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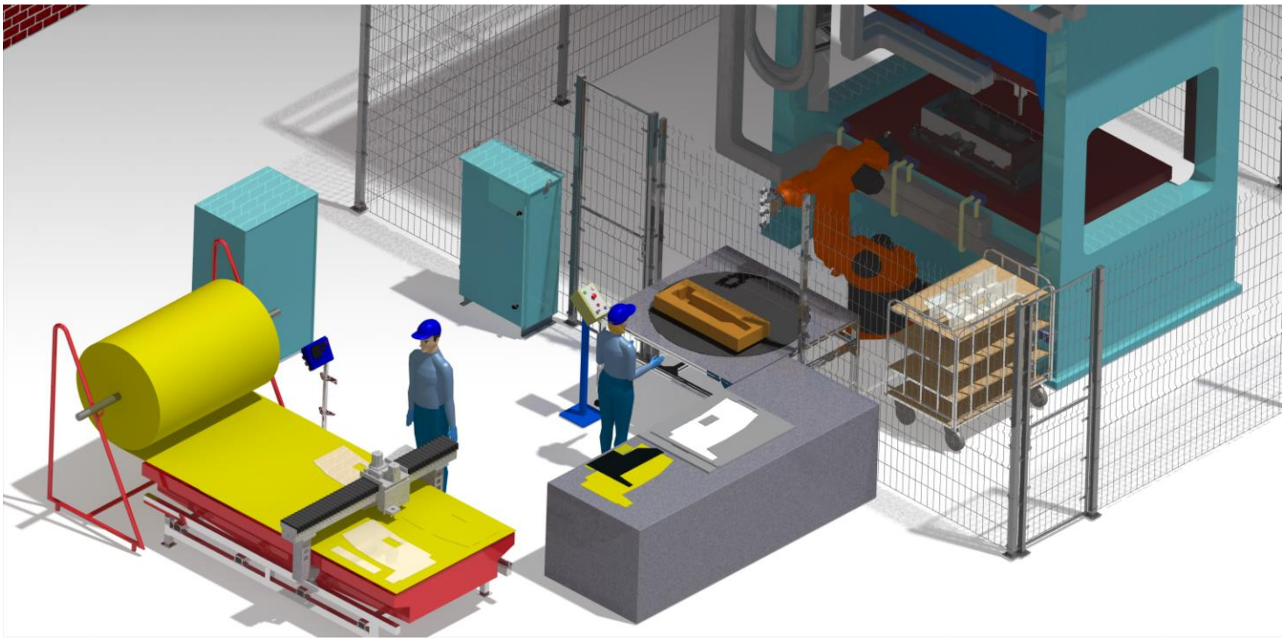

Development and Evaluation of Automation Concepts for an SMC Aircraft Interior Part

Master's thesis in Production Engineering

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Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

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Abstract

Commercial aviation aims for fuel-saving and environmental friendly aircrafts and at the same time wants to ramp-up production. The use of lightweight material such as CFRP is essential to achieve those ambitious goals but the state of the art production processes are expensive and involve much manual labour. Technologies such as the Hybrid SMC process emerged to close the gap between lightweight structures and cost-efficient production by their automation potential. However, the aerospace industry has little experience with highly automated processes and requests specific demands on quality, reproducibility and other aspects. This thesis analyses the process chain of an overhead stowage compartment (OHSC) sidewall panel manufactured of SMC to evaluate the automation potential. Therefore the DYNAMO++ and level of automation (LoA) concepts are used. The result is a matrix of possible automation solutions for the most time-consuming process steps. Subsequently, automation approaches gathered in a literature review are applied to develop solutions for a complete production system. Criteria for the evaluation are defined based on the needs in the aerospace industry. Costs, production lead time and quality are the most crucial ones. Discrete event simulation (DES) is used to verify the calculated production lead time before a utility analysis is performed to do the evaluation. The lean manufacturing approach proves to be the preferable concept to achieve the most efficient production system. Finally further improvements are suggested and evaluated including alternative shift system and tooling concepts.

Keywords: Sheet Moulding Compound, Level of Automation, Carbon Fibre Reinforced Plastics (CFRP), Discrete Event Simulation (DES), Lean Manufacturing, Aircraft Interior

Acknowledgements

First of all I would like to thank my supervisor Marc Fette for giving me the opportunity to conduct my master's thesis at the CTC GmbH Stade and for his engagement, time and feedback throughout the thesis.

