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How Additive Manufacturing can Support the Assembly System Design Process

PAPER WITHIN *Production Systems*

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Abstract

In product manufacturing, assembly approximately represents 50% of the total work hours. Therefore, an efficient and fast assembly system is crucial to get competitive advantages at the global market and have the right product quality. Today, the verification of the assembly system is mostly done by utilizing software based simulation tools even though limitations have been identified.

The purpose of this thesis is to identify when the use of additive manufacturing technology could be used in assessing the feasibility of the assembly system design. The research questions were threefold. First, identifying limitations that are connected with the used assembly simulation tools. Secondly, to investigate when additive manufacturing can act as a complement to these assembly simulations. Finally, to develop a framework that will assist the decision makers when to use additive manufacturing as a complement to assembly simulations.

The researchers used the method of case study combined with a literature review. The case study collected data from semi-structured interviews, which formed the major portion of the empirical findings. Observations in a final assembly line and the additive manufacturing workshop provided valuable insights into the complexity of assembly systems and additive manufacturing technologies. In addition, document studies of the used visualization software at the case company resulted in an enhanced understanding of the current setting.

The case study findings validate the limitations with assembly simulations described in theory. The most frequent ones are related to visibility, positioning, forces needed for the assembly operator, and accessibility between different parts. As both theory and case study findings are consistent in this respect, simulation engineers should be conscious of when to find other methods than simulation for designing the assembly system.

One such alternative method is the utilization of additive manufacturing. The thesis outlines a number of situations where additive manufacturing indeed could act as a complement to assembly simulation. The authors argue that the results and findings to a large degree are applicable to other industries as the automotive sector is very global and competitive in nature and encompasses a large variety of complex assembly operations.

A structured framework was also developed that could act as a decision support. The framework takes into account three dimensions that are crucial for the decision; (1) the assembly simulation limitation, (2) the context of the assembly and which parts are involved and (3) the possible limitations of additive manufacturing in the specific context. This impartial decision framework could help companies with complex assembly systems to know when to use additive manufacturing, as well as for which parts and subparts additive manufacturing is applicable. To increase the longevity of the decision framework, new improvements of assembly simulation tools and additive manufacturing technologies, respectively, should be incorporated in the framework.

Keywords

Additive manufacturing, AM, 3D-printing, assembly simulation, production system development, manufacturing engineering, path planning.

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1 Introduction

This chapter begins with a background and a description of the problem. It then states the purpose of the study and formulates the research questions. Finally, the delimitations and the outline of the study are described.

1.1 Background

In order to stay competitive in the global business environment, the industrialization process has to be effective and efficient. It also needs the ability to rapidly make changes and improvements to deliver high quality products in a shorter time (Choi, Chan & Yuen, 2002). To achieve this, the product development process and the production system development process need to be synchronized, and their interaction seamless (Twigg, 2002). Various methods and tools are being used to develop this competitive industrialization process (Berman, 2012). The purpose of an assembly system design is to maximize the relationship between throughput and the necessary costs (Bukchin et al., 1997).

The introduction of Computer Aided Engineering (CAE), and Computer Aided Design (CAD), during the second half of the 20th century was a revolution for the industrialization process and especially for product development. By using CAE software, Ford Motor Company cut the time to market by a third (Braunstein, 1999). CAE simulations are nowadays three-dimensional and used in product development as a tool to validate and analyze the design of the product from different perspectives and requirements.

In production, simulations have been used to validate product design and manufacturability as well as to ensure that products can be assembled without complications by identifying collision-free assembly paths and ergonomics for the operator (Gupta et al., 2001; Longo & Mirabelli, 2009). The advantage of using simulations is the time savings, which is achieved by minimizing the use of expensive physical prototypes (Seth et al., 2011). The digitalization of all manufacturing supporting tools, including simulations, is a part of industry 4.0 and a strategic part of the future industry, as a way to become more efficient by the use of IT-systems, automation, and intelligent manufacturing (Lasi et al., 2014).

The invention of Additive Manufacturing (AM) technologies that made it possible to print parts and components in real physical form, based on CAD drawings, was a recent revolution for the industry (Berman, 2012). AM technologies allow complex products to be manufactured in practically any shape in three dimensions. AM uses layer-by-layer technique, which makes it possible to print and manufacture parts and details without involving other complex and traditional manufacturing processes. The key advantage of using AM is the simplicity of printing out functional parts designed in CAD and simple objects are printed in less than one hour (Mawale et al., 2016; Berman, 2012). The application of AM in different industries has rapidly increased during recent years. Mawale et al. (2016) present a percentage utilization of the use of AM in different industries, presented in figure 1. The automotive business is among those that utilize this new technology the most.

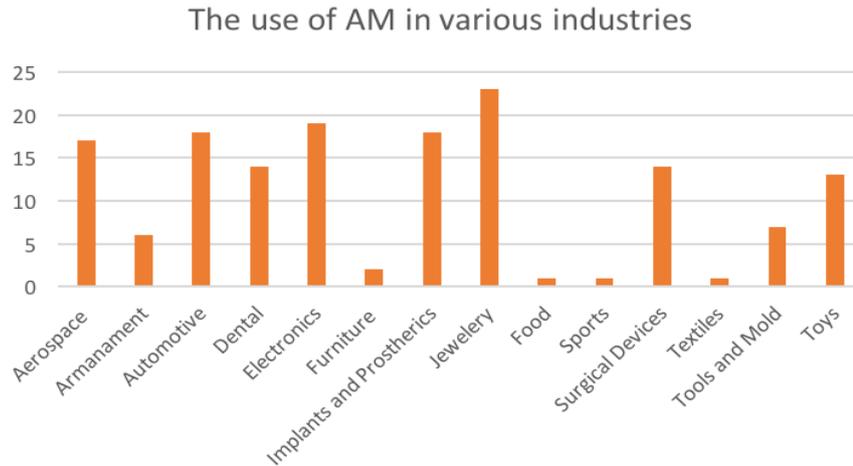


Figure 1: The use of AM in various industries

Since AM was first introduced, the evolution and improvements of 3D printers have mainly been focused around four areas: lower cost, more options for materials, colors and surface finishes or higher precision, and higher strength (Berman, 2012). As 3D printing equipment and technologies are being developed, possible applications are expanding and the opportunity to apply additive technologies in process areas other than product development are emerging. Parts, whether prototypes or final assembly parts, can schematically be used in five different areas within the industrialization process, as illustrated in Table 1.

Table 1: Usage of 3D manufactured prototypes and parts.

<u>Industrialization Area</u>	<u>Phase</u>	<u>Part type</u>	<u>Usage, examples</u>
Product Development	Design	Prototype	Functional testing
Manufacturing	Design	Prototype	Test of production system
Manufacturing	Production	Final Assembly Part	'Bridge manufacturing'
Manufacturing	Production	Final Assembly Part	Low volume production
Manufacturing	Production	Spare part	Production equipment

The focus of this study will be on AM prototypes in the assembly system design phase and how the usage of such prototypes can be complementing insufficient computer simulations of the same process.

1.2 Problem description

The design of the assembly system has to be initiated already in the product design phase to minimize time to market, to minimize the manufacturing cost and to increase the quality of the final product. In addition, the vast majority of the cost of production system design is related to decisions taken up-stream in product development (Pham & Gault, 1997).

To evaluate an existing production system design or when designing an all-new one, verifications need to be done so that parts can be assembled without complications in the running production. Extensive reviews of the involved products and its components as well as the production system details are required in advance of production start (Selvaraj et al., 2009). Conceptually, these reviews are included in the product development and goes under the terms Design-For-Manufacturing (DFM) and Design-For-Assembly (DFA) or, collectively, DFMA (Selvaraj et al., 2009).

Previously, the DFMA evaluations had to be done by using prototype parts that were often hand-made and therefore expensive and requiring long lead times (Seth et al., 2011). Also, the production system itself was often a mock-up, a pilot plant that did not sufficiently replicate the future real production environment in the plant. These deficiencies led to missed opportunities in improving the production system and, even worse, that the production system itself had to be re-designed later on in the industrialization process.

Recently, assembly simulation software has been developed to identify incompatibility problems between the product design and the production system design (Wang, 2016). Assembly simulation, or assembly motion simulation, is becoming a key component during the conceptual product design phase to discover potential issues in the assembly. It is also used to increase the efficiency in the assembly (Wang, 2016). This typically exposes design flaws and incompatibilities, either in the product or in the production system that for instance might cause collisions in the final assembly. Also production system simulations of the ergonomic aspects of assembly are evaluated. Furthermore, visualizations of the layout and work procedures can be simulated so that a more efficient and effective plant layout may be designed (Yang et al., 2013).

There is a number of software currently available on the market that deals with assembly feasibility, i.e. that the assembly of a product is viable. A simulation tool for evaluation of virtually validating the assembly system in advance is Process Simulate by Siemens. It is aimed at planning the movements, reachability, and placements of robotics (Siemens Process Simulate, 2016). A visualization and digital mock-up is the PLM Visualization tool. It creates virtual prototypes from several CAD systems to assess ergonomics in the manufacturing process (Siemens Visualization, 2016). Another software is the IPS Path Planner, which is used to assess feasibility for automatic assembly and disassembly. It is capable of calculating automatic assembly paths, the envelopes required for assembly and to assess clearances (Industrial path solutions, 2016). The IPS software is a tool specifically targeting the assessment of assembly feasibility and thus specifically appropriate to address the problems described in this study.

Like any software that aims at mirroring a real-life product and production environment, the computer-aided simulations contain flaws and limitations. In product development, even though simulations and software are steadily improving, this requires that physical tests still have to be executed. An example in the automotive area is the development of vehicle crash safety where computer simulations and real physical crash tests are complementing each other (Thomke, 1998).

In the design of the production system, simulations also can exhibit limitations in the ability to evaluate the feasibility and effectiveness of the assembly. Also, if undetected, software bugs will cause problems with product design and assembly misalignment and can occur as late as in the ramp-up of the production. When problems occur this late in the industrialization process, the production cost becomes very high, due to that investment in fixtures and tools have already been made and are expensive to change (Boothroyd, 1994). Furthermore, opportunities to use more effective production and assembly methods can be missed due to the simulation software deficiency.

The understanding of assembly simulation deficiencies, their severity and their frequency, needs to be surveyed. Also, the possible complement of using AM parts in the assessment of the assembly system has to be better comprehended. To take the right decision regarding when actually AM produced parts could assist and complement the assembly system design, a decision framework is needed. Currently, no criteria are defined for this type of decisions (Lindemann et al., 2015).

1.3 Purpose and research questions

An efficient and feasible assembly system is of key importance when designing the production system. The aim of this thesis is to investigate the possibilities of using AM as a complement to simulations in assembly system design.

The following research questions should be answered:

RQ1: What are the limitations of using assembly simulation tools in assembly system design?

RQ2: How can additive manufacturing be a complement to assembly simulation in assembly system design?

Once the limitations with assembly simulation tools are identified and the possible use of AM is considered, a framework can be developed to provide the contextual decision support in order to make the right choices.

RQ3: How can the decisions be supported by an AM applicability framework?

1.4 Delimitations

This report will exclude the usage of 3D parts in two areas. First, prototypes in product development and, second, final components in manufacturing either used for final assembly or for production equipment spare parts.

1.5 Outline

Next, in the second chapter, the theoretical background is presented. Covering the different areas needed in order to make connections and conclusions with the subsequent chapters. The methods used are described in chapter three and will show how the study has been structured and performed. The fourth chapter covers the findings of the study, both from the observations and interviews as well as from the literature review. This chapter also analyzes the presented findings. The discussion chapter will discuss the chosen methods and the findings. The thesis finishes with conclusions and briefly summarizes the main points.

2 Theoretical background

This chapter will present the theoretical framework of this study. It begins with a presentation of design for manufacturing and assembly, as well as design for additive manufacturing. It continues with an explanation of the concept of assembly simulation and how this tool can virtually validate the assembly system. Also the current limitations of this technology are discussed. Then, a description of additive manufacturing is provided, including current technologies as well as future possibilities and technological advancements. This chapter ends with a table that structures the theoretical background including the references that will be used as a basis for the empirical analysis.

2.1 Design for manufacturing and assembly

Product design is the first step in manufacturing and in the product realization process. Therefore, the most important decisions about the product and its design is taken this early, and will affect the whole process. If decisions regarding design and functionality are taken without having manufacturing in mind, these decisions often result in delays in the final product release (Boothroyd, 1994).

