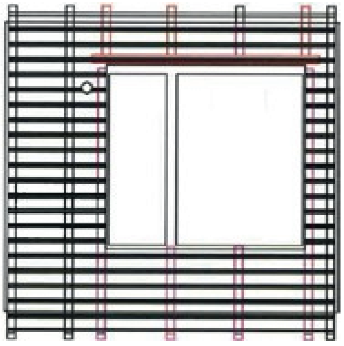

Figure 11 Type of EWE assembled on the SV assembly line.

Regarding the machinery used in the assembly process, only vertical siding panels and gypsum boards are fixed to the wall frame with nailing machines, while the step movements of the conveyor when the wall frame is assembled are controlled numerically. These are the only three numerically controlled operations. Unlike the ETO line, the cutting, supply, and positioning of the rock-wool insulation and gypsum panels are done with the involvement of operators. The programing of the machines for the numerically controlled operations is done manually on the SV line, while in the ETO assembly line these machine codes are sent from the planning department. The horizontal siding panels are assembled manually by hand pistols. This assembly line is used as a shared resource between the standardized exterior wall and garage wall elements.

4. Summary of results and discussion

At the outset of this chapter a summary of the three empirical studies will be presented. An analysis of these empirical studies and the conceptual framework follow. This is followed by a discussion about the framework, and the chapter concludes with the research limitations.

4.1. Levels of automation in off-site manufacturing

This study resulted in the first two appended papers. The data collection and analysis in this study were related to processes and systems used on two EWE assembly lines. In the first paper the current HTA and LoA of the ETO assembly line (Figure 8) were in focus. In the second paper the data about the current HTO and LoA of the SV assembly line (Figure 10) were added and a comparison of the two assembly lines in terms of HTA and LoA was in focus.

Table 4 Summary of HTA for the two assembly lines. The numbers of stations correspond to the numbers indicated in figures 8 and 10.

Assembly line	ETO		SV	
Work station	*N. of operations*	*N. of tasks*	*N. of operations*	*N. of tasks*
1	3	15	4	32
2	3	18	5	25
3	2	14	4	19
4	1	3	3	8
5	\	\	6	25
6	2	8	\	\
7	1	3	5	33
8	3	16	3	11
9	1	4	\	\
10	2	9	\	\
11	3	16	\	\
12	2	12	\	\
13	1	6	\	\
∑	24	124	30	153

As described in section 3.3.1, the HTA method and LoA taxonomy and matrix are used to divide the processes of two assembly lines into work stations, operations, and tasks and to define and represent the level of automation for every task. The process on the ETO assembly line was divided into 12 stations, 24 operations, and 124 tasks when the EWE described in Figure 9 is assembled. On the other hand, the process on the SV assembly line, for the given type of EWE (Figure 11) was divided into 7 stations, 30 operations, and 153 tasks (Table 4).

The HTA indicates a short depth and long width of the work stations on ETO assembly line. The HTA in the SV assembly line shows the workload distributed over about half the number of work stations of the ETO line and also has a longer depth. It can be observed that stations 4, 6, 7, 9, and 13 in the ETO line and stations 4 and 8 in the SV assembly line have significantly fewer tasks than the other stations, which is related to either unbalanced manual work or that the tasks are machine-operated. The stations with unbalanced manual work are 4, 7, and 13 in the ETO assembly line and the abovementioned stations in the SV assembly line. The stations whose work is performed by machines are 6 and 9 in the ETO assembly line. Line balancing, therefore, is one of the possible improvements, which is in the line with findings of (Fasth & Stahre, 2008).

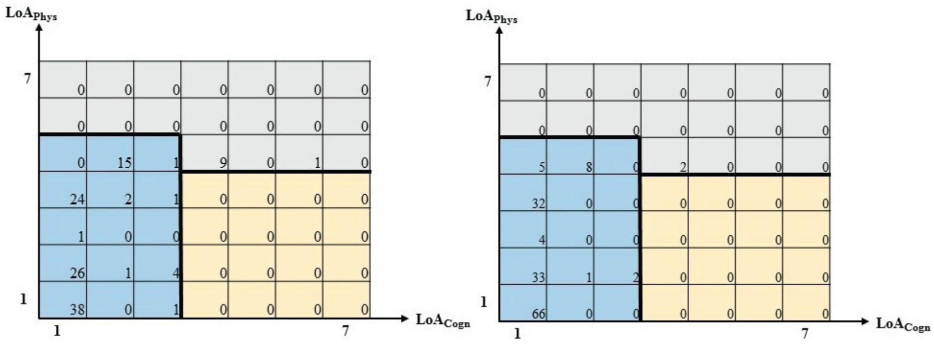

Figure 12 LoA matrices for the ETO (left) and SV (right) assembly lines.

By using the LoA taxonomy (Table 3) the identified tasks in both the ETO and SV assembly lines were classified according to their physical and cognitive LoA. The LoA matrices are shown in Figure 12. The majority of tasks for both assembly lines are classified in the area of manual assembly and monitoring. However, the ETO assembly line consists of more tasks with both higher cognitive and physical levels of automation.

The results show that over 95% of the off-site exterior wall element (EWE) assembly tasks are performed manually (blue area in Figure 12). Especially high are the numbers of LoA 1:1 tasks (38 in ETO and 66 in SV). These are “pick and place” tasks where operators use their own body strength and knowledge. Much of material and tool handling are of this type of task. The next significant group of tasks (26 in ETO and 33 in SV) are done by operators with their own knowledge and simple hand tools, such as hammer, LoA 2:1. Equally present in both assembly lines are tasks that require the operator’s own knowledge and flexible hand tools, like nailing hand pistols, LoA 4:1. In the gray area (machine assembling) of the LoA matrices, tasks performed by CNC machines (10 in ETO and 2 in SV) are found. There are nine LoA 5:4 tasks performed at stations 1, 9, and 10 (Figure 8) and two LoA 5:4 tasks at station 3 (Figure 10). The nailing machine for the horizontal side panels (station 6 in Figure 8) performs a LoA 5:6 task due to the absence of a machine code. There are fewer operations and tasks in total on the ETO assembly line than on the SV line, which is related to higher levels of physical automation, i.e., more manual tasks are required to substitute for work performed by machines. The fact that the SV assembly line was not initially designed nor substantially redesigned for the assembly of EWEs explains the amount of pure manual work and lower physical and cognitive automation. As described by Groover (2016), one of the obstacles for automation is a high number of product variants. However, the SV assembly line has lower physical and cognitive LoA than the ETO assembly line.