I also want to thank the members of the project team of the Hybrid SMC project, especially Martin Hentschel for constructive feedback and input for the thesis, Remo Hinz and Alexander Schäfer for the participation in my workshops. Also, my thanks go to all employees of the CTC GmbH Stade for supporting me in every aspect.

Moreover, I would like to thank Chalmers University of Technology for widening and deepening my engineering knowledge as well as my thesis's supervisor Liang Gong and my examiner Prof. Björn Johansson. Many thanks also to my opposition partner Katrin Jaacks for her continuous feedback throughout the thesis work.

Last, I wish to take this opportunity to thank Prof. Dr. Axel Herrmann and Dr. Martin Röhrig for giving me the chance to start my engineering career at the CTC after writing this thesis.

Hamburg, 2016-08-31

Filipp Köhler

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Abbreviations

AC	Aircraft
ATH	Aluminium Trihydrate
BMC	Bulk Moulding Compound
CFRP	Carbon Fibre Reinforced Plastics
CNC	Computer Numerical Controlled
CF SMC	Carbon Fibre Sheet Moulding Compound
CT	Cycle Time
DES	Discrete Event Simulation
FAA	Federal Aviation Administration
FST	Fire, Smoke, Toxicity
GF SMC	Glass Fibre Sheet Moulding Compound
HTA	Hierarchical Task Analysis
LCA	Life Cycle Assessment
LoA	Level of Automation
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
NRC	Non-recurring Costs
OEE	Overall Equipment Effectiveness
OHSC	Overhead Stowage Compartment
QA	Quality Assurance
RC	Recurring Costs
SA	Single Aisle
SCARA	Selective Compliance Assembly Robot Arm
SMC	Sheet Moulding Compound
SMED	Single Minute Exchange of Die
SoPI	Square of Possible Improvements
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TFP	Tailored Fabricated Patch

1 Introduction

This chapter introduces the thesis and clarifies its aim and purpose. It will set the study into context and outlines the problem in form of three research questions. Finally, the chapter gives an overview of the study.

1.1 Thesis Context

To achieve commercial aviation's goals of fuel-saving and environmentally friendly aircraft the use of lightweight material is essential. Carbon fibre reinforced plastics (CFRP) are one of the most promising materials for this purpose (Fette M. , Wulfsberg, Herrmann, Stöß, & Rademacker, 2015). At the same time both Boeing (2014) and Airbus (2015), the biggest players in the world market, will ramp-up the production of their best-selling products during the upcoming years to match an increasing demand. This triggers the need for more efficient or new production processes and a technology transfer from state of the art concepts (single shape, manually tailored) using prepreg into semi-automatic, integrated and cost efficient production processes (Fette, Stöß, & Schoke, 2015). Most of the current technologies involve great amounts of manual work to cut and drape prepreg or textiles. Moreover the use of autoclaves and epoxy resins with long curing times leads to lengthy processes. The Sheet Moulding Compound (SMC) technology as a compression moulding technology yields the possibility to shorten those curing times by the use of alternative resins such as vinyl ester or unsaturated polyester (Fette M. , Wulfsberg, Herrmann, Stöß, & Rademacker, 2015). Furthermore it shows potential to automate upstream processes as most often the complexity of preforms is reduced. However work out the right level of automation is not trivial as the industry has no experience with highly automated processes and strict demands on part quality and complete traceability. Nevertheless the literature provides numerous manufacturing automation approaches that could be applied to develop suitable concepts.

1.2 Purpose and Objective

The purpose of the thesis is to analyse the SMC process chain of an aircraft interior part from a holistic perspective. The potential to automate parts of the chain or the whole chain shall be identified in the context of future challenges within the aerospace industry.

The objective is to evaluate possible automation concepts. The different concepts will be compared by using appropriate methods and a statement about the most suitable concepts shall be made at the end of the thesis. Evaluation criteria are production lead time, costs (NRC, RC), flexibility and other factors that are influenced by the complexity and variants of the product as well as the applied materials and required quantities.

1.3 Research Question

The automation of production processes within the environment of the aerospace industry raises several issues due to the strict requirements and limited choice of production processes. The SMC technology shows potential to be automated partially or fully. So this thesis will answer the following questions:

- What are suitable concepts to automate the production of the chosen aircraft interior part?
- What is, according to the selected criteria, the most favourable of the developed concepts?
- Is there any potential for optimisation that further enhances the performance of the previously chosen concept?