Design-for-manufacturing and design-for-assembly (DFMA) are concepts of designing products with manufacturing as a priority as early as possible in the process. The purpose, and the goal, of using DFMA is to facilitate the manufacturing processes and reduce cost and time to market (Boothroyd, 1994; O'Driscoll, 2002). Furthermore, O'Driscoll (2002) claim that the quality increases by using these concepts.

The importance of the two concepts, introduced as early as in the 18th century, is today even greater than it was 200 years ago. With a high competitiveness in the global market and customers requiring higher quality, more complex products, larger volumes of products, and higher customization, this results in the need of lower production and assembly costs (O'Driscoll, 2002). As mentioned earlier, DFMA should be applied early in the development process to minimize the number of different parts and components to facilitate the assembly and manufacturing process (Barbosa & Carvalho, 2013).

The list below is the DFA criteria as outlined by Kuo et al. (2001):

- Minimize the number of parts, fasteners, variants, assembly movements and directions.
- The design should provide easy access for locating surfaces, simple handling and transportation, and symmetrical parts.
- The design should avoid difficult fitting operations, difficult adjustments, and avoid possibilities to assemble parts wrong.

The two concepts have been very influential in the industry and many organizations have adopted the principles of DFMA with success (O'Driscoll, 2002), (Boothroyd, 1994). According to O'Driscoll (2002), the possibilities by implementing DFMA in the product development are:

- Reducing assembly operations by 53%.
- Reducing time to market by 50%.
- Cutting assembly time by 61%.
- Reducing defects in assembly by as much as 68%.

2.2 Design for Additive Manufacturing

Several opportunities have been identified by using additive manufacturing, for example decreasing tool cost, production of complex shapes, as well as increasing the functionality of the products (Laverne et al., 2015).

As mentioned in the previous chapter, DFMA is a methodology for designing products considering constraints and capabilities of the manufacturing processes. The first phase of the manufacturing process is the design of the product. A design that does not consider the manufacturing and the assembly consequences will unavoidably lead to an ineffective and inefficient manufacturing process. Thus, manufacturability aspects have to be evaluated as early as possible in the design phase. Since additive manufacturing is developing into final product manufacturing, there is a demand for a method that considers the manufacturability of additive manufacturing with the product performance. Without this alignment, the additive manufacturing technology would not be fully utilized. This new method can be called Design For Additive Manufacturing, DFAM (Ko et al., 2015).

According to Rosen (2014), the purpose of DFAM should be, unlike DFM, to “maximize product performance through the synthesis of shapes, sizes, hierarchical structures, and material compositions, subject to the capabilities of AM technologies”. When deciding to produce a product by additive manufacturing or not, the first thing to identify is whether that product can be produced more economically by a conventional manufacturing process. If so, additive manufacturing may not be the most beneficial method. However, if the product possesses complex geometries or will be produced in smaller volumes, additive manufacturing could be more favorable (Rosen, 2014).

As additive manufacturing is a relatively new manufacturing technology, a methodology for decision-making regarding the selection of additive manufactured parts is missing and much needed (Lindemann et al., 2015). The key question in additive manufacturing, to be successful and achieve financial benefits, is to be able to tell which parts to produce. Consequently, Lindemann et al. (2015) presents a workshop concept for part selection. The purpose is to support inexperienced users when taking decisions about which parts to produce with additive manufacturing technology. This workshop concept consists of three main phases.

The first one is the information phase. Here, the AM technology is presented to the ones being involved. Using product examples, the different advantages are introduced and technical limitations are described. The aim of this phase is to provide a necessary understanding of the technology, since the target group consists of representatives without this knowledge. Assessment is the second phase and during this, the number of gathered parts should be reduced and ranked together with AM experts and part owners. The outcome of this phase is a first selection of appropriate parts. The final and third phase is the decision phase. The goal here is to identify specific parts that signify the biggest advantage for additive manufacturing.

2.3 Assembly simulation software tools

Assembly simulation tools have during the past decade developed to be a very important tool to analyze and ensure a competitive product design within the manufacturing industry. Path planning, within assembly simulation, refers to the planning and position of the installed parts and subparts from the storage (start) to the final position (goal) at the product (Liu Xinhua et al., 2011). A prerequisite for path planning is the existence of a collision free start and goal for the part which

should be assembled (LaValle, 2006). The assembly is based on CAD parts, and no physical prototypes are needed (Liu Xinhua et al., 2011). New software automatically finds paths for the assembly operation, and only requires a start and a goal for the part, which are to be assembled, illustrated in figure 2 (Industrial path solutions, 2016). The software will automatically find a collision free path and detect critical clearances, which can cause problems. Certain parts can be difficult to path plan, due to tight and complex design, and this require the simulation engineer to glide the part on surrounding surfaces to reach the assembly goal (Industrial path solutions, 2016).

The assembly simulations cannot only detect compatibility problems, it also enables finding new opportunities in the design of the product (Da Silva et al., 2013). Opportunities can e.g. be to use an easier and faster assembly process by finding product design errors and assembly compatibility errors or the operation itself (Martín et al., 2013). Regarding simulation for assembly, the most important advantage is to find and eliminate collisions between parts, i.e. to find collision free assembly paths to facilitate the assembly process (Zhang et al., 2015). In figure 2 an assembly simulation of a tunnel bracket in a car, is shown.

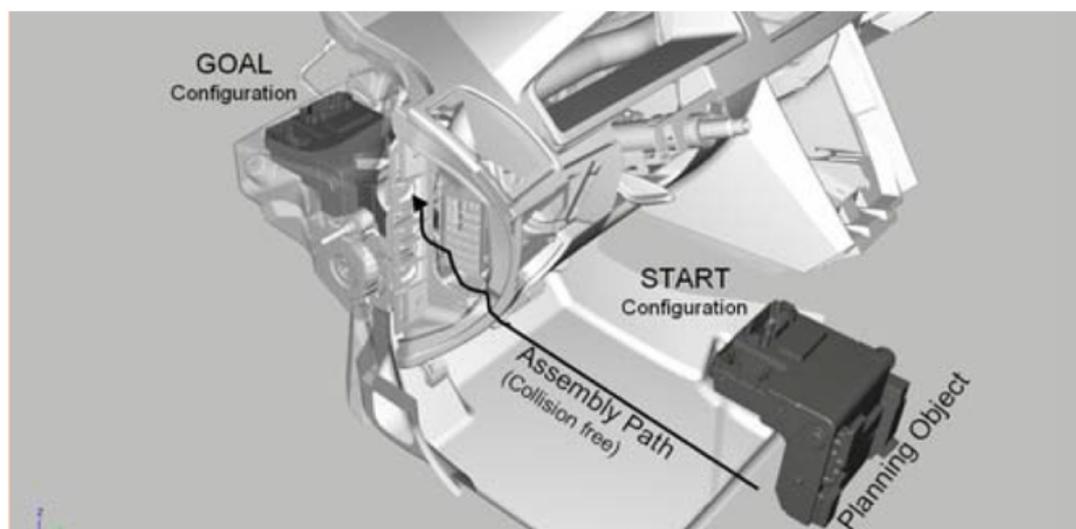
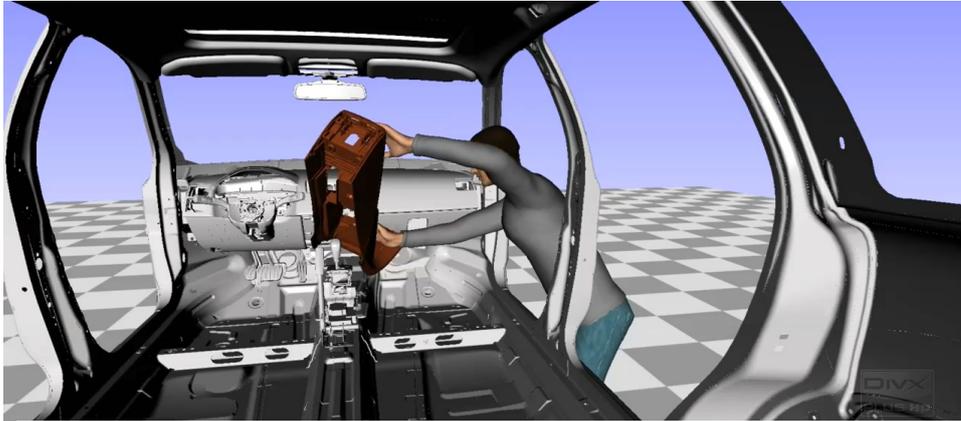


Figure 2: Assembly path planning with start and goal.

Customized products and shorter product development processes make it difficult to verify assembly ergonomics with traditional physical prototypes. This is due to the time it takes to build physical prototypes, therefore simulation has been used to verify more complex products with less material and energy consumption (Martín et al., 2013).

Ergonomics in assembly systems is also seen as a central part of the quality assurance. Numerous researchers have found a relationship between ergonomically problems and quality outcome in assembly (Lämkuil et al., 2008). A high physical load in assembly processes results in higher quality errors compared to a lower level of physical load (Falck et al., 2012). Falck et al. (2012) claims that the level of complexity in operations also affects the quality outcome.

More complex operations are related to a higher degree of quality problems than less complex operations. Therefore, it is crucial from an ergonomic and quality perspective, to find and eliminate high physical load in assembly operations. Since physical prototypes are time consuming and expensive to use (Martín et al., 2013; Seth et al., 2011) simulation for ergonomics are used to shorten the development process and save time (Dukic et al., 2007). In figure 3, a simulation is used to evaluate the ergonomics for an operator.



<http://www.fcc.chalmers.se/software/ips/ips-imma/>

Figure 3: Manual assembly simulation of a tunnel bracket.

In simulation tools, ergonomics includes portions to verify and predict the fit, clearance, reach, and sight for the operator (Dukic et al., 2007). Even though time and money can be saved by the use of simulation to verify ergonomics and production system compatibility, there are drawbacks and areas, which are difficult to evaluate in simulations. Dukic et al. (2007) and Lämkkull et al. (2009) show in their study of simulation for ergonomic assembly different areas that are difficult to judge in simulation, these are:

- Reach distance
- Space needed for hands during assembly e.g. accessibility
- Hand access
- Pressure and pull forces
- Simulate different forces and sound, e.g. torque and traction
- Virtual data without references to the reality
- View

Beyond these areas, which were identified in the study, Dukic et al. (2007) found that the judging of how complex different operations would be for the operators depended on the simulation engineer, which also is described by Germanico Gonzalez-Badillo et al. (2014). The simulation engineer's knowledge and experience influenced the assessment of complex operations and the decision whether the assembly is appropriate or not. Furthermore, Germanico Gonzales-Badillo et al. (2014) describe the importance of force feedback in simulations, which has improved the accuracy in position and collision in virtual assembly. The importance of force feedback has also been identified by Gupta et al. (1997), Lim et al. (2007), Xia et al. (2013), and Lawson et al. (2016). Even though this research is related to Virtual Assembly and simulation,

it demonstrates the importance of getting knowledge and feedback of the forces involved in an assembly operation.

2.4 Additive Manufacturing

The additive manufacturing (AM) technologies allow complex products to be manufactured using layer-by-layer techniques. The key advantage of using AM is the simplicity of building functional parts designed in computer-aided design (CAD) (Mawale et al., 2016). The AM technologies are constantly developing and the application areas are expanding. In the production process, these technologies can be used to assess human interaction (Gardan, 2015). Depending on the requirements and the future use of the parts, materials such as polymers, thermoplastics and metallic powder are used (Mawale et al., 2016).

In the next two subsections, different AM technologies are described as well as the current general limitations.

2.4.1 Additive manufacturing technologies

Today there are several variants of AM technologies and new ones are constantly evolving. In principle, however, four different categories can be distinguished depending on which basic technology is being used: laser, flash, extrusion, and jet technologies (Gardan, 2015). Each category is explained below in more detail.

Laser technologies

Three subcategories can be found within laser technologies and are described below and shown in figure 4.

SLA – Stereolithography is an early technique developed in the mid 1980's and is today one of the most commonly used AM technologies (Gardan, 2015). The SLA method is using photopolymerization, a process in which light, a laser beam, is scanning a photopolymer surface to selectively solidify photosensitive resins. After the first layer is shaped, the process is again repeated (Yang et al., 2016).