Based on the LoA analysis for both assembly lines, a large potential for improvements is identified in tools and material handling. On the SV assembly line, stations 1, 2, 3, 4, 5, and 7 have material and tools placed outside of the operator’s reach. This causes unnecessary movements. On the ETO assembly line, the materials and tools are placed much closer to the actual assembly. The cause for this is the current assembly line layout and lack of the space for material and tool storage.

From informal interviews with the operators an observation was made regarding the flow of information. The main information carriers for the manually performed operations are printed papers, i.e., shop-drawings. According to the operators, these are one reason for mistakes in the assembly line. Reading and interpreting shop-drawings under time pressure, when unique EWEs are assembled, lead to occasional misinterpretations of what, where, and/or how things should be done. This is especially the case with the ETO assembly line process where the number of different window, door, and/or electrical box placements is very high.

4.2. Time studies and possible improvements

The results of the time studies performed on different EWEs are presented in the first part of this section. After that, a summary of workshops where possible improvements for the ETO and SV assembly lines were discussed is given.

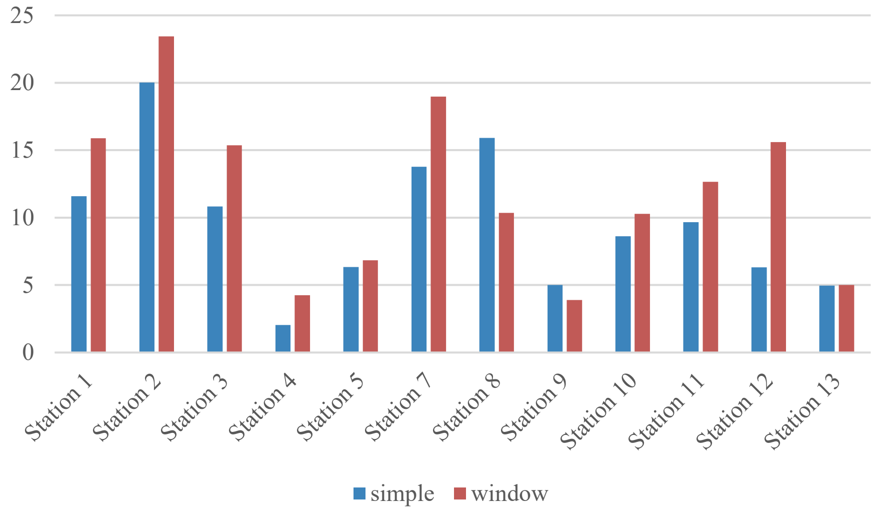

Figure 13 Cycle times [min] on the ETO assembly line. Comparison between two types of EWEs with vertical panels: simple plain wall and wall with window units.

The assembly of three different types of EWEs on the ETO assembly line was considered. Therefore, some variation of EWEs is covered in this study. The cycle times of two types of EWEs with vertical siding panels are plotted together in Figure 13. The first one is a simple EWE without any window, door, or electrical unit. The second one is an EWE with window units of intermediate assembly complexity.

The third type of EWE that was considered in the time study was assembled with horizontal siding panels and a roof section. This type of EWE is highly complex in terms of the required assembly operations. The results of time studies are shown in Figure 14.

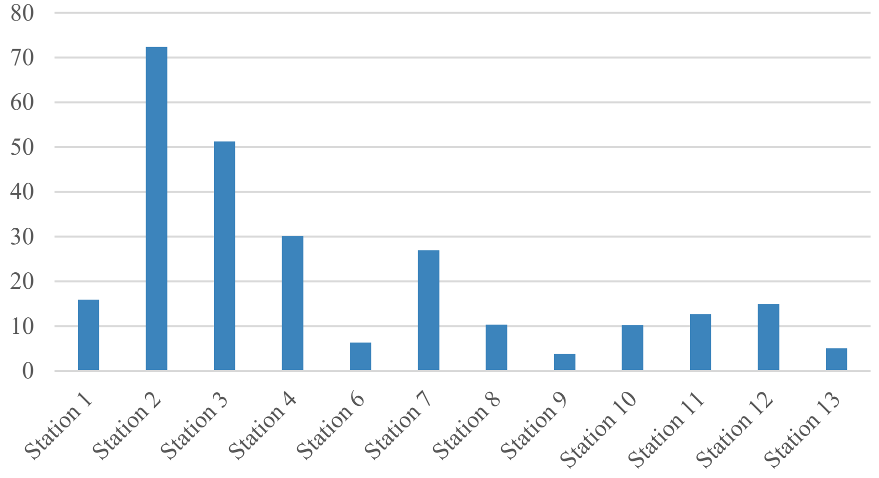

Figure 14 Cycle times [min] on the ETO assembly line for the EWE with horizontal siding panels and a roof section.

The type of EWE for which the assembly on the SV exterior line was analyzed in the time study is the wall depicted in Figure 11. The cycle times of seven work stations are shown in Figure 15.

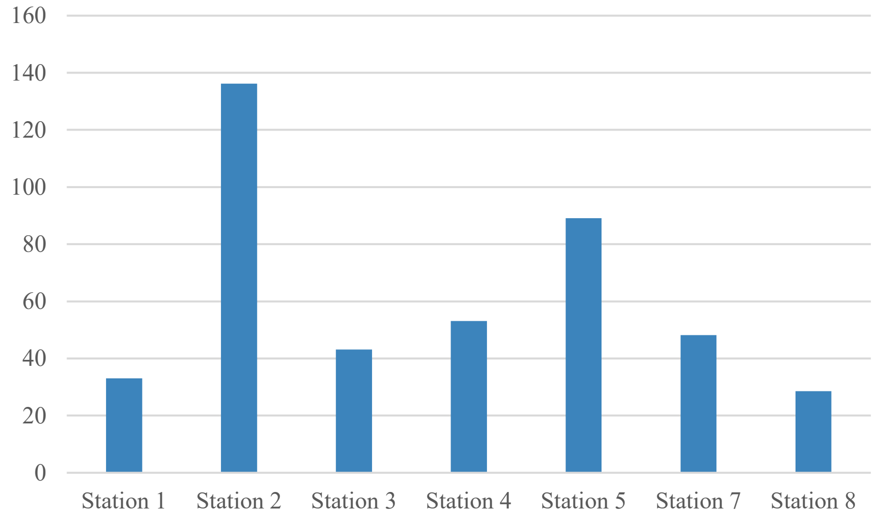

Figure 15 Cycle times [min] on the SV assembly line for the EWEs with horizontal siding panels.