1.4 Scope

The thesis will use a new multi-material design concept for the overhead stowage compartment also known as hatrack as a representative example of an aircraft interior part in terms of requirements and quantity. The processes studied to produce the product are the newly developed Hybrid SMC process for the sidewall and the state of the art cutting and folding process to produce the housing and perform the assembly. Both processes are described in more detail later in this thesis. The focus is on the Hybrid SMC process while the steps related to assembly and finishing are neglected. The thesis will cover three different scenarios with different annual production rates that are described later on.

1.5 Thesis Outline

The thesis includes 8 chapters. The *Background* (chapter 2) summarises the state of the art knowledge of the three technological pillars Sheet Moulding Compound, aircraft interior and automation which are essential for the thesis. The chapter finishes with a review of automation concepts within the SMC industry that are already in use. The following chapter *Methodological Approach* describes how the SMC process is analysed to identify the automation potential and outlines generic approaches to enhance the degree of automation. Moreover the chapter concludes with presenting appropriate evaluation methods to make reliable statements about the most suitable concept.

Before the automation concepts are designed chapter 4 describes the base line process without any automation in the form of a process description and process time estimation. Moreover, it identifies the automation potential by using the presented methods. Subsequently, concepts are developed (chapter 5) and evaluated (chapter 6).

Finally the thesis concludes with a discussion of the findings (chapter 7) and a conclusion (chapter 8). A schematic figure of this outline is shown in Figure 1-1

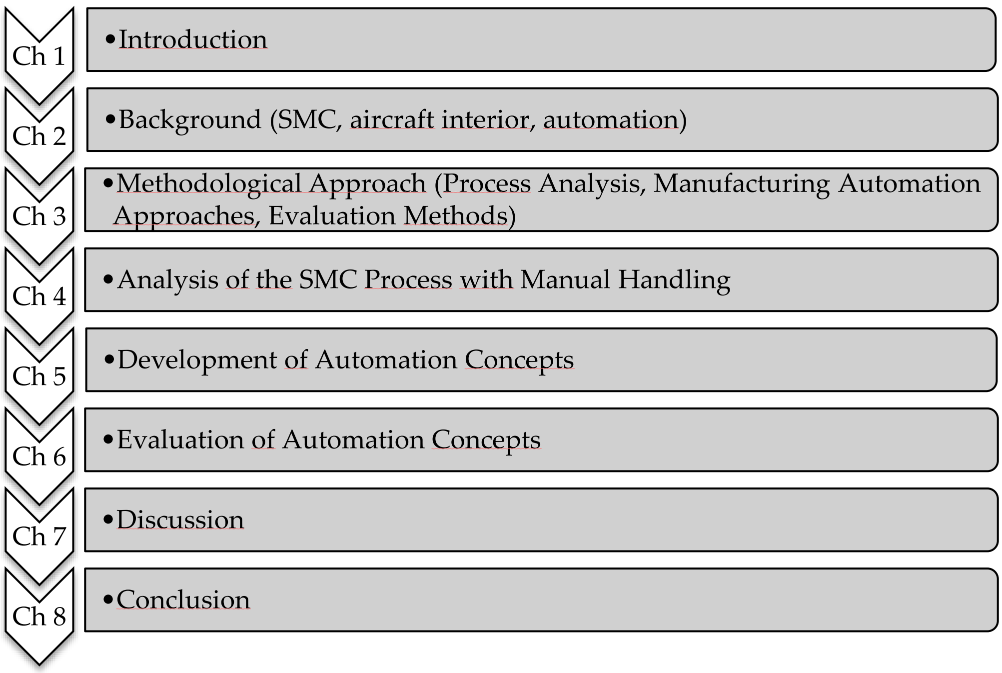


Figure 1-1: Master thesis outline

2 *Background*

The background covers the three major technological topics relevant for the thesis. It enables the reader to gain a thorough understanding of Sheet Moulding Compound, aircraft interior parts, and automation. This is inevitable to understand the needs and challenges for possible automation concepts. The chapter concludes with a review of already used automation concepts, mainly outside the aerospace industry.

2.1 Sheet Moulding Compound

Sheet moulding compound combined with a downstream compression moulding process is a widespread continuous production line process (Palmer, Savage, Ghita, & Evans, 2010) used in the automotive industry since the 1950s (Advani & Sozer, Short Fiber Composites, 2010). Although its diversity is characteristic (McConell, 2008) SMC most often consists of chopped glass fibres and polyester resin complemented by fillers and other additives (Teodorescu Draghicescu & Opran, 2014). The processing includes the process steps preparation of the SMC as a semi-finished product, compression moulding, demoulding and further mechanical processing (Mitschang & Hildebrandt, 2012). Excellent mechanical properties at low weight, high degree of design freedom and possible customization are some of the most frequently named properties of SMC products. Automotive, aerospace and the mass transit industry are the most common users.