Recently, researchers have been applying SLA to make ceramics directly (Griffith et al., 1995). These parts will have a higher stiffness than a standard part and they can also resist temperatures up to 200°C. To obtain parts with a higher accuracy, micro-SLA methods can be used. This allows precise fabrication of complex microstructures in 3D (Zhang et al., 1999).

SLM – Selective Laser Melting. A metal powder material is spread using a roller to provide an even surface. A laser beam then fuses this powder at pre-determined spots from the software design data. This process is repeated and the material is bonded with the previous layer. Materials processed include steel, stainless steel, cobalt chrome, titanium and aluminum (Gardan, 2015).

SLS – Selective Laser Sintering. Here, the powder is not melted, as is the case for SLM, but is only heated with a laser to a temperature so that the surface tensions of the grains are overcome and the powder can fuse together on a molecular level. This way, the thermal distortion is minimized (Pham and Gault, 1997). Materials used include polyamide, steel, titanium, alloys and ceramic powders. Several of these materials are cheap, non-toxic and require only low-powered lasers. However, the final parts must be subjected to an extensive cooling time. Also, the porosity of the material can be controlled but requires a post-treatment to harden the final part.

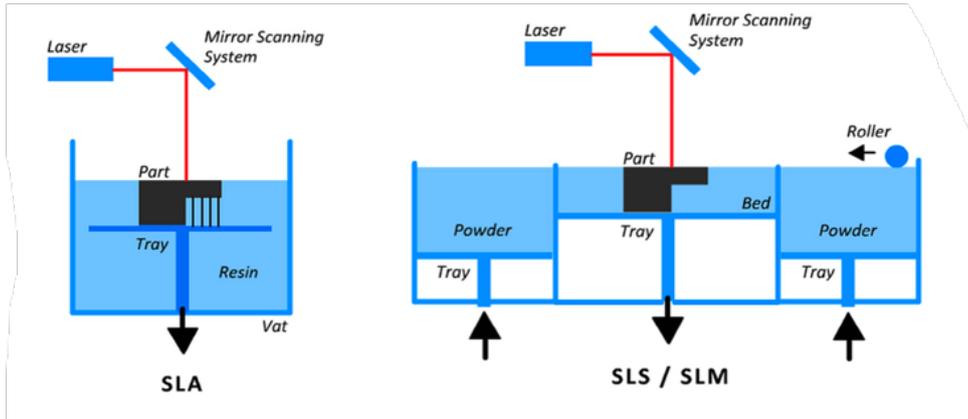


Figure 4: Description of SLA and SLS/SLM (Gardan, 2015).

Flash Technology

As an attempt to reduce lead-time and increasing the build speed, DLP – Digital Light Processing, has been developed from the SLA technology. This new technology, also known as FTI – Film Transfer Imaging, uses photopolymerised materials, where a film is covered in resin and then exposed to a UV flash of light from a projector, layer by layer, hence the name ‘flash technology’. Different from the laser printer, the DLP projector targets the complete layer and not just lines or points. Because of this, the DLP/FTI method avoids the more time-consuming scanning time of a laser and thus becomes much quicker than other methods (Gardan, 2015). Figure 5 shows schematically a DLP/FTI process where the building platform is angled upwards and where the light source is angled downwards.

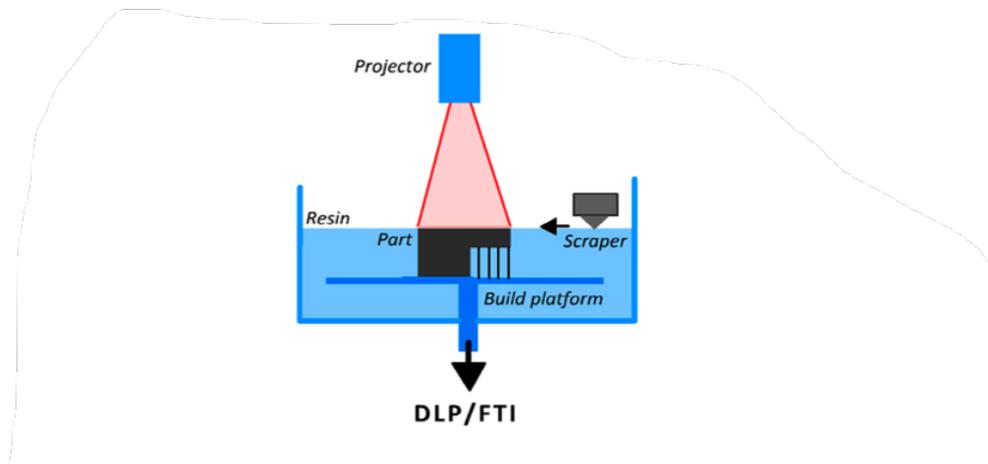


Figure 5: The process of making DPL/FTI parts by using flash technology (Gardan, 2015).

Extrusion technologies

FDM – Fused Deposition Modeling is a layer additive manufacturing process using a thermoplastic filament. The most commonly used materials are ABS, PLA and PC. The filament is extruded through a heated nozzle to build each cross section of the part, figure 6. The nozzle is then moving up vertically to repeat the process for a new

layer. This process has become the most used in the low cost segment. A disadvantage, however, is that the resolution is comparatively crude, 0.25 mm, and that it is also very time consuming, frequently taking days to build one complex part (Gardan, 2015).

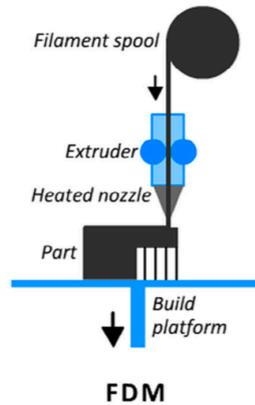


Figure 6: Description of FDM process (Gardan, 2015).

Jet technologies

MJM – Multi Jet Modeling uses two different photopolymer materials; one for the actual part but also one for supporting the structure. Droplets of the materials are deposited with several jets. Layers are built until the final part is ready. UV lamps are used to cure the material. The gel-like support polymer is removed by a water jet (Gardan, 2015).

Another method is the 3DP – Three-Dimensional Printing and also known as CJP – Color Jet Printing. A layer is produced by spreading a thin layer of powder, by the help of a roller, the powder is then selectively merged by inkjet printing of a binder. Repeatedly, the build tray goes down to make the next layer. Using colour cartridges, 3D printers can manufacture coloured parts directly (Gardan, 2015).

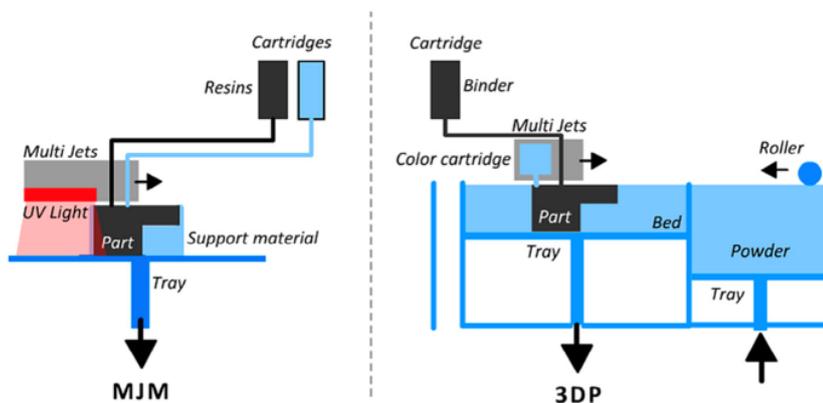


Figure 7: Description of MJM and 3DP process (Gardan, 2015).

2.4.2 Current general limitations with additive manufacturing

Even though the benefits of AM are many and the technology is constantly developing, there are also some challenges associated with the use of AM. The most important ones, in general terms, are described below.

Shape optimization

It is important to optimize the shape of the part with the functional and/or design specifications of the 3D-printer in mind. This will have a significant impact on manufacturing of the part, how much material has to be used and the time consumption needed for producing the part. In addition, the required energy costs are influenced by the shape and in the end the cost of production of the 3D-printed object (Oropallo & Piegler, 2015).

Pre- and postprocessing

Not all 3D-printers produce completely finished parts directly, but may require both pre processing as well as post processing, including for instance actions like removing supports, improve surface quality, or complete some features. Both pre and post processing bring challenges that affect the process of additive manufacturing (Oropallo & Piegler, 2015). Poor dimensional accuracy, in relation to conventional processes, may lead to significant and expensive requirements for post processing (Baumers et al., 2015). The limited surface finish and part resolution are particular downsides of the material extrusion technology category, e.g. FDM (Gao et al., 2015).

Printing methodologies

There are several methodologies and techniques to use when producing parts with AM technologies and they all have specific advantages and disadvantages. The choice to use the one or the other may have substantial effects on the mechanical or physical properties of the product (Oropallo & Piegler, 2015).

Error control

Every manufacturing process includes occasional errors, which also applies to AM processes as some of the current machines that are available lack quality control systems. The errors can be divided into three categories; data preparation, process errors, and material errors. The latter two are difficult to avoid and error correction may be a better solution (Oropallo & Piegler, 2015). Build failure and quality issues can lead to increased costs associated with process predictability and repeatability (Baumer et al., 2015).

Build Materials

Currently available build materials are limited and using non-standard materials inevitably leads to higher costs (Baumers et al., 2015). For SLA technology based AM, there is a high material cost (Gao et al., 2015).

Multi-material printing

When it comes to printing parts that only consist of one material, there is a vast variety of different options to choose from, but when parts comprise multiple materials, the selection is more limited (Oropallo & Piegler, 2015).

Hardware and maintenance issues

Similar to the challenges with error control, the current machines that are available are not flawless and require maintenance. This could for instance include issues associated with materials or specific processes. Therefore, it is necessary to have

regular quality checks to ensure the excellence of the operations, which could be both time consuming as well as disrupting the manufacturing processes (Oropallo & Piegl, 2015).

Cost effectiveness

When the required volume increases, i.e. medium to high production volumes, the process economics become unfavorable and the cost effectiveness decreases (Baumers et al., 2015)

Part orientation

The orientation of the part can be changed by either altering the CAD model or even the STL file. This is done to maximizing, or minimizing, one or several manufacturing outcomes such as the time it takes to build that part or what level of quality is required. Depending on the purpose and how the part is to be used, one can choose a part orientation that meets certain requirements at the expense of other properties. Anisotropic parts obviously require careful consideration of the part orientation. In some cases, the process itself might put considerations on the orientation (Oropallo & Piegl, 2015).

Slicing

Processes belonging to the layered manufacturing techniques require that the computer file could be divided into slices in order to manufacture the part. In order to find the best geometry of the slices, the part is intersected with horizontal planes. The thickness of the layer determines the height of the slice and the most common method of slicing is when all the slices have the same layer thickness. Occasionally, the slices change vertically from the original geometry and causes problems such as reduced surface quality and poor accuracy (Oropallo & Piegl, 2015).

Speed

The manufacturing time of a part can for every process be a limiting factor, although AM in some cases can be seen as faster due to the short set up time and its ability to produce the whole part at once. The complexity of the part and process complexity are related to the planning time, which can both be time consuming and challenging (Oropallo & Piegl, 2015). A slow process speed increases the indirect costs (Baumer et al., 2015).

Design for additive manufacturing

In order to fully utilize the capabilities of AM, the design process needs further development. For instance, the current CAD software was not initially designed with the thought of AM. The bottleneck of the CAD software is the geometric complexity and operations on a large number of features. Since the choice of materials is still limited with AM, other manufacturing processes may be more suitable. In addition, due to the rapid development of AM technologies, the learning curve becomes very steep, hence the designers need to be up to date with the developments and quickly adapt to the changes.

2.5 Theoretical framework

In table 2 below, the theories in this chapter are summarized and structured for assembly simulation and additive manufacturing technologies. This provides the first step towards a conceptual AM applicability framework.

Table 2: Theoretical framework.