While analyzing the recorded process at the SV assembly line, it was observed that non-value adding tasks were dominating the process. Therefore, an additional classification and quantification of tasks was made (Table 5) into the following:

1. Value adding (VA); Task of placing a value object in its final position.
2. Non-value adding necessary (NVAN); Handling of materials and tools at the place of assembly.
3. Waiting (W); Waiting during the assembly cycle.
4. Time losses (L); Long relocations of objects and non-ergonomic movements.

Table 5 Classification and quantification of tasks on the SV assembly line. AL: assembly line.

Station	*1*	*2*	*3*	*4*	*5*	*7*	*8*	*AL*
VA [%]	6	1	1	1	1	5	0	2
NVAN [%]	59	8	21	3	12	53	14	19
W [%]	6	90	65	93	76	17	60	68
L [%]	28	2	13	3	11	25	26	11

The first part of the workshops was an introduction to the HTO and LoA findings from the first study and the times studies presented above. Based on this information it was discussed and decided as to which stations were critical in the assembly line. That was the first goal of both workshops. The chosen stations in the ETO assembly line were stations 2, 3, and 7. These stations were chosen due to the low physical and cognitive LoA and high cycle times that were above the takt time of the assembly line (30 min). The chosen stations in the SV assembly line were stations 1, 2, 3, 5, and 7. Here the choice was mainly made according to low LoA, the distribution of operations and tasks (HTA) among stations, and the shares of non-value adding tasks. Stations 1 and 7 were chosen because of a large share of NVAN tasks and stations 2, 3, and 5 because of the time losses. The waiting times were high due to a lower number of operators, which was the case only during the day of recording. Therefore, this could have not been deemed a deciding factor. The summary of discussions about possible improvements in the two workshops is given in Table 6.

Table 6 Summary of possible improvements.

ETO assembly line			SV assembly line		
Critical station	*Problem*	*Improvement suggestions*	*Critical station*	*Problem*	*Improvement suggestions*
Station 2	Interpretation of paper drawings	Digital information carriers	Station 1	Software changeover time	Upgrade machine control unit
Stations 2 and 3	Measuring, cutting, positioning, and assembly of air and nailing studs around the roof section	CAD controlled laser positioning; CNC prefabrication of unique wooden studs	Stations 1, 2, and 3	Material handling	Further study on the task level to design a different layout
Station 3	Time-consuming material handling and positioning	Material storage above the work station	Station 3	Positioning of tools	Different layout
Station 3	Many manual operations	Better hand tools and machines and more operators	Station 5	Siding panels below the window units	Prefabricated siding panels
Station 7	Measuring, cutting, positioning, and assembly of siding panels around the roof section	CAD controlled laser positioning; CNC prefabrication of unique wooden siding panels	Station 7	Disassembly of electrical boxes	DFA

After looking through the recorded material, problems at critical work stations were identified. There were two problems related to station 2 on the ETO assembly line. The first was related to the interpretation of paper drawings when unique parts are to be assembled. The suggested improvement was acquiring the technology of digital information carriers to help operators obtain the operation instructions. The second problem, present in both station 2 and station 3, was related to operators measuring, cutting, positioning, and assembling air and nailing studs around the roof section of the EWE. These are the most complex elements that are assembled on the ETO assembly line. The suggested improvements were to aid operators in positioning of air and nailing studs using CAD controlled laser projection and to prefabricate these unique air and nailing studs using the CNC machine. The same type of problem and suggested improvements held for the siding panels at station 7. Two additional problems were identified at station 3: time-consuming material handling and positioning and many manual operations. The suggested improvements included repositioning the material storage above the work station and having better hand tools and machines as well as more operators working at this station.

The first problem at station 1 on the SV assembly line was related to the software changeover time between EWEs and garage elements. The suggested improvement was to upgrade the control unit so that this changeover could be controlled digitally without the loss of time. Material handling over long walking distances was the identified problem at stations 1, 2, and 3. The suggested improvement was to study the process further and work on a design for a different layout. The same problem and improvement was the positioning of tools at station 3. The problem identified at station 5 was related to the siding panels that are positioned below the window units. These siding panels are manually processed during the assembly process by cutting out the groove needed for positioning. The suggested improvement was the prefabrication of these siding panels with a CNC machine. Finally, the problem at station 7 was related to the disassembly of an already prefabricated electrical box unit during the assembly in order to complete the assembly of other parts. The suggested improvement was to redesign the EWE with electrical box units so that it can comply with the assembly line constraints.

4.3.Problem areas and types of waste

The results presented in this section are published in the third paper. The results were obtained after an analysis of the workshop discussions. First, problem areas were defined based on the observations, and then each observation was brought into relation with eight types of waste.

Table 7 Overview of the problem areas and their presence in the case companies in terms of number of observations.

Problem area	*Case a*	*Case b*	*Case c*	*Case d*	*Case e*
Material handling	4	2	2	1	1
Internal logistics	4	1	2	0	1
Assembly system	3	3	5	6	5
Work balancing	2	1	1	4	1

Four problem areas were defined: material handling, internal logistics, assembly system, and work balancing. The grouping of observations into problem areas and case companies is shown in Table 7. The problem areas were characterized as follows:

(1) Material handling refers to the activities of moving materials, subassemblies, and tools from their storage to the point of assembly. Operators must walk long distances to fetch materials, components, and/or subassemblies (all cases). A structure or replenishment of intermediate storage is not defined (a, b, and c). Here also included are issues of non-ergonomic activities that the operators perform during material handling (a). Working environment: issues caused due to a lack of systems that effectively collect dust and material and tool residuals.

(2) The internal logistics problem area is related to the material flow between different process groups within the factory. Problem instances can be related to the available capacity of resources such as trucks (a and b)

planning of work orders for trucks (a and c), truck route and factory layout (a, c, and e).

(3) Assembly system problem area refers to observations that occur in, or are related to, assembly processes, equipment, control, and operators. Physical and cognitive LoA in the assembly processes are relatively low and non-optimal, although the design process is performed using ICT tools that can provide CAD/CAM data to the production (a, d, and e). Another observation relates to the usage of paper-based drawings in the production while digital information is already available, making a prerequisite for a shift towards digital information carriers (a, d, and e). Some operations of the assembly process are non-ergonomic (d and e). Idle times on the assembly line are observed (c and d). Parallel support processes, which supply the assembly line with parts and components, produce more than needed (c), have a long setup time (e), could be part of the assembly process instead (b and c), and have an illogical positioning of machines (b and c). There is a lack of preventive maintenance (a and d) of machine resources. The assembly lines lack flexibility for special variants. This leads to double work on some parts since there is no other way to realize certain designs with the available assembly process (b, c, d, and e).