2.1.1 Material and Production of Semi-finished Products

SMC contains resin and fibres of various kinds. Most commonly a thermoset matrix and short fibres with a usual resin to fibre ratio of 2:1 are used (Advani & Sozer, 2010) (Kenig, 2001). The automotive industry utilises vinyl ester or unsaturated polyester type resins with low shrinkage and high strength, respectively (Kenig, 2001). The aerospace sector on the other hand prefers epoxy or phenolic resins (Advani & Sozer, 2010).

Besides the type of resin numerous additives, whose proportion can be up to 50% by weight (Berthelot, 1999), have a great impact on the processability and properties of the final product. Fillers like calcium carbonate, talc or aluminium hydrate increase the hardness, rigidity and dimensional stability and improve the electrical strength. The latter filler is especially important for fire retardancy as it contains 35% of hydration which is released in the event of fire. Furthermore, adding powered polyethylene improves surface quality and impact strength. Thickeners (magnesium or calcium oxide and hydroxide) are applied to control the mouldability and viscosity of the SMC while peroxides act as catalysts and accelerators. Adding colour pigments to the list of additives an infinite number of formulations (Subramanian, 2012) can be created

The most typical fibres in SMC are randomly oriented, chopped E-glass fibres with a length between 25 and 50 mm (Mitschang & Hildebrandt, 2012). However all commonly in composites used fibre types are suitable namely carbon fibres, natural fibres, different glass fibres, and recyclates or hybrids of those. They all provide their strengths and weaknesses (McConell, 2008). Nevertheless the type is not the only factor that influences the properties of the final part. The various fibres can be more or less aligned and their length can differ too. As shown in Figure 2-1 there is SMC-R with randomly oriented fibres, SMC-D with directional but discontinuous ones and finally SMC-C with directional and continuous fibres (Advani & Sozer, 2010). The anisotropy and mechanical strength in fibre direction increase with the length and alignment as well as with a rising fibre proportion in the compound (Berthelot, 1999).

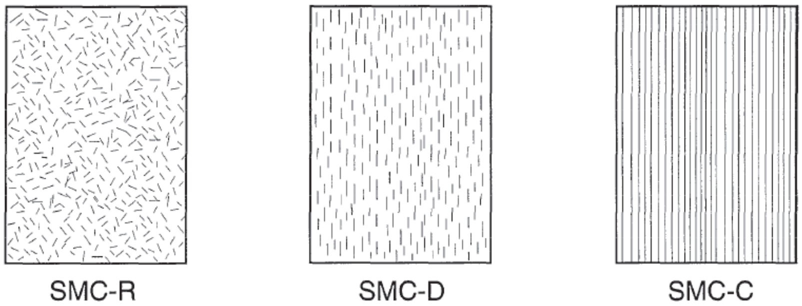


Figure 2-1: Different length and direction of fibres in SMC (Berthelot, 1999)

The production of SMC is a continuous process illustrated schematically in Figure 2-2. The premixed and thickened resin is placed on a nonporous polyethylene sheet and the random or directional fibres are added to it. The thickening or B-staging of the matrix is necessary to ensure a proper bonding between fibres and resin. A second matrix carrying film is applied and after the enclosed sheet passes through a compaction zone, which impregnates and consolidates the fibres, a roll takes up the material to a coil. The now soft and tacky compound (Berthelot, 1999) needs to mature several days under certain environmental conditions such as low humidity. (Advani & Sozer, 2010)