Hierarchy 0	Hierarchy 1	Source	Hierarchy 2	
Assembly simulation	Compatibility		Physical incompatibility	
			Boundary conditions	
			Positioning	
	Ergonomic	Dukic et al., (2007), Lämkkull et al., (2009)	Visibility	
			Accessibility	
		Dukic et al., (2007), Germanico Gonzales-Badillo et al., (2014), Gupta et al., (1997), Lim et al., (2007), Xia et al., (2013), Lawson et al., (2016)	Forces-traction	
			Forces-torque	
			Forces-pressure	
			Over shoulders	
			Strenuous motions	
			Heavy lifting	
			Boundary conditions	
		AM Technology	Oropallo & Piegl, (2015)	Size and shape
			Oropallo & Piegl, (2015), Baumers et al., (2015), Gao et al., (2015)	Build material(s)
Oropallo & Piegl, (2015), Berman, (2012), Baumers et al., (2015)	Manufacturing time			
Oropallo & Piegl, (2015), Baumers et al., (2015), Gao et al., (2015)	Pre- and postprocessing			

3 Method and implementation

The method and implementation chapter presents our research design, including a description of the case study, the used techniques for data collection, how the data has been analyzed, as well as the quality of our research.

3.1 Research Process

The work started officially in January 2016 with a pre-study including a literature review to provide a deeper knowledge in the research area of assembly simulation. Based on the pre-study, three research questions were created and formed.

To answer the first and second research questions, *What are the limitations of using assembly simulation tools?* and *When can additive manufacturing be a complement to assembly simulation?*, a literature review and a case study were performed. This was done in order to understand the limitations with assembly simulations and the possibilities with AM as a complement. In parallel with the literature review the case study was carried out to gather empirical data regarding the use of simulations and the problems related to this in a real scenario. The reason for choosing this approach was to gather and compare both theoretical data and empirical data from two different perspectives (Williamson, 2002).

The case study included semi structured interviews, observations, and a document study. The data collection techniques covered areas regarding experiences with assembly simulations and other techniques to assess assembly feasibility. The output and results from the first and second research questions formed a basis for the third research question, *How can the decisions be supported by an AM applicability framework?*

The findings from the literature review and the case study were combined and analyzed and provided the base for the results and conclusions. Figure 8 outlines the included segments during the whole study.

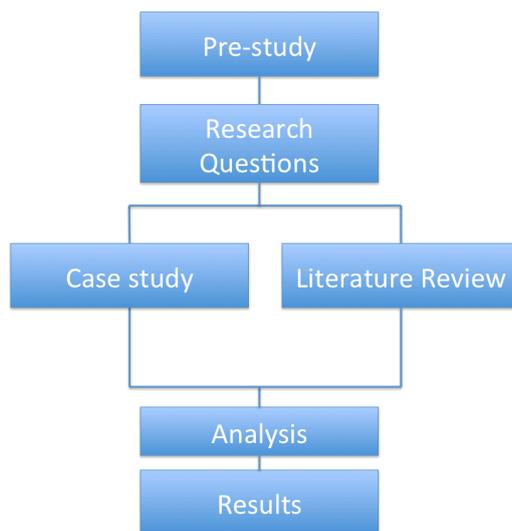


Figure 8: The research process.

3.2 Research Methods

This section will describe how the research was designed, which methods were used and why they were chosen. In principle, two methods are utilized; a case study complemented with a literature review.

3.2.1 Case Study

A case study is to investigate a contemporary phenomenon in its natural setting by using multiple sources as data collection (Williamson, 2002). Yin (2014) argues that the more the research question tries to explain a current situation, the more relevant a case study is. In our case, it is essential to explain how well the assembly simulation tools work and if additive manufacturing techniques can be utilized. Also, this method is useful when the research questions demand an in-depth investigation, e.g. understanding of a complex manufacturing system.

A prerequisite for a case study is that the researcher has access to a significant amount of data (Yin, 2014). This data usually resides in the three different categories of sources, i.e. interviews, documents and records, and field observations. The case company made relevant employees available for interviews, both employees working with simulation and manufacturing in general, as well as managers at the manufacturing department. Observations were performed in the actual production environment with the intention to identify problem areas in the assembly of the product. The researchers were also given access to relevant share point data regarding product design and CAD drawings.

In our research, a single case study was performed at one automotive company based on the contextual environment and the units of analysis. The choice of case company was based on the use of virtual tools in assembly system design and manufacturing. Volvo Cars was therefore selected, due to the exclusive use of virtual tools in assembly system design. The case, product development projects on the SPA-platform, is an embedded one with two units of analysis. The first unit is the limitations of assembly simulations and the second one the possibilities of using additive manufacturing (Yin, 2014). Case boundaries for this study are chosen so as to be more representative of the new Scalable Product Architecture (SPA) platform for Volvo vehicles, which all new Volvo models are based on. No specific project was selected, due to the similarities the SPA based vehicles have. SPA vehicles are today built in the Torslanda plant and this is also where the case study is performed.

The case study first aims at answering the question if simulations of the manufacturing assembly system exhibit any limitations. If not, simulations can be assumed to be reliable enough to ensure a flawless assembly. On the other hand, if deviations between simulations and the actual assembly are detected, it should be investigated if AM could work as a complement to simulation. In order to investigate if AM is a suitable solution a number of criteria for decision support should be identified.

3.2.2 Literature review

Literature reviews play an important role in research; it provides the researcher with a context and a background, which is crucial for the understanding and the result (Williamson, 2002). As a first step, in the early phases of this study, a literature review was conducted to understand the background and the current use of AM in the industry, which was important to obtain a deeper understanding and context of AM. The review was also needed to be able to formulate the research questions and the aim of the thesis. Assembly simulations in engineering have also been investigated in the current literature to understand and get a picture of the research in the area, as well as a deeper knowledge of the assembly simulation tools and their limitations.

An extended literature review was performed in the area of AM and assembly simulation. The sources for the literature review were mainly academic journal articles, which are the most useful type of source in a literature review (Lewis et al., 2012). Still, some conference proceedings and books have been investigated during the review. Textbooks have only been used to get a background and knowledge about the experts in the area (Lewis et al., 2012). The databases Scopus, Google Scholar and Primo (Jönköping University Library) were used to find journal papers and conference articles. The document types in the search have been limited to journal articles in the area of engineering; e.g. biochemistry has been excluded even though some research around 3D-printing of biological parts have been made but is not deemed relevant for our purposes.

During the literature review, different search terms and keywords were used in order to find relevant content. Since researchers use various terms for the same technology and tools, the combination of the search terms and key words had to be arranged structurally. For example, AM has been developed a lot since the first journal published an article in the area, and nowadays the term 3D-printing is commonly used to describe the same technology.

To find relevant articles to answer the research questions, the following terms were used:

- Simulation AND verification AND additive manufacturing OR 3D-printing OR rapid prototyping.
- Additive manufacturing
- Additive manufacturing OR 3D-Printing OR rapid prototyping
- Path Planning AND Simulation

The search was aimed at 'keywords', 'titles', and 'abstracts' to obtain an overview of the areas.

3.3 Data Collection

Because of the chosen research design, several methodology instruments were used. These instruments additionally contributed to triangulating the data and strengthening the validity of results (Yin, 2013). Williamson (2002) argues that different data sources are appropriate for case studies. Therefore, interviews, observations, and document studies have been chosen for this thesis.

Interviews

Interviews are one of the most commonly used data collection methods in case studies and typically collect qualitative data. The advantage of interviews is for example a high response rate compared to other methods (Williamson, 2002). The participants for the interviews were selected to enable reaching our aim and get our research questions answered. The respondents included simulation engineers, project managers and production system developers. The aim of the interviews was twofold. First to gain knowledge of areas where they experienced that the simulation was not enough and incomplete. Second, what possible usage of additive manufacturing could be found. In addition, some general information about their project processes was also included in the interviews. To get exhaustive and complete answers, semi structured interviews were conducted in this study. The semi structured interviews allowed the researchers to ask follow-up questions as a complement to the pre-determined list of questions. In this way, the possibilities to come up with more relevant questions during the interview would be beneficial for the study (Williamson, 2002).

The outline of the conducted interviews is presented in table 3. All interview questions are shown in appendix 1.

Table 3: Interviews conducted.

Date	Position	Focus	Method	Time
2016-02-25	Concept development	AM Technologies	Semi-structured	45 min
2016-03-31	Manufacturing Engineering	Simulation for assembly and ergonomics	Semi-structured	45 min
2016-04-04	Manufacturing Engineering	Simulation method developing	Semi-structured	30 min
2016-04-04	Manufacturing Engineering	Assembly simulation	Semi-structured	30 min
2016-04-08	Research and development	Design engineering/ Simulation	Semi-structured	30 min
2016-04-08	Manufacturing Engineering	Simulation and manufacturing exterior	Semi-structured	30 min
2016-04-18	Manufacturing Engineering	Development of assembly and production software	Semi-structured	1h

Observations

Observations have been used in this study to give the researchers a better picture of the complexity of assembling a car, and the problems associated with this. The observations were also used to get a picture and an understanding of the production system design at the case company in its natural setting (Williamson, 2002). The first observation was a guided tour at the assembly line of the new SPA-platform and the researchers had the possibility to ask questions to both the assembly workers as well as the tour guide. During the observation, the researchers identified various problems related to research question one. Parts and sub-systems details included in the car were also identified during the observations, to see these parts being assembled in real, and not only in a CAD environment, which is possible through observations (Williamson, 2002).

The second observation was carried out in the prototype workshop with 3D-printers and the manufacture of parts. Also the after-treatment of these parts was observed to understand how the finishing touch was executed. These observations provided a better context to be able to answer research question two. The observations made it possible to analyze and understand a certain problem in its natural setting (Williamson, 2002).

Document study

By studying the CAD files of the SPA-platform, the researchers gained understanding of the specific setting or policies that were needed for our study. The documents provided very useful information about the platform and the ingoing components and gave insights in the organization (Williamson, 2002). Advantages with document studies are that the researchers get a broad coverage, an extended time span, stable environment with the possibilities to repetitions, and in an unobtrusive nature, which means it required no involved participants from the company (Tellis, 1997).

The documents were gathered from the main visualization PLM software named Teamcenter. This program consists of all the information about the various car models, including detailed CAD drawings of every part that assemble the car. The CAD files and the visualization of the cars brought us information about which parts of the car are prone to cause problems in the assembly by for instance being positioned in a complex setting. In addition, the areas containing numerous cables and wires are important, as these constitute a major production challenge.

Furthermore, the study of the assembly simulation software provided information of situations where simulation was not enough and support was needed.

3.4 Data Analysis

The data analysis for this research was mainly divided into four steps. First, the data from the observations of the assembly lines and the prototype workshop was analyzed and summarized. The data from the observations was divided into different problem areas and was later used as a support for the document study where parts and sub-part were analyzed in the visualization software. The data from the observations and document study were then combined to find patterns regarding complex assembly operations and was then connected to the reality from the observations. This was then used as a support during the interviews.

The second step was the analysis of the data from the interviews. Here, the researchers transcribed the data from the taped interviews and complementing it with the notes that were taken. This made it easier to summarize and analyze. After this, familiarization with the data was necessary in order to be able to make different categorizations. There were two main categories of data, namely simulation within product development as well as simulation within production development, the latter one related to the thesis units of analysis. For each of these two categories, two groups of respondents, simulation engineers and project managers, were included. Once the data was structured and accessible to analyze, relationships between the answers were identified and categorized into two problem areas; compatibility and ergonomics.

The third step was the literature review and followed the same process as the other data collection techniques, the first steps being familiarization and categorization of the gathered data. The aim of the literature review was to get a good foundation of knowledge within the subjects of assembly simulation and additive manufacturing to build the theoretical background as outlined in chapter two as well as the connection

with the empirical data in the decisions support matrix. This required an extended review with focus on only gathering useful data and trying to categorize it in such a way it would be easier to complement the case study and reaching the goal of the study.

The last step in the data analysis were the combination of the data from the literature study and the interviews which created the foundation for the decision support matrix presented in chapter 4, where the empirical data from the interviews are combined and summarized with the findings from the literature review.

3.5 Research Quality

The value of a research study is to a large extent relying on the quality of the data and that no biases are contaminating the sources. In principle, the research and the quality of the project and its findings are judged on two criteria: validity and reliability (Williamson, 2002). The former is about measuring accuracy and what the study sets out to measure. The latter, reliability, is whether the same results and findings are obtained in repetitive research under the same circumstances.

3.5.1 Validity and reliability

For this study multiple data collection techniques have been used to reach as high validity as possible. The description of the methods used in this study, described earlier in chapter 3, makes it possible for other researchers to repeat the study again under the same circumstances. The description of how the interviews, observations and literature review was performed in this study will ensure the reliability, since it allows others to repeat the study with the same results (Williamson, 2002). The use of more than two data collection techniques in the case study made it possible to reach triangulation. The advantage of triangulation is that the gathered data are more likely to be reliable if it's gathered by more than one method (Williamson, 2002). Furthermore, the comparison of the empirical data and the literature review will ensure the internal validity of the study, which is presented in chapter 4.