(4) In this paper, work balancing is referred to as unevenly distributed operations and tasks on the assembly lines for wall modules (all cases) or unbalanced productivity between all departments to form a whole product (house), causing bottlenecks (a and d) and thus having unnecessary work-in-progress. Companies are either producing parts in batches for intermediate storage or are ordering materials or subassemblies from suppliers in batches.

The second goal of the workshop was to associate observations to eight types of waste. The observations on the other hand rarely related to only one type of waste. The occurrence in the case studies was summed both per problem area and per type of waste.

By interpreting the numbers of waste observations in Table 7, it is possible to differentiate between types of waste and problem areas in terms of their significance. This is based solely on the assumption that eliminating waste can contribute to an improved resource efficiency (Liker et al., 2009). Below, the types of waste, in terms of their significance, are briefly discussed in descending order.

Table 8 Connection between problem areas and eight types of waste in case companies. Superscript is used to denote the number of waste observations per problem area if it is higher than one in a particular case.

	Over prod.	*Wait.*	*Trans.*	*Inapp. proc.*	*Unn. inv.*	*Unn. mot.*	*Def.*	*Unus . h. p.*	∑
Material handling			a^3, b, c^2, d, e	a	a^2, b, c	a^3, b, c^2, d, e		b	22
Internal logistics		a^3, b, c^2	a^2, c, e	a, b, c, e	a^2	c, e			18
Assembly system		a, c^2, d^2	b, c	a^3, b^3, c^5, d^6, e^5	c	b, c, d	d	b, c	36
Work balancing		b, c, d^3, e		a, d^3,	a	a, e			13
∑	0	17	14	31	8	15	1	3	

The waste of inappropriate processing (1) is present in the assembly system areas of all case companies and is, by the number of observations, the most significant waste identified. It points out that the processes of assembly, parallel support, and assembly control should be improved. As can be seen from the table above, the processes of internal logistics and work balancing can be done differently to improve the prefabrication efficiency.

The waste related to waiting, transporting, and unnecessary motions (2) are the second most significant group of types of waste, present in almost all case companies and problem areas. The waste of waiting is mainly related to work balancing, while the waste of transporting and unnecessary motions is mainly related to the area of material handling.

The waste of unnecessary inventory (3) is less present, while the waste of overproduction has not been identified. This might be explained due to the fact that all companies operate by orders, and the final products are always produced in the right amounts.

The waste related to defects and unused human potential (4) were two less significant types of waste. This can be dependent on how the primary data were collected and the research questions that were used. Since neither quality control nor human resources were the primary focus in the five case studies, the result in this study can be biased and not show the real significance of these two types of waste. However, the waste from defects in prefabrication processes was comprehensively covered in the study by Johnsson and Meiling (2009).

An interesting example of types of waste that occur concurrently is identified in the problem area of material handling. Since material handling is performed manually in most of the cases, the operators walk certain distances every time to fetch material from the intermediate storage, which is a repetitive waste of unnecessary motions. At the same time trucks are used to replenish materials in the intermediate storage. Therefore, the waste of transporting is present. Hypothetically, having systems for automatic instead of manual material handling would eliminate these two types of waste or at least decrease their impact.

Of all the problem areas, assembly systems are related to the highest number of waste observations, counting all types of waste in all the cases. This can be an indicator of a primary problem area in wall module assembly. The second significant problem area is material handling, followed by internal logistics and work balancing.

What is important to notice is that different types of waste and problem areas are interrelated. The change/improvement made in one problem area can cause either positive or negative changes in other areas. Likewise, eliminating one type of waste can lead to the elimination as well generation of another type of waste. Therefore, to optimize and improve certain parts of the prefabrication process, a holistic view is needed (Barker & Naim, 2004). The examples of related types of waste are overproduction and unnecessary inventory and waste related to transporting and unnecessary movements (Liker et al., 2009). Depending on the work organization, some operations done within the assembly process are, in other companies, included in the parallel support processes for assembly. To describe the interrelations between assembly systems and work balancing problem areas with types of waste, an example is given: shifting an operation that is part of an assembly sequence to be a parallel support for the assembly instead can possibly reduce the waste related to waiting and unnecessary motions, yet it can generate the waste of transporting, depending on the new physical location for this operation.

4.4. Discussion about the empirical studies

In this section the findings from the empirical studies are analyzed from the perspective of product variety, production volumes, and off-site manufacturing (OSM) system flexibility. The focus is on the applicability of the approaches and methods to the identification of the development potential.

The classification of LoA is closely related to the automation ability characteristic of RMSs. However, as only a few part variants are considered in the study, and there are no data regarding current or future product variety and demand, it is difficult to reliably determine the possible dynamic LoA that are characteristic of RMSs.

Considering the total count of operations found in human assembling and monitoring areas of LoA matrices, it is clear that the flexibility at the assembly line, both in functionality and capacity, is largely achieved through operators. The numbers of operators, as the most flexible resources in terms of functionality, were possible to determine from the video recordings. Although, another approach is needed to determine the productivity of operators when different wall variants are assembled.

By doing HTA and LoA analyses of the recorded videos of assembly line processes it is possible to document the occurring waste as well. That is why the findings of studies 1 and 2 served as input data, together with the secondary data of other case studies, in terms of observations for study 3.

Measurements of automation levels provide an analysis of both manufacturing systems and processes simultaneously. Also, they give insight into how the flexibility is achieved in all manufacturing system constituents, but only in the sense of whether it is achieved through highly flexible manual work or through machinery and numerical control. It is, however, not possible to document the exact range of functionalities or capacity of non-human manufacturing system constituents since only one EWE variant was followed through the assembly process.

However, an interesting example could be observed from the recorded material. On the ETO assembly line were two nailing machines, of which one was used for the nailing operation of the horizontal panels (station 6 in Figure 8) of the EWE (Figure 9) and the other used for the vertical panel nailing (station 5 in Figure 8) stood still. Therefore, not only did it stand still while the observed wall was assembled but it also stood still while all other EWEs from that project were assembled. Since the takt time at this assembly line is 30 minutes, and it is assumed that on average one project has 10 walls, the average time of one of these machines being still can be as much as 5 hours whenever the other type of panels is being assembled. In this case it is possible to classify both machines as being dedicated, i.e., having focused flexibility. Knowing that there are only two defined basic types of panels with two more variants, it becomes obvious that the product part belongs to the platform. However, instead of having one machine with adjusted functionality for these panel variants, the functionality is divided between two machines. This indicates that using automation level measurements is a good mapping technique to a certain extent but should be complemented with additional data in order to complete the information about functionality, capacity, product variants, and volume demand.