4 Findings and analysis

In this chapter, the empirical findings are presented and supported by the theoretical research. It starts with a case company description and the context in which the research has been done. It continues with a presentation of the assembly simulation limitations. Then, possibilities with the use of additive manufacturing are described but also when the technology of AM limits its utilization. The chapter concludes with a decision support framework for when assembly simulation is insufficient and whether AM in that case could be a complement.

4.1 Case Company Description

The case study was performed at Volvo Car Group, which was founded in 1927 and has focused on the automotive business and producing cars since the very start. As of 2010, Volvo Cars is owned by the Chinese holding company Geely (Volvo Car Group, 2015).

Even though the head office is located in Gothenburg, Sweden, there are several product development and manufacturing sites around the world. In the manufacturing area, major assembly plants are located not only in Sweden but also in Belgium, China, Malaysia and, in the near future, the USA (Volvo Car Group, 2016). This is why the industrialization processes and tools have to be as global and standardized as possible.

Volvo Cars product line-up comprises a range of premium vehicles in several segments and is represented by a set of sedans, wagons and Sport Utility Vehicles (SUV's). Today, products are based on the newly in-house developed platform, the Scalable Product Architecture, (SPA). This platform integrates a scalable and modular design and allows multiple cars on the same platform. The first car produced on this platform is the all-new XC90 (Volvo Car Group, 2015). The scalable architecture also allows manufacturing sites and assembly operations to adopt similar operational models.

The industrialization process comprises all the steps needed for a technical vehicle project to be realized, i.e. from ideas through conceptual development of the product, sourcing of parts, the production system and the final assembly of the vehicle. Thus, the industrialization process does not include pre-phases, e.g. planning of which products to produce, nor does it include post-phases such as marketing and sales. During the technical vehicle project, engineers from mainly the Research & Development (R&D) and the Purchasing & Manufacturing (P&M) organizations work together to make sure the entire industrialization process becomes an effective, efficient and seamless one. In addition, external suppliers and partners are involved in most deliberations.

To enable a seamless transition from product development in R&D to the manufacturing and assembly capabilities in P&M, an organization, Manufacturing Engineering (ME) in P&M, has been established. The main task of ME is to prepare assembly capabilities at an early stage, even before the final product design is frozen, and, if necessary, even propose product design changes to make the product better suited for assembly. By necessity, several of the tools and processes in ME need to be aligned both with R&D and P&M, in particular because of the need to be able to exchange information.

Engineers in R&D are mainly using CATIA, Computer Aided Three-dimensional Interactive Application, from Dassault, as the main tool in product design. The

vehicle and sub-system parts are structured within a so-called E-BoM list, Engineering Bill of Material, reflecting the parts involved and how the car is built up. The CATIA program is very accurate and powerful and with only small deviations detected. The top priority is the functionality of the parts but the design engineers also let the manufacturing engineers be part of the process of examining whether the parts are optimized for assembly. However, the design engineers do not regularly work with DFA or DFM.

In ME, the engineers need to use both information of the product, e.g. from CATIA, and specific analytical tools to develop the assembly process. The tool that is used for automatic verification of assembly feasibility is called Industrial Path Solutions (IPS), which is a math-based software.

All organizations involved in the industrialization process uses tools that are either computer based software or physical parts. The latter are mostly produced, in-house or bought externally, by traditional manufacturing means. Recently, however, additive manufacturing parts have been added. By far the most common purpose of utilization is within R&D, e.g. prototypes for concept development testing functionality.

ME teams have complemented the assembly simulations with physical testing using handmade prototypes that have been made by traditional means of manufacturing. This is time consuming but can still provide some judgment of a fault free assembly process.

For additive manufacturing parts, Volvo today utilizes two Selective Laser Sintering (SLS) printers, one Fused Deposition Modeling (FDM) and in the Product Design (Design) department a Polyjet machine. This year, Volvo will invest in a new FDM printer, which will allow more possibilities and advantages, including different materials, bigger volume, and a better surface finish. Furthermore, in the next year or so, a printer with the ability to print products in metal is also expected to be purchased, something that today has to be bought externally. The experience, again mainly from R&D, is that the more complex a product or part is, the more profitable it is to print it out, compared to regular prototyping. The usage of these three machines is today exclusively related to either product development or product design purposes and not for assessing the assembly design process.

4.2 Limitations with assembly simulation

The experience at Volvo with the software for assembly feasibility is that it is generally accurate and reliable. This is in consistency with generic findings in literature (Da Silva et al., 2013). Two main purposes of assembly simulation, ergonomic aspects and collision-free assembly, it is the former that is most cited in the case study when it comes to drawbacks. The root cause is often the standards around ergonomic assessments and how the limits are construed (Dukic et al., 2007; Lämkuil et al., 2009). In reality, of course, there is no single ergonomic threshold that is valid for all operators and the borderlines in the assembly simulation software are often questioned by the simulation engineers. The task of setting ergonomic thresholds is usually assigned to one of the employees in the involved simulation departments.

The other assessment made in assembly simulations, is determining whether two parts are allowed to collide or not. Even though the simulation program provides a sharp threshold of compatibility or not, in most cases, the simulation has to be

complemented with the engineers' own ability to determine the situation (Germanico Gonzales-Badillo et al., 2014). Thus it becomes easier and easier the more experience the engineers have. In addition, as the different cars use similar product modules and similar technical solutions, the same experience can be utilized also for a broader spectrum of cars. Consequently, the challenge is when a completely new model is introduced and the previous familiarity is finite.

When an assembly problem is identified, either because the ergonomic threshold is exceeded or there is a collision between parts, two routes of action are possible and initiated from the ME department. If the conflict is not severe, i.e. requiring only minor assembly design modifications, the simulation engineer will propose a changed assembly set-up. In this situation, the activities remain within the P&M organization. If, on the other hand, a significant change of the assembly operations is required, the simulation team will have to return the product to the R&D organization to evaluate if a product design change is more favorable.

The assembly simulation team most often is populated by engineers from the ME organization. To improve the quality and speed of correctly simulating an assembly process, and if necessary suggest changes in either the assembly or product design, a team should ideally include also representatives from suppliers of parts and sub-systems for the vehicle. In that case, the team would benefit from each other's knowledge and could more easily predict the assembly process. However, this is seldom achievable as it would be very time consuming. Also, the company cooperates with a large number of global partners and suppliers whom are spread all over the world making such a team composition impractical.

Often, simulation engineers from the outset suspect that a proposed assembly process will be impossible. However, as the assembly simulation is progressing, frequently the outcome in reality is actually more favorable than anticipated. This is a conservative approach that brings attention to the seriousness of the task. If the preconception were the reverse, i.e. always expecting a smooth assembly, this would arguably lead to a higher number of issues exposed only in later phases of the assembly evaluation. On the other hand, if warnings are issued more often than not, becoming a habit, it could possibly mean that the operators in the production would not take the warnings seriously enough. Thus, the simulation engineers need to strike a realistic and fact based balance in their approach.

The vehicle parts that are most critical from an assembly feasibility point of view, are those involving complex cabling or consisting of many subparts. In this case, the simulations are not able to anticipate how the actual assembly could be performed. Other identified critical parts are those with complex fasteners, e.g. door and panel trims.

A number of critical assembly operations were identified on a sub-system level. For interior assembly operations, they include complex electrical wire systems, interior trim, which includes trims on A and B pillars, and operations in the center console. The first area involves long flexible structures and the second area requires exact forces of pressure to be mounted correctly. The third area relates to assembly in a cramped area where both movement and visibility of the operator is limited. For the exterior assembly operations, the assembly of bumpers with clips and other fasteners were identified as complex and difficult operations. Again, larger flexible structures entail a difficult operation. These observations of critical assembly operations match the limitations identified in assembly simulations.

The sections below are divided into eight main fields where the assembly simulation software applicability is limited, either from a compatibility or from an ergonomic point of view.

4.2.1 Compatibility related limitations

The compatibility related assembly simulation limitations are less pronounced compared to the ergonomic limitations. In general, the three areas that are most frequently mentioned are physical compatibility, positioning and boundary conditions (Da Silva et al., 2013). The case study identified the former two and also in several different contexts.

Physical incompatibility

A major advantage of a simulation program is the ability to detect a collision free assembly path of parts. This is also normally a situation that the software is very capable of achieving. However, a critical area of the assembly simulation process is where a collision between two, or more, parts is actually a pre-requisite for assembly. This is because the collision requires a deformation of one or more of the involved parts. An example is a 'snap closure', where a collision and a deformation are actually required. This is a fairly frequent event in assemblies in cramped spaces involving small parts. The challenge, however, is that the simulation engineer must have the ability to determine whether the collision is correct and anticipated or unacceptable. In other words, the simulation software has to be complemented by the judgment of an experienced simulation engineer.

Positioning

Parts and details that most often are a challenge when simulating the assembly process, are those made of rubber, containing tabs and sealings. These details are usually relatively small and the possibility to envision how they will behave in reality is very difficult. In practical terms, this means difficulties in assessing if a tab will be placed in the right direction, as the consequence of failing to do so, will lead to a lack of sealing capacity in the product.

Boundary conditions

Also for compatibility issues, as for ergonomics, a drawback with the simulation program is that it stops when the predetermined limits are exceeded, in this case when collisions occur. This means that the program does not provide information of how much incompatibility there is between parts, or, in other words, how far from a suitable solution the assembly design is.

4.2.2 Ergonomically related limitations

From the case study, five main areas appeared as important to address regarding the reliability of the ergonomically related assembly simulations. For all identified areas, the same simulation limitations have been found also in literature (Dukic et al., 2007). The five major areas described in more detail below, are those associated with visibility, accessibility, forces and torques, strenuous motions and the boundary conditions.

Visibility

One drawback with the assembly simulation software is that in those virtual environments, the circumstances appear very clear and ideal. For example, the possibility to lighten up specific areas or to color certain surfaces or even exclude

undesirable parts is easily made. However, this is of course not the case in reality for the operator. This limitation was also identified by Lämkkull et al., (2009). At the assembly line it can instead be difficult to distinguish parts from each other, and to see if wires and “clips” are assembled correctly behind panels etc. Dukic et al., (2007) also addressed these visibility drawbacks.

Accessibility

In an environment where the maneuverable space from an operator’s viewpoint is limited, the simulation tool is often inadequate to simulate the human motions and ergonomics required to make the assembly motions. Both Dukic (2007) and Lämkkull (2009) corroborate this. The context in which this was identified is typically either in the interior of the car or exterior confined spaces, such as the headlamp houses. The root cause for this simulation limitation is the challenge of developing a sophisticated representation of the human motion capabilities. The motions that a human can perform in real life are usually more advanced than a crude ergonomic simulation tool can portray.

Required forces

Difficulties and limitations with using the simulation software also revolves around correctly simulating forces of pressure and traction as well as torques needed in the assembly. Lim (2007) and Xia (2013) both cite three types; pressure forces, traction forces and torque. In the case study, the most frequently found examples are those requiring exact pressure forces when mounting various interior panels of the car. Also torque related limitations were found but traction forces were not explicitly identified, which is different from what Lawson (2016) has found in his research. Lawson (2016) found that traction forces were difficult to examine in simulations.

Strenuous motions

Strenuous motions (Falck et al., 2012) are an aggregate name for a variety of operator motions that present difficulties when simulating this kind of motions in a computer model. One example is the ‘over the shoulders’ movements. The programs limitations are related to how well the human body and its movements are replicated in the model. In this particular motion, the shoulder movement is simulated around only one joint and thus the articulation is not perfectly simulating the human movement when lifting items with two arms. In addition, the program is only replicating the average person and does not easily provide a tool to assess situations with humans of other statures.

Other limiting ergonomic motions are those inside the car and mounting interior parts where the workers have to turn and use strenuous motions in order to assemble the parts. In addition, lifting heavy parts can be problematic to simulate and is important because failure to identify and assess this motions can cause ergonomic problems, especially regarding long term health consequences.

Boundary conditions

A drawback with some of the simulation software is that it stops as soon as it finds out that an ergonomic threshold is reached. This means that the program does not provide information of how far from a feasible solution the evaluated assembly design is. The consequence is twofold. Firstly, the boundary conditions, in this case the ergonomic thresholds, have to be well balanced against other assembly requirements. Secondly, the simulation engineer will be restricted in finding alternative solutions because of the uncertainty of knowing how far from an approved solution one is.

4.3 Additive manufacturing possibilities for assembly assessment

An advantage with AM parts would be the reduced time to produce a certain part or prototype compared to traditionally prototypes (Mawale et al., 2016; Berman, 2012). In this case, AM benefits would be that in those situations where the design has to be changed and the time is very limited, it would contribute with making the time from idea to new part testing shorter. This reduced time would also contribute to lower costs as well as fewer people having to be involved in the process (Berman, 2012).

In contrast to ordering handmade prototypes, which in most situations at Volvo require redoing the initial drawings to make them work as prototypes. Utilizing AM parts would allow everyone working with programs such as CATIA to directly order the desired parts or details through their computer files, and drawings should not be needed.

AM parts can be used in situations where the assembly requires pressures or torque of for example smaller plastic parts, an area where the simulation software frequently fails to simulate. As AM parts can be produced quickly, they can be utilized for final verification if this has been missed in earlier industrialization phases and time becomes the main problem. In addition, using AM in later phases will facilitate the assembly verification since the actual car then is available for testing and this is faster than creating a virtual environment and simulation software.

During the case study, one thing that was repeatedly highlighted was that using AM, compared to computer simulations, would provide a better impression of some of the attributes such as testing and verification of the size and weight of the parts in relation to the assemblers' ergonomic qualifications.

The case study showed, that if AM parts were to be manufactured, they would likely be in either of two categories; One is smaller parts of the interior of the car and the other category is exterior parts, e.g. lamps.

Another frequently identified occurring problem area is the assembly of head and tail lights. This type of simulation is very complex and the current software is limited and is not able to simulate the assembly process in an adequate way. Hence, in some cases additive manufacturing could be used in order to ensure that the assembly will be possible. However, this will only be applied when the simulation engineer has failed to simulate the process.

Another empirical finding of when AM parts have been involved in the process is the assembly of the fuel cap. This assembly requires both pressure and torque forces, which the simulation program has difficulties with envisioning. In this particular case, a part of the side of the car has been produced together with the tank module and tubes in order to verify the whole assembly process.

According to the empirical findings, some engineers' experience of the assembly simulation programs is that those parts that are not static i.e. have the ability to flex and bend, are the ones causing most uncertainties. The most common situation is the module in the doors, which consists of several smaller parts and assembles as a whole package, which implies that the totality being rather flexible. In this situations, the simulation program identifies many collisions between the involved small parts. However, in practice, the assembly is indeed possible due to the fact that the module is rather bendable and the collisions are not hindering the assembly process.

One of the reasons why some departments at the case company are currently not utilizing AM in their work of assembly system design, is mainly due to the lack of knowledge and communication with the department that controls the AM machines. Other departments cite that this technology simply is new and that possible application areas have not yet been thoroughly investigated. However, there is already an interest in applying this technology, in particular for teams that operates in the early stages of the industrialization process when no physical models are yet available.

A further utilization of AM, other than producing vehicle parts, could be to print tools or parts of tools in order to assess how well it would work in the assembly.

An advantage with producing the cars with the SPA platform is that if one solution works on one car, it is most likely to also work on other car models, with only smaller and foreseeable adjustments. It also means that identified problems could be evaluated and solved and applied similarly on all models.

One of the most crucial factors when deciding if AM should be used as a complement to the simulation is that the manufacturing engineering manager is fully onboard and invests in both time and the personnel that it would require.

4.4 AM technology limitations

Even when assembly simulations have proven to be inadequate, and a physical simulation of the assembly process using additive manufacturing parts would be promising and worth pursuing, there can be technological limitations in actually producing the specific parts by using additive manufacturing techniques (Oropallo & Piegl, 2015).

An obvious obstacle is that the sheer size and shape of a part cannot be manufactured, as the available AM printers today are not capable of producing larger objects. An example is the long chromed parts that 'surrounds' the exterior of the car and is rather flexible. In this case, the technology is not yet readily available to produce such a part. Another example is that parts using certain materials are not frequently available to print using AM. Metal parts are still rare to produce by AM and other materials are not yet available at all.

A final example that might hold back the utilization of AM parts is the finishing touches that are required for some AM technologies. Although this usually is not a hindrance for assembly assessments, it adds extra time and cost for the production of AM parts (Oropallo & Piegl, 2015).

4.5 Framework for when utilizing AM

A list of concerns appears when assessing the simulation tool from an ergonomics viewpoint. Three areas appear to be questioned. One is that the simulation software is not sophisticated enough to replicate complex human movements such as lifting things over the shoulder. The human joints and muscles are much simplified in the model and will only provide a rough estimation of what the consequences for a human would be in real life. A second area is the accurate forces and torques that are required in some assembly. Also here the simulation does not provide a good enough estimation of this assembly phase. A third generic area is that most simulation tools only provide a standardized model of ergonomic thresholds to be used. This means that different assembly scenarios are more difficult to examine.

Gravity and flexible materials are two factors that combined present another challenge for the simulation engineer. Currently used software does indeed attempt to simulate the assembly of flexible materials but only to a smaller extent. The reason is that this process requires very complex mathematical calculations. In addition, it is not enough to have program skills but the simulation engineer also need to have experience from how the parts behave in reality. In practice, this puts a significant challenge of correctly simulating flexible materials such as cablings, which, challengingly enough make up a significant proportion of the assembly process.

Problems with simulations of the assembly process are described previously. In addition, specific parts or systems that are difficult to simulate, e.g. flexible materials such as cabling, are also described.

4.5.1 Content of the applicability framework

To summarize and provide a data framework to support when to use AM, table 4 has been developed. The framework is intended to be used by simulation engineers and managers when new and complex assembly operations are to be designed, and when simulations are not enough to ensure the assembly feasibility. The matrix covers three dimensions; *Assembly simulation* feasibility, types of *System/parts* involved and whether *AM technology* parts could be utilized as an option to assembly simulation.

Assembly Simulation is on an overarching level, *Hierarchy 0*. It is in turn divided into *Compatibility* and *Ergonomic* on a *Hierarchy 1* level. *Compatibility* is the sheer physical interaction between parts and machinery. *Ergonomic* is focused on the capabilities of the personnel. The table also includes, in the column *Source*, references to theory and empirical findings where simulation limitations have been identified. On a *Hierarchy 2* level, both *compatibility* and *ergonomic* are sub-divided into more specific limitations, such as ‘over shoulders’ movements in *ergonomic*. The *General* column only summarizes all the relevant areas where assembly simulation limitations have been empirically found, here identified by ‘yellow’ ‘Sim.’ boxes.

For the four columns of *System/parts*, the most frequent parts with assembly limitations are identified.

In practical terms, *AM technology* limitations will be an obstacle for fully utilizing AM but this is dependent on the specific assembly environment. Four areas have been identified, including ‘size and shape’.

Several areas stand out regarding which parts and contexts are of concern in the simulation tool and where, possibly, using AM parts in physical simulation would be of interest. In table 4, these areas are marked ‘AM’ in ‘green’ boxes. As can be seen, they are distributed between *compatibility* and *ergonomic* for the four *system/parts* groups. The most commonly cited area is when so called ‘flexibles’ are used. This can be cables, bendable plastic parts etc. A second category is where a precise hand movement is needed, e.g. snap closures. A third area is where the space in which the assembly is done is in a confined area where human body movement is limited.

Table 4: General applicability of AM in assembly evaluation as a complement to assembly simulation. *A larger table is found in appendix 2.*

Hierarchy 0	Hierarchy 1	Source	Hierarchy 2	General	System/parts				
					Flexibles	Flexibles & fixings	Snap closure parts	Complex boundary conditions	
Assembly Simulation	Compatibility	(Da Silva, 2013), Empirical findings	Physical incompatibility	Sim.	AM		AM		
		Empirical findings	Boundary conditions	Sim.					
		Empirical findings	Positioning	Sim.	AM				
	Ergonomic	(Dukic, 2007), (Lämkuil, 2009), empirical findings	Visibility	Sim.		AM		AM	
		(Dukic, 2007), (Lämkuil, 2009), empirical findings	Accessibility	Sim.				AM	
		(Lawson, 2016), empirical findings	Forces-traction	Sim.					
		(Xia, 2013), empirical findings	Forces-torque	Sim.			AM		
		(Lim, 2007), empirical findings	Forces-pressure	Sim.	AM		AM		
		Empirical findings	Over shoulders	Sim.					
		(Falck, 2012), empirical findings	Strenuous motions	Sim.				AM	
		Empirical findings	Heavy lifting	Sim.					
		Empirical findings	Boundary conditions	Sim.					
	AM technology	(Oropallo and Pieg, 2015)	Size and shape		Depending on the specific environment				
		(Oropallo and Pieg, 2015), (Baumers, 2015), (Gao, 2015)	Build material(s)						
		(Oropallo and Pieg, 2015), (Berman, 2012), (Baumers, 2015)	Manufacturing time						
(Oropallo and Pieg, 2015), (Baumers, 2015), (Gao, 2015)		Pre- and postprocessing							

Legend: Sim. Assembly simulation limitation
AM AM viable alternative to simulation

The findings are summarized in table 4 from a generic viewpoint when no specific industry or product is investigated. In general, the simulation tools are quite adequate in detecting compatibility issues. However, the programs normally stop when a collision occurs. This means that the degree of incompatibility is difficult to assess and hence how extensive a change need to be to fix the problem, either on the parts or the assembly process.

The possibility of complementing simulations in the automotive context is an adaption of the generic findings above but with the specifics of the different systems and parts involved. There are several instances where AM parts in a physical demonstration would likely provide an added benefit to the simulation. Most frequently cited are various types of flexible parts and modules. An example is one of the interior modules in the passenger compartment that needs to be pressed, with a certain force, into a rigid set of fixings. A physical evaluation with AM parts could provide a better, and more exact, assessment than a computer simulation. Another area is snap closure parts such as a fuel cap assembly. Finally, some of the assembly work is executed in surroundings where space is rather cramped and involves a complex set of movements. An example of this latter category is the headlamp assembly.

When applying the generic findings, from table 4 above, in the automotive environment, the applicability of AM in this context is shown in table 5.

Table 5: Applicability of AM in automotive assembly evaluation, as a complement to simulation. A larger table is found in appendix 3.

Hierarchy 0	Hierarchy 1	Source	Hierarchy 2	General	Vehicle system/part									
					Flexibles					Flexibles & fixings	Snap closure parts	Complex boundary conditions		
					Interior panel	Door module	Surrounding details	Cabling	Rubber sealing	Front bumper	Cable fixings	Fuel cap	Head and tail lights	
Assembly Simulation	Compatibility	(Da Silva, 2013), Empirical findings	Physical incompatibility	Sim.		AM		AM		AM				
		Empirical findings	Boundary conditions	Sim.										
	Ergonomic	(Dukic, 2007), (Lämkuhl, 2009), empirical findings (Dukic, 2007), (Lämkuhl, 2009), empirical findings (Lawson, 2016), empirical findings (Wu, 2013), empirical findings (Lim, 2007), empirical findings (Falck, 2012), empirical findings Empirical findings	Positioning	Sim.			AM		AM					
			Visibility	Sim.							AM			AM
			Accessibility	Sim.										AM
			Forces-traction	Sim.										AM
			Forces-torque	Sim.										AM
			Forces-pressure	Sim.		AM								AM
			Over shoulders	Sim.										
			Strenuous motions	Sim.										
			Heavy lifting	Sim.										
			Boundary conditions	Sim.										
	AM technology	(Oropallo and Pieg, 2015) (Oropallo and Pieg, 2015), (Baumers, 2015), (Gao, 2015) (Oropallo and Pieg, 2015), (Berman, 2012), (Baumers, 2015) (Oropallo and Pieg, 2015), (Baumers, 2015), (Gao, 2015)	Size and shape	AM			large size	large size						
			Build material(s)	AM										
Manufacturing time			AM											
Pre- and postprocessing			AM											

Legend:

- Sim. Assembly simulation limitation
- AM AM limitation
- AM AM viable alternative to simulation
- AM AM not viable alternative to simulation because of AM technology limitations

Several areas have been identified where simulation is not sophisticated enough to provide guidance on the assembly evaluation, and hence an AM part would be a complement in a physical demonstration. These areas are identified by ‘green’ ‘AM’ boxes in tables 4 and 5. However, a pre-requisite, obviously, is that these corresponding parts actually can be manufactured using AM technology. In some cases, limitations of the size of the part, the material used or other hindrances make the AM part assessment impossible. These general areas are marked ‘amber’ in ‘AM’ boxes.