Another interesting observation from the first two studies is the inappropriateness of the SV assembly line, initially built and designed for garage walls, for the assembly of fully standardized EWEs. This is directly related to the problem of developing a dedicated system for only one part family and not considering future product development. The result is a paradox in the sense that the assembly process of a standardized product part where narrow range of functionality is needed must be supported with highly flexible manual work to compensate for the lack of functionality.

The HTA and LoA measurements and time studies presented in the studies 1 and 2 give a static picture of only several EWE variants. Since the assembly of other variants can employ additional operations, the balancing of assembly jobs between working stations can differ (Battini et al., 2010). An analysis of the manufacturing process when both process and product variability are considered is needed. Furthermore, EWEs are only one of several structural systems. The manufacturing systems and processes of all product parts, not only EWEs, should be taken into consideration to obtain a holistic picture of OSM in the case company.

An interesting example related to shared resources for part families can be given in relation to the outcome of the workshops in study 2. Analyzing the suggestions made for the ETO assembly line showed an indication of a need for a shared manufacturing resource, such as a CNC machine for the prefabrication of unique studs and panels that should be assembled around the roof section.

Using the workshop technique has shown to be useful when possible solutions for the critical operations are discussed. By presenting the analysis findings of the manufacturing processes and systems, the company representatives can relate these to findings from their own experience and point of view. This enabled engagement during the discussion about deciding on critical working stations and assembly moments and their possible improvement solutions. However, the participation of representatives from manufacturing system suppliers in such workshops can also be beneficial, as their knowledge about available technologies and the latest technological advances can contribute to the identification of the most relevant solutions.

Defining problem areas and mapping occurring types of waste in OSM systems and processes where human labor is used are important aspects for the development of OSM. Being aware of problem areas and being capable of weighing between them is important when focusing development efforts. Quantification is needed to bring solid facts forward. The approach in study 3, on the other hand, gives indication of problem area importance.

The occurring types of waste in processes, however, gives no input into the variability induced by product variants and process variation. Reducing waste and increasing efficiency and productivity are goals of every MC-oriented company, yet looking solely into the types of waste occurring in processes provides little input for the development potential.

4.5. Conceptual framework

Combining the frame of reference and the analysis of the empirical studies, the research purpose is addressed by formulating a conceptual framework for the identification of development potential in OSM systems in timber house building. The central focus of the framework is the alignment of OSM systems to the requirements of product design. However, not only product design but also production strategy, future demand and development, and OSM processes are taken into consideration as change drivers so that a comprehensive set of requirements for the flexibility of OSM systems can be identified. Critical operations can be identified using an analysis of OSM processes.

The framework is formulated by synthesizing methods from the theories of MC, changeable manufacturing systems and manufacturing system development. The goal is to discover the development potential of current

OSM systems. However, development potential can be considered not only for the implementation of changeable manufacturing systems but also for the DMSs if the requirements point to that need. Therefore, the development potential can be identified in the range between dedicated, reconfigurable, or flexible solutions. The framework is based primarily on the notion that modern manufacturing paradigms achieve responsiveness in terms of market demand by developing manufacturing systems whose constituents embody an adequate type of flexibility for the given product part produced (ElMaraghy et al., 2013; Terkaj et al., 2009). Three basic alignments at the system level are given, as follows:

High volume standardized product parts should be produced using DMSs: To produce a standard product part that is shared across all product variants, and that has stable and predictable demand, a manufacturing system does not need a high range of functionality but rather highly automated equipment that can reliably produce high volumes.

A variety of predefined and anticipated product parts of medium volumes should be manufactured using RMSs: For a variety of predefined product parts that can form different part families and that can also change over time, a manufacturing system that can reconfigure between current families and has the ability to reconfigure according to future demand in terms of functionality and capacity, with a minimum penalty in terms of cost and time, is needed. This system is characterized by customized flexibility.

Unique product parts of low volumes that are unpredictable with regard to future demand and development should be produced using FMSs: Product distinctiveness gives the highest value to the customer but lies outside the product solution space and therefore can have variable requirements for the manufacturing system in terms of functionality and capacity. In this case, a flexible manufacturing system that has a wide range of built-in general functionality and capacity is needed. Table 9 is given in order to visualize these three basic types of OSM system alignment.

Table 9 Examples of three basic types of OSM system alignment.

Product parts	*Requirements*			*Manufacturing system*	
Level of customization	*Variety*	*Volumes*	*Future demand*	*Type of MS*	*Type of flexibility*
Platform standard	Low	High	Predictable stable	DMS	Focused
Platform variant	Medium	Medium	Predictable or unpredictable variable	RMS	Customized
Unique	High	Low	Unpredictable variable	FMS	General

The conceptual framework consists of three parts: analysis, synthesis, and evaluation (Figure 16). In the analysis part, production strategy, future demand and development, products, current processes, and OSM systems are mapped and analyzed. Manzini et al. (2004) regard product, manufacturing process, and manufacturing systems as three manufacturing variables that play a crucial role in every step of the manufacturing system design process. In the synthesis part the basic design of a manufacturing system is formulated, which is then evaluated in the third step. The frameworks and methods for manufacturing system design found in the literature also include steps such as advanced/detailed design, its evaluation, and its implementation (Andersen, Brunoe, et al., 2017). However, as this conceptual framework aims at discovering the development potential, these steps are not included.

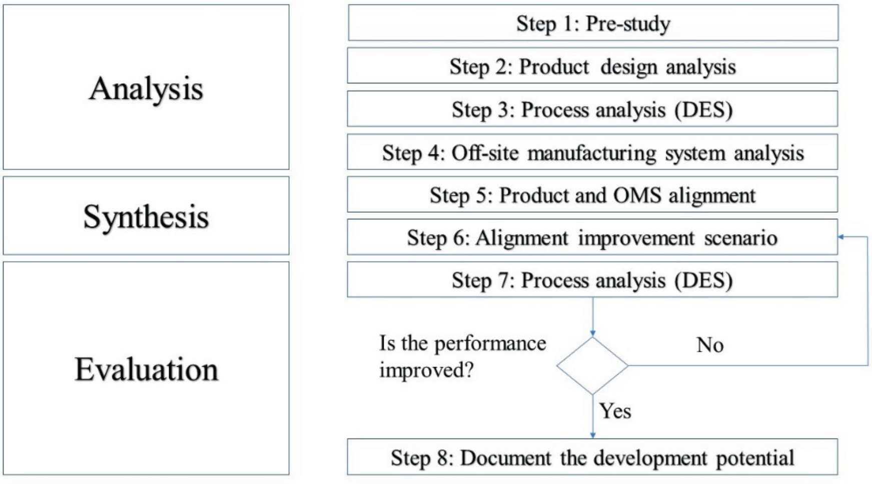

Figure 16 The three parts and eight steps of the proposed conceptual framework.

The analysis consists of four steps. **The first step** is a pre-study. The goal is to clarify the production strategy of a firm, current and future demand, and future development (Hvam et al., 2008). These are potential change drivers for the manufacturing system development (Wiendahl et al., 2007) and form one part of the requirements for OSM system design. Data regarding annual production volume, fluctuation of future demand, and the future plans of the firm regarding production strategy should be documented (Andersen, ElMaraghy, et al., 2017) to enable later quantification during synthesis and evaluation (Lotter & Wiendahl, 2009). Potential change drivers of a firm can be also related to demand volatility, product variety, and strategy.

The second step aims at product design analysis. The importance of realizing product design analysis has been advocated in many studies aiming at production system or process development for MC (AlGeddawy & ElMaraghy, 2009; Persson et al., 2009; Schoenwitz et al., 2017). What is meant here in regard to product design analysis is the mapping of the product platform, and the product uniqueness in case ETO or MTO production strategies are to be implemented. A platform can consist of standardized parts that are shared among all house variants and a range of predefined parts that are shared across many variants. However, unique parts should add the highest value to the customer and are project-specific due to the individuality of customer preferences. In the case of CTO and SV strategies, customization is not realized through uniqueness but rather through predefined distinctiveness embedded in the product platform.

Therefore, a description of a product (house) design on all structure levels is needed, where it is clear what is predefined (a platform) and what differs from project to project (uniqueness) (Lotter & Wiendahl, 2009). There are several ways of dividing a house structure into hierarchical levels found in literature (Bjork, 1990; Schoenwitz et al., 2017; Vibæk, 2013). However, in this thesis the following categories and top-down hierarchy for a building/house structure will be used: systems, elements, sub-elements, components, and materials. To illustrate each category, the following list is given with examples:

- Whole building/house
- Systems: roof, volume element, staircase, services, etc.
- Elements: floors, exterior, gable, and inner walls
- Sub-elements: window and door units
- Components: preassembled parts combining timber and rock-wool insulation that are, for example, joined together with windows to form a window sub-element
- Materials: timber studs and panels, insulation, etc.

Together with the analysis of product platform and uniqueness it is necessary to document both the relevant characteristics of each house structure, such as dimensions and bill of materials (BoM) data to enable the quantification of the house parts and to define the technical boundary conditions for a manufacturing system solution (Lotter & Wiendahl, 2009).

Documentation of part families within a product platform is another important aspect related to the potential development of RMSs. If the part families are not specified in the platform, the following methods can be used for their identification (Abdi & Labib, 2004; Manzini et al., 2004).

The data collection is realized through an analysis of a documented platform for the predefined house parts. Furthermore, information obtained from product data management (PDM) or building information modeling (BIM) systems provides input in terms of the house's uniqueness and BoM data (Andersson et al., 2009; Lidelöw et al., 2015). A good way of integrating and representing all the above mentioned data is by using the product variant master PVM method (Harlou, 2006; Hvam et al., 2008), which has already been used by several scholars in the context of house building (Kudsk, Hvam, Thuesen, et al., 2013; Malmgren et al., 2011; Thuesen & Hvam, 2011; Wikberg et al., 2014). The following analysis of processes and systems and the data obtained can be represented in the PVM model as well.

The third step is the analysis of the OSM process with the current systems in place by making process models and performing discrete event simulation (DES) analysis. According to Duray (2011), taking process variation into account when choosing a manufacturing system for MC is as important as product volumes and variety. Determining where changeability should be implemented when developing a manufacturing system is crucial (Schuh et al., 2009). Therefore, different levels should be considered in the analysis of the process. This should be done in a top-down manner starting from the segment level in the case where a firm assembles modular volumes in the factory, as described in Figure 17. Otherwise, if the modular volume assembly is done on-site, two process models should be created (system and cell/machine/workstation level). OSM (right-hand side in the figure) is decomposed into levels that correspond to the house structure levels (middle of the figure). Factory level in this context refers to the whole production process.

The goal is to identify the crucial operations and bottlenecks in the whole process that would facilitate the identification of development potential. Process mapping is needed so the process model can be created. The data can be taken either from IT systems if a company is documenting project lead times or manually by doing time studies. The data of a statistically sufficient number of projects should be collected to feed the model and perform DES analysis. The result of the first three steps is the set of requirements for the OSM systems.

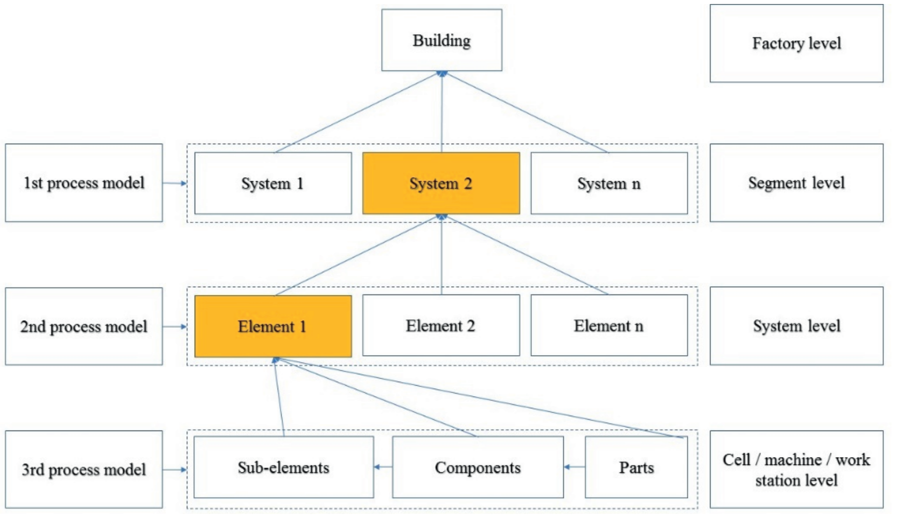

Figure 17 The scope of process models in the case where the firm has an off-site assembly of modular building volumes. The yellow rectangles represent examples of the house structures where a bottleneck can occur during their manufacturing. Levels of OSM (according to Jepsen (2014) and Benkamoun (2016)) are on the right-hand side of the figure.