Taking into account all three dimensions, i.e. assembly simulation limitation, system/parts and AM technology limitations, two specific areas have been identified in the automotive context as areas where AM is not a viable alternative to assembly simulation. These are marked ‘red’ ‘AM’ boxes. The first instance is the surrounding details and production of very long exterior chrome strips. The AM machines is currently not able to provide these parts. The second example is of the same nature, namely long and flexible cabling.

For both the compatibility and ergonomic areas, boundary conditions are not identified as exhibiting limitations in the case study findings. The same is also true for the ergonomic areas of traction forces, over shoulder movements and heavy lifting. These areas are consequently not colored, i.e. yellow, amber, green or red, in tables 5.

5 Discussion

This chapter begins with a discussion of the chosen methods, including the case study and the literature review, together with a presentation of the quality of the research, i.e. the reliability and the validity. Furthermore, the chapter also discusses and analyzes the findings of the research, where each of the research questions is discussed separately. Finally, the authors discuss what limitations the findings are connected with and what possible implications there are in this case it self but also in other contexts.

5.1 Discussion of methods

The subject matter of this thesis, additive manufacturing (AM) and its utilization in the assembly system, is an area that incorporates two distinct areas, each of them the subject of intense development in many industries. AM is a technology area that is developing rapidly where its utilization is changing almost day-by-day (Mawale et al., 2016). This means that there is a shortage of scientific papers on the subject. In contrast, the assembly system itself and the research that has been done is that research area has many academic publications. Thus, the combination of the two areas required also a combination of methods, i.e. case study research and literature review, so that they would complement each other to fill the gap in the theory by the empirical findings.

It was assumed, from the beginning, that interaction between the different methods, i.e. the case study and the literature review, would be required as the study was progressing. One such example is the facts and findings that were emerging from the interviews and that would have to be compared with literature studies.

With these pre-requisites, a project plan was developed that was taking into account both elements of the methods that were going to be used, i.e. case study and literature review.

5.1.1 Case study

As the preparations for this study were being made, it became gradually clearer, that a case study would be the main source of information. Before starting the case study, however, a thorough literature study was made to get a solid base and a background to which to start from (Williamson, 2002). This would also begin building the connection between the theoretical framework and real life practicalities.

The interviews were made with a broad selection of respondents, including personnel both familiar with one or several areas within; assembly work, simulation techniques, and additive manufacturing. The interviews were conducted in a semi-structured way. This meant, that a base set of questions were developed, most often based on literature findings, which provided a backbone for the interviews (Williamson, 2002). Then, as the case study developed, and the authors were becoming more familiar with the subject, the interviews became more of a discussion between the parties. This allowed a more probing and following-up approach than early on in the study. In several situations, statements from one interviewee could be matched against the views from another person to understand how generic some of the experiences were.

A challenge in several of the interviews was the frequent usage of abbreviations that represented vehicle projects and different parts of the vehicle. To cope with this, a simple manual was developed and used to provide an oversight of the company's

vehicle project denomination and the structure building the complete vehicle from its parts and subsystems.

An anticipated outcome of the interviews was the necessity of follow up interviews with those individuals that had most experience in the subject. This was done at the expense of broadening the interviewee clientele but proved worthwhile at the end as some valuable insights were gained that otherwise perhaps would not have been the case.

In parallel with the interviews, a number of observations were granted. This provided a very valuable contrast to the interviews and theoretical findings. It also put the authors in a slightly more comfortable position during the interviews as having seen the issues at first hand gave them a better chance of understanding the responses and answers and thus allowed a better chance of formulating relevant and more insightful follow up questions.

Observations were made in mainly four different areas, within the frame of the case of the new SPA-platform. To understand the overall complexity of the assembly process of the SPA-platform, observations were made in the assembly plant. This allowed the authors forming a good understanding of the complexity of the entire manufacturing process and in what context and circumstances the workers have to perform the manual work of the assembly process. In addition, studies of pre-production processes were performed in an environment that allowed a better close up of the process albeit in slightly less routine production surroundings. A third observational area was the simulations and the computer based modeling. This was an entirely different context as it took some getting used to understanding the tool itself and how it relates to the assembly workers daily work life. A final observation area was around the additive manufacturing. This was done in a separate workshop area where the two SLS machines and the FDM machine were placed and the AM parts produced. The first area, assembly plant observations, was a pre-requisite to get an understanding of the thesis subject as a whole. The other three areas, pre-production, assembly simulation and AM observations, were more related to the findings in the interviews.

The usefulness of the case study method was the combination of different techniques ranging from very theoretical input to real life practicalities and the possibility to combine new research findings with experiences from people who have worked with the subject for several years. In having just a single case study, the authors had the possibility to go in-depth into the various subjects. The authors argue that multiple case studies would, at the expense of an in-depth single case study, have made it more difficult to draw the conclusions that this thesis achieved in doing.

5.1.2 Literature review

Three subject matter areas were included in the literature review, i.e. manufacturing assembly, assembly simulation, and additive manufacturing.

The assembly system is an important and well-researched area within production system development. A number of scientific papers are also available and the concepts of DFA and DFM are thoroughly discussed. Both concepts stress the importance of connecting product design development with manufacturing.

Assembly simulation articles are mainly directed at a specific simulation software. In many cases, the articles are from the software producers themselves, which implies that the impartiality can be questioned, and no real drawbacks are usually presented. Scientific papers that cover the generics of this subject are less frequent, and many of

those that are presented are focused on the ergonomic simulations and Virtual Reality (VR). In addition, this subject area is also changing and improving so fast that the review process of scientific papers is a hindrance to make available the development in this area. The authors found this specific literature review area more challenging than the other two, as there was both a scarcity of papers and that they were not entirely unbiased.

The third subject matter area, additive manufacturing, is another area, which is changing fast. The content of these papers are mainly related to the technology advances and the utilization of the printers in various contexts.

The authors discovered, however, that literature covering the combination of all three subject matters was rare indeed. Consequently, there is a strong need for a joint effort to develop this particular area.

5.1.3 Reliability and validity of the research

Both the reliability and the validity of the research are generally improved if the data and facts gathered are from multiple sources (Williamson, 2002). In this report, the main sources are the interviews, observations and the document study in the case company and complemented by the literature reviews.

The reliability of a study is high if similar conclusions can be drawn in repetitive research under the same circumstances (Williamson, 2002). The research process was developed to structure a systematic step-by-step approach that included several methods and data collection techniques. This was done in order to strengthen the reliability and making it possible for any future study that aimed at reiterating the concept expecting to find similar results.

The validity of a study is measured in two dimensions; the internal and external validity. The internal validity is if the study measures what is intended to be measured (Williamson, 2002), i.e. if additive manufacturing can be used as a complement to assembly simulations. The research question one was answered with a number of contexts where assembly simulation present limitations. Research question two addressed in what situations additive manufacturing would work as a complement to assembly simulation and this was provided both on a generic level and for the case company environment. In addition, research question three was answered with a framework to support the decisions on when to utilize AM. The authors believe that the main findings of assembly simulation limitations, and when and where additive manufacturing could be utilized, are successfully covered in the thesis.

This study is very dependent on the case study findings in the case company. The external validity measures how well the findings can be generalized and applied in other settings (Yin, 2014). The findings within the same company, in various global manufacturing sites, are directly applicable to other parts of the case company, as it utilizes identical processes and tools in all their locations. If the findings are applicable also from a general automotive industry point of view, depends on to what degree other companies uses similar processes and tools. In reality, this industrial sector is very global and highly competitive and alliances and partnerships forces the benchmark solutions to be quickly adopted by most companies. Therefore, the findings can arguably also be valid for other automotive businesses. The applicability of the findings for any other industrial business is entirely dependent on the industrial context. The authors argue, however, that the case company and most

other automotive companies operate in a highly complex assembly environment and covers a wide range of assembly operations having at their disposal both assembly simulation capabilities as well as additive manufacturing techniques.

5.2 Discussion of findings

This section discusses the findings from the case study and literature review. It is divided into three parts, one for each research question. In addition, the limitations of the research as well as the theoretical and practical implications will be discussed.

5.2.1 RQ1- *What are the limitations of using assembly simulation tools?*

The global competitiveness has led to a heightened focus on developing processes and tools that cut costs and shorten lead times for new products (Choi et al., 2002). Consequently, the simulation and virtualization of the industrialization process, involving assembly and planning, has arisen in recent years (Gupta et al., 2001). The design of the manufacturing and assembly processes are nowadays said to start already in the product design phase. An example of this thinking is the simulation, using software tools, in the design of the assembly process (Gupta et al., 2001; Longo & Mirabelli, 2009).

In the literature, a number of scientific papers give an account of the possibilities that information technology provides in assessing assembly feasibility. Martín et al., (2013) and Zhang et al., (2015) both summarize the advantages and opportunities that assembly simulation can offer. In general, the advantages can be summarized as a key component in concurrent engineering, in this case the parallelization of product development and production system design.

The assembly simulation software is covering one or several of the following three aspects. In assembly plant layout and design, the simulation tool can help organize the overall layout of the facility. For the assembly itself, assembling systems and parts for the final product, the software can assess the path that is required to assemble the product without colliding with other physical components (Dukic et al., 2007; Zhang et al., 2015). The third area is the ergonomic aspect of the people involved in the assembly process (Falck et al., 2012).

Both literature (Dukic et al., 2007) and case study findings identify areas and limitations of the software where either the reliability has to be questioned or where a different tool set than assembly simulation has to be used. The limitations are either related to the compatibility of components, i.e. collision free paths, or the ergonomics of the assembly maneuver.

For the ergonomic limitations, which is the most cited area both in literature and in the case study findings as well, five major areas emerge: visibility, accessibility, required forces, strenuous motions and boundary conditions. Comparing the findings from literature and the case study observations there is a match for all but one of the five areas, namely boundary conditions. For the required forces, which from the literature findings are divided into traction, torque and pressure, the case study resulted in identifying limitations both for torque and pressure but not for traction. For strenuous motions, in literature studies divided into over-the-shoulder movements, heavy lifting and generally strenuous motions, the case study exposed none of the former two but strenuous motions were cited in several instances.

For the compatibility findings, three areas were identified in literature: physical incompatibility, boundary conditions and positioning. As with the ergonomically limitations, all but one of the three were also found in the case study and, again, the exception is the boundary conditions.

The limitations of boundary conditions, both in the ergonomic and the compatibility area, did not show for specific parts or specific environments in the case study, although cited in literature. However, it may be that these shortcomings are a general feature of the assembly simulations and not explicitly directed at special circumstances.

In summary, the reliability of assembly simulations are generally of a high order. The limitations that do exist are clearly identified both in literature and in the case study of this thesis. This means, first, that simulation results in these latter circumstances, are possible to treat with caution and, secondly, that countermeasures can be put in place that mitigates the assembly simulation shortcomings.

5.2.2 RQ2 – *When can additive manufacturing be a complement to assembly simulation?*

Additive manufacturing techniques are rapidly evolving and the automotive industries are among the forerunners in adopting this new technology in their industrialization processes (Mawale et al., 2016). Even though the pace of improvement is very high, not least the cost going down and the affordability making it available also for smaller companies, there are a number of areas that present obstacles to the widespread usage of AM. Literature generally identifies several categories that are making it difficult in adopting the technology in certain contexts. The limitations of AM technologies from literature can be summarized in different categories as outlined in chapter 2.4. Several of them are of a type that is only valid for a specific context. One example is the need for some of the AM technologies that are used, for pre- and post processing of the parts. Obviously, if the finish of the product is of less concern, e.g. in assessing functionality, this is not a hindrance. Another example is the somewhat scarce availability of which materials that can be used and when assessing how much of a hindrance this is, of course is totally dependent on the purpose and utilization of the AM part.

Generally, when assessing when AM parts could be used for assembly feasibility when simulation is inadequate, most situations in the case study were deemed suitable. These situations are a combination of what aspect of the assembly is assessed, e.g. ergonomic and over shoulders movement, and in what context the assembly is, e.g. snap closure parts. For the purpose of this thesis, i.e. determining if AM parts could be utilized for assembly feasibility purposes, there was however one area that stood out in the case study as a hindrance of using AM, namely size. In the case study, two types of parts that are of a larger size are the wirings and cable packages and the other one is the flexible chromed surrounding parts at the exterior of the car. For the former, wirings, this shortcoming of AM technology is of particular concern since for the assembly simulation this was clearly identified as a limitation.

In summary, with one exception, i.e. the larger sub-systems of wirings and surroundings, the concept of using AM parts for assembly feasibility studies was deemed satisfactory by the authors.

5.2.3 RQ3 – *How can the decisions be supported by an AM applicability framework?*

The empirical findings cover a broad spectrum of the engineering and manufacturing fields. In addition, employees working daily with assembly issues as well as more senior managers having a less than operational knowledge all provided input. Consequently, the assembly simulation area and the possible use of AM in assembly have been covered from a variety of viewpoints that make the findings arguably a fair representation of the status in the case company. What was raised in the interviews were, almost by default, the issues and concerns that the employees have experienced. In other words, when the simulation programs are working adequately, these circumstances are usually not mentioned or described

The findings in literature and the observations from the case study provided a thorough view of assembly simulation limitations and when AM could provide a complement. To provide a structured approach for taking decisions involving simulations and AM, a tool needed to be developed that would assist in these decisions. This tool, or framework, would guide the decisions makers to make the right choice by examining the context for any given assembly situation. For this framework, three dimensions need to be considered.

The first dimension includes identification of whether the assembly simulation is trying to assess an area that has been found difficult to evaluate by most software. Secondly, in what context, i.e. physical part and the specifics of the situation, is the assembly occurring. Thirdly, to answer if the technology of AM itself is a hindrance under the circumstances as outlined in the second dimension.

Table 4 in chapter 4.5.1 provides a conceptual framework for how to support decisions of if to use AM in a general context and table 5 in the case study automotive environment.

5.3 Limitations of the Research

The focus of the thesis work has been the case study at one particular automotive company. The authors argue that similar findings would occur also in other manufacturing and engineering industries as the complexity and broadness of different assembly techniques is mirroring other large-scale industries. However, in industries of a very different kind, such as the electronics industry, the outcome and the conclusions are not foregone. Hence, the reliability and validity of the thesis would be strengthened if other manufacturing companies were to be included in a multi-case study (Yin, 2014).

As assembly simulation tools are improved at a high rate, the deficiencies will obviously diminish over time. One example is the capacity of the software needed for simulating and articulating complex anatomical movements of the assembly operator. With more computer storage available in the near future, the assembly simulation programs will improve and even eliminate some of today's limitations. At the same time, however, the familiarity of the technology of additive manufacturing will, and is, increasing in most companies and industries (Malware, 2016). This will arguably lead to a wider usage of AM techniques, including assessment of assembly feasibility.

5.4 Implications of the Research

Literature has identified a number of situations where assembly simulation programs have shortcomings (Dukic et al., 2007; Lämkuil et al., 2009; Xia et al., 2013). The case study of this thesis was also able to confirm most of these drawbacks. This is an advantage since the simulation limitations then becomes well known. With this prerequisite, countermeasures can be taken that either are just an awareness that the simulation results should be treated with some caution or that an alternative to assembly simulation needs to be found.

The research has also identified a number of situations where additive manufacturing could act as a complement to assembly simulation. Although the case study was performed in just one industrial manufacturing environment, the authors argue that the similarities with other assembly operations make the results transferable also to these.

By far the biggest implication of the study is the matrix, table 4 and 5, which will provide an impartial decision support when additive manufacturing can be a complement to assembly simulation. This decision support model has been tested during interviews at the case company. Validation of the model requires testing also in other companies.

The applicability and longevity of the research is largely dependent on the rate of improvement for two of the main technologies that are involved, i.e. assembly simulation and AM technologies. As both are improving, i.e. simulation shortcomings are diminishing and the AM concept improving to make it more feasible to utilize, the specific content of the matrices will change. This means that the decision support matrix will evolve with the improvement of the two technologies.

6 Conclusion and future research

This chapter concludes the thesis with the main points presented and a discussion of future research.

6.1 Conclusion

In product production, assembly approximately represents 50% of the total production labor of a product (Boothroyd et al., 2010). Therefore, an efficient and fast assembly process is crucial to get competitive advantages at the global market and get the right quality. The design of the production system, including assembly, starts when the product design is still unfinished.

A major step in assessing the feasibility of the assembly system design was the introduction of simulation tools and computer software. Even though the assembly simulation tools are predominantly capable of replicating real-world circumstance to a large degree, limitations still exist.

The aim of this thesis has been to identify when assembly simulation is limited and if additive manufacturing, also known as 3D-printing, can work as a complement to simulations in these situations. In addition, the researchers wanted to develop a framework that could act as a decision support for when AM could be used.

The thesis uses a case study method including literature review, semi-structured interviews, and a document study to fulfill the research aim. The case study was conducted at the case company Volvo Car Group, which exclusively work with assembly simulations as verification of assembly paths and collisions. The case study was complemented by a literature review.

The findings from the case study confirm that there are limitations with assembly simulations regarding difficulties in assessing visibility, forces needed for the assembly operator, positioning, and accessibility between parts and subparts. That the assembly simulation limitations identified in literature are replicated in real world observations are advantageous since the simulation engineers can then treat the results with caution. Another expedient solution would be the utilization of other methods than simulation.

One such emerging technology is additive manufacturing. The research has identified a number of situations where additive manufacturing could act as a complement to assembly simulation. The authors argue that the results and findings to a large degree are applicable to other automotive companies as the global competitiveness in the automotive business is forcing companies to benchmark and adopt similar processes and tools. Furthermore, as the automotive industrialization environment is encompassing a large variety of complex assembly operations, it is argued that findings in the case study company can be transferred also to most other manufacturing businesses.

Decisions on when and where to adopt additive manufacturing as a complement to assembly simulation should be taken in a conscious way, based on facts, and avoid biases from the people involved. Hence, a structured framework was developed that could act as a decision support. The two matrices in chapter 4 provide an impartial decision support when additive manufacturing can be a complement to assembly simulation. The resulted framework will help companies with complex assembly

processes to know when additive manufacturing should be used, as well as for which parts and subparts additive manufacturing is applicable.

6.2 Future research

The results and findings in this thesis are to a large degree based on the processes, tools and experiences from the case company. Even though this context in a global and competitive context with a wide variety of assembly operations, the study could benefit from input from other types of manufacturing sites. One suggestion is a small scale, low production volume manufacturing operation. Another one could be an industry that is more automated, e.g. electronics companies. By doing multi-case studies, the quality, reliability and validity of the research would improve.

The most important and valuable findings of this thesis are the decision support tables. The basic structure of the tables, i.e. assembly simulation limitations, the assembly context and the parts, plus the AM limitations in the specific context, will arguably remain. However, as they are relying on the limitations of the assembly tools and the perfection of the additive manufacturing techniques, the content will inevitably change over time. Consequently, there is need for regularly updating the content of the tables with the advances of the two technologies.

Methods for supporting the assembly system design when neither AM or simulation is applicable are not included in this study, due to time constraints, this would though be an interesting topic in future research. Furthermore, the applicability of the decision support table for other simulation types, such as virtual reality (VR) is another interesting area which would be interesting to see in future research, due to the similarities in challenges related to force feedback in virtual environments.

7 References

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8 Appendices

8.1 Appendix 1: Interview questions

Interview questions

Simulation projects

- How could a simulation project be carried out?
- How much time is spent on an average project?
- Is there any specific part this department focuses on?

Technology/software

- Which software is used in the simulation project?
- Is that the only one or could there be multiple softwares?
- Have you experienced any limitations with the simulation software?
- Is there any specific parts or details that are more difficult than others?
- How accurate is the simulation software, how frequently do problems occur?
- Is there any specific areas or parts that are often problematic?
- How severe could the problems be?
- Are some problems more severe than others?
- In which stage of the simulation process does most of the problems occur?
- What is done to prevent or correct the problems?
- What do you think could be useful in order to facilitate the simulation work and reduce the problems?

Prototypes and additive manufacturing

- To what extent do your department use physical prototypes?
- What was the aim with those prototypes?
- Is there any specific part that often requires physical prototypes?
- Which attributes of the product are better to evaluate with simulation respectively AM?
- Do you have any experience with additive manufacturing in your work?

If yes,

- What parts or details have been printed out using AM?
- How was the decision made to use AM parts?
- Were there any decision criteria when deciding to utilize AM?
- What were your experiences of utilizing AM?

If no,

- Why did you decide not to use AM?
- What do you think would be necessary for you to start utilize AM?

What additional limitations or requirements exist for simulation and AM?

8.2 Appendix 2: General AM framework

General AM framework

Hierarchy 0	Hierarchy 1	Source	Hierarchy 2	General	System/parts					
					Flexibles	Flexibles & fixings	Snap closure parts	Complex boundary conditions		
Assembly Simulation	Compatibility	(Da Silva, 2013), Empirical findings	Physical incompatibility	Sim.	AM		AM			
		Empirical findings	Boundary conditions	Sim.						
		Empirical findings	Positioning	Sim.	AM					
	Ergonomic	(Dukic, 2007), (Lämkuil, 2009), empirical findings	Visibility	Sim.		AM		AM		
		(Dukic, 2007), (Lämkuil, 2009), empirical findings	Accessability	Sim.				AM		
		(Lawson, 2016), empirical findings	Forces-traction	Sim.						
		(Xia, 2013), empirical findings	Forces-torque	Sim.			AM			
		(Lim, 2007), empirical findings	Forces-pressure	Sim.	AM		AM			
		Empirical findings	Over shoulders	Sim.						
		(Falck, 2012), empirical findings	Strenuous motions	Sim.				AM		
		Empirical findings	Heavy lifting	Sim.						
		Empirical findings	Boundary conditions	Sim.						
		AM technology	(Oropallo and Piegler, 2015)	Size and shape	Depending on the specific environment					
			(Oropallo and Piegler, 2015), (Baumers, 2015), (Gao, 2015)	Build material(s)						
(Oropallo and Piegler, 2015), (Berman, 2012), (Baumers, 2015)	Manufacturing time									
(Oropallo and Piegler, 2015), (Baumers, 2015), (Gao, 2015)	Pre- and postprocessing									

Legend: Sim. Assembly simulation limitation
AM AM viable alternative to simulation

8.3 Appendix 3: Vehicle specific AM framework

Vehicle specific AM framework

					Vehicle system/part										
					Flexibles						Flexibles & fixings	Snap closure parts	Complex boundary conditions		
Hierarchy 0	Hierarchy 1	Source	Hierarchy 2	General	Interior panel	Door module	Surrounding details	Cabling	Rubber sealing	Front bumper	Cable fixings	Fuel cap	Head and tail lights		
Assembly Simulation	Compatibility	(Da Silva, 2013), Empirical findings	Physical incompatibility	Sim.		AM		AM		AM		AM			
		Empirical findings	Boundary conditions	Sim.											
		Empirical findings	Positioning	Sim.			AM		AM						
	Ergonomic	(Dukic, 2007), (Lämkull, 2009), empirical findings (Dukic, 2007), (Lämkull, 2009), empirical findings (Lawson, 2016), empirical findings (Xia, 2013), empirical findings (Lim, 2007), empirical findings Empirical findings (Falck, 2012), empirical findings Empirical findings Empirical findings	Visibility	Sim.								AM		AM	
			Accessibility	Sim.										AM	
			Forces-traction	Sim.											
			Forces-torque	Sim.										AM	
			Forces-pressure	Sim.	AM									AM	
			Over shoulders	Sim.											
			Strenuous motions	Sim.											AM
			Heavy lifting	Sim.											
	Boundary conditions	Sim.													
	AM technology	(Dropallo and Piegler, 2015) (Dropallo and Piegler, 2015), (Baumers, 2015), (Gao, 2015) (Dropallo and Piegler, 2015), (Berman, 2012), (Baumers, 2015) (Dropallo and Piegler, 2015), (Baumers, 2015), (Gao, 2015)	Size and shape	AM				large size	large size						
			Build material(s)	AM											
			Manufacturing time	AM											
Pre- and postprocessing			AM												

Legend:

Sim.	Assembly simulation limitation
AM	AM limitaton
AM	AM viable alternative to simulation
AM	AM not viable alternative to simulation because of AM technology limitations