The fourth step is the documentation of OSM system characteristics. Despite the fact that critical operations can be discovered during process analysis, the characteristics of all systems and their constituents in OSM should be documented. However, this implies that not all of the manufacturing systems would be included in the analysis as for some house parts manufacturing can be outsourced. The system and cell/machine/working station levels are in focus. The data from process mapping can be used to list all the OSM systems and related constituents. The manufacturing system constituents can be divided into physical and logical aspects according to Rösiö (2012), and they should be mapped and described as follows:

- Physical aspects: Is it an assembly line, cell, or machine? What type of machine or tool is it? How is material handling performed, and what are the number of operators? What layout of the system is needed?
- Logical aspects: How are planning and control executed? What are the instructions or machine codes?

Once this information is obtained, the functionality and capacity range of the existing systems and their constituents should be documented. Furthermore, the enablers of changeable functionality and capacity, i.e., modularity, integrability, and automation ability, should be taken into consideration when documenting the characteristics of the manufacturing systems in place. In this way, the flexibility of the current systems can be described.

The synthesis part of the conceptual framework consists of two steps (Figure 16). **For the fifth step,** the alignment of OSM systems with the requirements obtained should be established. In other words, the alignment of the functionality and capacity of the OSM systems in place is made with the requirements identified from the analysis of production strategy, current market, future demand and development, and predefinition/uniqueness of the house design. In this way, a mismatch can be identified.

In the sixth step, the identified mismatch can be used to create a scenario for an alignment improvement. In fact, several scenarios can be created where solutions for manufacturing systems embody the appropriate type of flexibility with the needed changeable or static functionality and capacity. The outcome of the third step, i.e., process analysis, can be used to focus on specific critical operations. A workshop technique can be used where both firm representatives and scholars should participate. Moreover, the understanding of different flexibility dimensions by manufacturing equipment suppliers is crucial as they have a great role in enabling changeability (Tolio et al., 2010). Therefore, the presence of supplier representatives during the workshop is suggested.

Deciding on flexibility type and its dimensions of functionality and capacity for the proposed solutions should be done according to the requirements identified in previous steps. There are several proposed ways of measuring and quantifying the flexibility of manufacturing systems found in the literature. Terkaj et al. (2009) proposed a method to analyze flexibility through an ontology of flexibility. Chryssolouris (1996) proposes methods to measure different types of flexibility that are relevant for manufacturing systems. He also derives an analogy between manufacturing and mechanical systems, where the flexibility of a manufacturing system is viewed similar to a dampening factor of a mechanical system. Maler-Speredelozzi et al. (2003) address the issue of quantifying the convertibility of a manufacturing system by proposing metrics for convertibility as a determinant of flexibility.

In the seventh step, alignment improvement scenarios are used to create new process models and perform DES analysis. This time a bottom-up approach should be used starting from the cell/machine/work station level up to the system or segment level in order to evaluate the proposed scenario's effect on the whole OSM process. The scenario giving the best result in terms of the OSM systems' performance should be used to document the development potential (8th step in Figure 16).

4.6. Discussion about the conceptual framework

The discussion in this section is related to the conceptual framework and comprises several aspects: manufacturing system flexibility, production strategy, possible issues with data collection, what the data analysis can lead to, how the framework can be used, and finally the automation.

Manufacturing systems are rarely absolutely reconfigurable, flexible, or dedicated. Most often it is a combination of these (Terkaj et al., 2009), and it is case-specific. In fact, there is no universal formula for the successful implementation of changeability.

The risk of having DMSs and FMSs that are fixed in terms of flexibility is a situation where changes in production volumes occur due to a change in demand or strategy of the firm. Therefore, consideration of reconfigurability and RMS is an important aspect due to the modularity and integrability characteristics that would enable a change in functionality and capacity by the addition or removal of modules (Lotter & Wiendahl, 2009). The question is whether it should be invested in general flexibility that can be used over time or in narrower focused flexibility and enablers of reconfigurability, so the system can evolve over time (ibid.).

The importance of considering the strategy and possible product development in the long term together with the current offering is highly important when reconfigurable solutions are considered. In the long-term development and changes that are foreseeable, the reconfigurable solution should have enablers of modularity and integrability. However, for short-term changes, the reconfigurable system should be optimized in terms of flexibility for the current product platform. Considering reconfigurability in the OSM systems of the single-family house sector offering catalogue houses can be potentially beneficial due to the highest degree of repetition regarding the relation between product variety and volumes (Johnsson, 2013).

It can be discussed whether engineer-to-order and select-a-variant strategies correspond to MC; however, in this thesis it is regarded that MC has no single form but rather can be implemented to different extents (Barlow et al., 2003) as long as there is predefinition of products, processes, relationships, and knowledge (Johnsson, 2013).

The availability of manufacturing data can be an issue when obtaining data for the DES study (Salama et al., 2017). If there is no feedback system, such as an overall equipment efficiency (OEE) system that constantly collects manufacturing data, then the data must be collected manually. Due to the number of observations that are needed to claim statistical validity, it can be a time- and resource-consuming process to collect these data. Moreover, the time required to build the process models and perform DES (Mostafa et al., 2016) adds to the complexity of this framework step. Another difficult task to perform might be mapping the product uniqueness. In the case where the company has an open building system, it might be a large variation of unique product parts.

The conceptual framework was formulated with the aim to be used both for the existing products and off-site manufacturing systems as well as for the design of the new manufacturing system of the newly developed building system. Furthermore, the application of the framework should also be possible in multi-family house building.

As the development potential might consist of reconfigurable and flexible solutions, this would lead to a larger reuse of resources, therefore contributing to the development of manufacturing platforms (Michaelis, 2013).

The analysis part of the framework can lead to the conclusion that the product design and solution space are not aligned with the strategy, therefore leading more towards product development than to OSM system development.

Even though it is the most important aspect of manufacturing system development (Manzini et al., 2004), the investment study is not included in the conceptual framework as it aims at discovering the development potential of OSM systems. However, it might constitute a solid background for such study.

Considering a solution that employs some form of automation, it must always be digitally supported by planning, control, and design systems. The pitfall can be that the automation can physically address the problem perfectly on the shop floor yet create even bigger problems at the other end of the production process, for example in the design phase. The more product customization is used, the more significant the logical part of the system becomes.

The framework can rather lead to the identification of hybrid solutions for particular OSM moments where both manual and automated work are employed. Therefore, merely considering full automation is not the goal but rather choosing optimal solutions based on the requirements for the system. However, there are manufacturing system suppliers that aim at developing almost completely automated robotic systems (Randek, 2017) not only for the prefabrication of plain elements but for the volume elements as well. These systems will possibly be integrated with CAD/CAM or BIM systems and would be capable of handling product variety.

4.7.Limitations

The theory presented in the frame of reference is not tied to a specific continent or country. However, the empirical studies were performed at one particular case company within the Swedish house building industry. The LoA measurements presented in study 1 are based on one observation at each EWE assembly line. The presented conceptual framework does not include investment analysis in the evaluation part but can be used as a solid background study where the next step can be an investment analysis. One limitation of the conceptual framework is that it is assumed that the product parts are manufactured/assembled in-house. Another limitation of the framework is that it is assumed that the product offering of the company is aligned with customer preferences.

5. Conclusions

In this chapter, the main conclusions of the research are outlined, and the theoretical and industrial contributions follow. Finally, comments about possible future research are given.

The research presented in this thesis is driven by the current need in the house building industry to further develop towards MC. From a theoretical perspective, it addresses the knowledge gap regarding the development of MC in timber house building. It represents an effort towards gaining a better understanding of how OSM can be developed in regard to being one of three main MC capabilities. More specifically, the purpose of this research was to increase the knowledge on how the development potential of OSM systems can be identified regarding MC-oriented timber house building.

The case study research method was applied, and theories of MC and changeable manufacturing systems were used to synthesize a conceptual framework for the identification of the development potential of OSM systems. The methods presented in the empirical studies are applicable for this purpose due to the possibility of obtaining the flexibility characteristics of the systems in the factory. However, these methods are not comprehensive enough due to the narrow and static focus on manufacturing systems and processes, without considering process and product variation. Instead, a comprehensive analysis of (1) the strategical and market aspects of the firm related to development in the future; (2) product design, where both product platform and customer-specific parts are mapped; (3) an OSM process analysis of all systems in the factory using DES; and (4) the OSM system constituents is proposed. In this way, the flexibility requirements of the future OSM systems can be obtained and therefore also the identification of possible solutions where the manufacturing system has the right type of flexibility for the given part family. This can lead to the identification of development potential ranging between dedicated, reconfigurable and flexible solutions. The identified solutions should be evaluated by means of process models and DES. Therefore, the quantification of manufacturing performance change when a solution is implemented can be obtained. The outcome of the framework provides a solid background for further investment analysis.

5.1. Research contributions

Theoretical contributions in this thesis were mainly made by applying existing tools, methods, and theories in a new context. Measuring the LoA of processes and systems in EWE assembly lines was the application of the existing framework in a new context. Moreover, the mapping of eight types of waste was, to the author's knowledge, applied for the first time in the context of single-family timber house building. The conceptual framework presented in the thesis is a synthesis of methods and theories presented in a frame of reference where changeability is for the first time put into the context of OSM. However, obtaining the requirements for OSM systems through the analysis of product platform and uniqueness is what differentiates this framework from other frameworks for manufacturing system design found in the literature.

As the house building industry needs further development and orientation towards MC, the role of research might be in paving the way by bringing up relevant methods, tools, and theories that can be applied in the industry. Concluding with the conceptual framework, this thesis presents a theoretical foundation and a synthesized stepwise way towards OSM system development. Moreover, the awareness raised in terms of different manufacturing system paradigms and types of flexibility and their connection to product variety and structure might be very useful in decision making processes when investments in OSM systems are made. Although the proposed conceptual framework has not yet been validated, it is to a large extent built on existing and industrially proven methods. Therefore, this thesis can serve as a set of guidelines for timber house building companies in their shift towards MC and better responsiveness to changing market conditions.

5.2. Future research

The logical research continuation would be the validation of the conceptual framework presented in section 4.5. The framework can be tested and validated in the main case company and, preferably, in other case companies as well. By applying the framework in different settings where other production strategies and other types of products are manufactured off-site, for example for multi-family timber houses, a better overview of how the OSM systems of Swedish timber house building can be developed towards MC.

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Appendix A: Search strategy

	Search strings			Inclusion criteria	#
1	"offsite production" OR "off site production"				11
2	"offsite manufacturing" OR "off site manufacturing"				6
3	"offsite fabrication" OR "off site fabrication"				16
4	"offsite prefabrication" OR "off site prefabrication"				9
5	"offsite construction" OR "off site construction"				44
6	(house OR building OR "construction industry" OR "construction company" OR "building industry") AND (preassembly OR pre-assembly OR prefabrication OR "prefabrication industry" OR prefab OR "prefab industry")				266
7	"prefabricated housing" OR "prefabricated house building"				11
8	"modern methods of construction"				29
9	(house OR "construction industry" OR "construction company" OR "building industry") AND ("system* building" OR "building system")	AND	"mass customi*" OR customi* OR modular* OR automat* OR lean OR agile OR leagile OR configur* OR reconfig* OR flexib* OR platform* OR "information technology" OR ICT OR BIM OR robot*	Type of publication: Peer reviewed journal articles Language: english	113
10	"building industry"				515
11	"home building" OR "homebuilding" OR "home building industry" OR "homebuilding industry"				61
12	"house building" OR "housebuilding" OR "house building industry" OR "housebuilding industry"				82
13	"industriali?ed building system" OR "industriali?ed house building" OR "industriali?ed home building" OR "industriali?ed construction" OR "industriali?ed timber house building" OR "industriali?ed building" OR "industriali?ed construction" OR "industrial housing" OR "industriali?ed housing"				97
14	(house OR building OR "construction industry" OR "construction company" OR "building industry") AND "built environment"				428
15	"mass housing"				26
	∑				1714
	∑ (after duplicate removal)				1492
	Removed after the first screening				1339
	Removed after the full-text screening				109
	Added from the backward citation search				14
	Chosen for the content analysis				58

Appendix B: LoA comparison between ETO assembly line and other case studies

	The case company	*Previous case studies*					
Companies	A	B	C	D	E	F	G
Production area	House building	Engine parts	Chemistry	Electronics	Cooling modules	Trucks	Vessels
Type of assembly	Line	U-cell	Line	U-cell	Job shop	Line	U-cell
Type of assembling	ETO	ATO*	ATS**	ATO	ATS	ATO	ATO
Number of stations	12	4	9	5	8	5	9
Average LoA_{Phys}	3	1	5	3	1	3	1
Average LoA_{Cogn}	1	1	5	5	1	-	1

*assemble-to-order
**assemble-to-stock