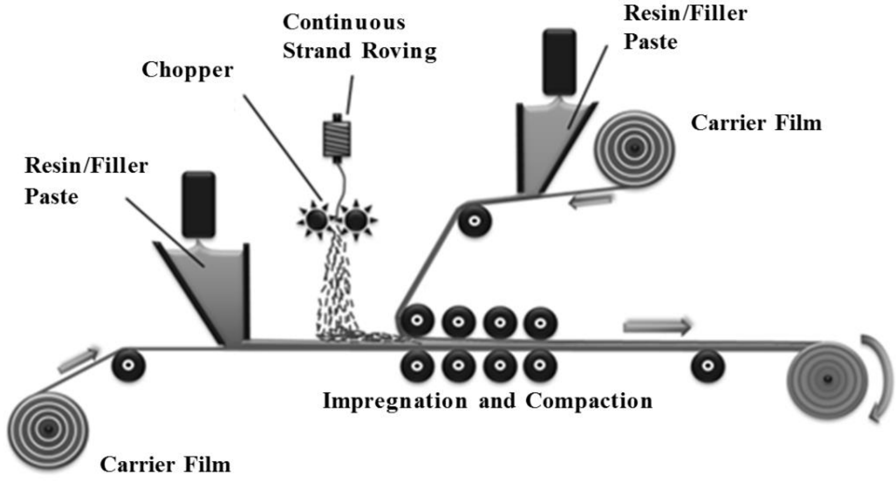


Figure 2-2: Schematic view of the production of SMC (adapted from Fette M. et. al., 2015)

2.1.2 The Compression Moulding Process

After the SMC matured it is cut into pieces. The shape is not necessarily adapted to the mould's dimension (only 50 % -80 % of the area is covered). In fact it differs in terms of complexity up to the fact that multiple layers of individual strips are stacked on top of each other before placed into the mould's cavity (Schuh, 2007). The described procedure is illustrated in the two left images of Figure 2-3 The mould has a steady temperature between 140 °C and 160°C (Mitschang & Hildebrandt, 2012) and a laser or scribe lines mark the exact position of the so called preform

(European Alliance for SMC/BMC, 2007). This initial placement influences the final part properties to a great extent. As the position determines the way the material flows it affects the content and direction of fibres especially at the part's edges. Now the mould is closed and the viscosity drops as the charge heats up whereas the cross-linking of the thermoset matrix begins. Combined with the applied 80 to 120 bar pressure (Teodorescu Draghicescu & Opran, 2014) the resin starts flowing and filling the cavity (Mitschang & Hildebrandt, 2012). Under this flow the fibres re-orientate perpendicular to the flow direction (Kenig, 2001). While the process continues the resin starts to gel and is finally cured.

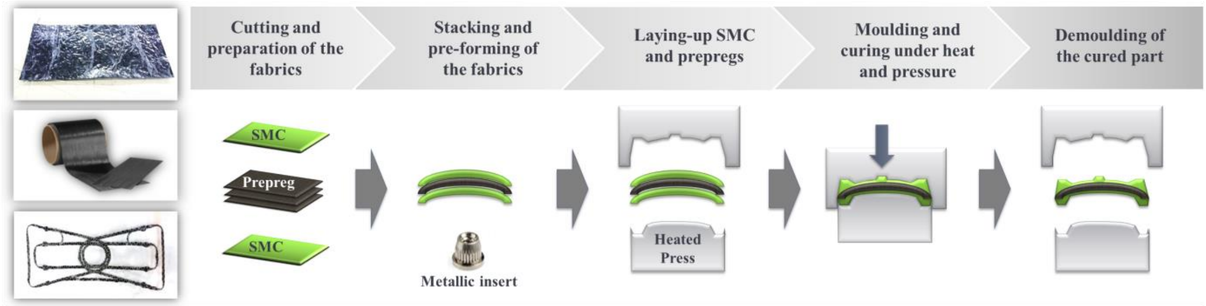


Figure 2-3: Compression moulding process cycle using SMC and prepreg material (Wulfsberg, et al., 2014)

Afterwards the finished part is ejected and de-flashed with abrasive paper as shown on the right side of Figure 2-3 (European Alliance for SMC/BMC, 2007). Between de-moulding and any kind of mechanical processing the part needs to cool down to avoid residual stresses introduced by a different thermal expansion through the thickness and in different cross-sections (Advani & Sozer, 2010). Further downstream the product is machined (holes, cut outs etc.), painted or joined with other parts.

Although the underlying thermoset cure process is well established since the 1960s, the rapidly changing market environment holds on-going challenges. Recent developments within the area are In-Mould Coating to reduce sink marks and provide a topcoat-like surface as well as in situ real time monitoring (European Alliance for SMC/BMC, 2007) (Subramanian, 2012). The SMC process has several advantageous and disadvantageous properties. On the one hand it is fairly simple, cycle times can be short, and the part quality is highly repeatable but on the other hand large initial investments in moulds and presses are necessary, the material must be stored under certain environmental conditions, and can just be processed for a limited time period (Advani & Sozer, 2010). Likewise the finished part has specific characteristics which are described in the next passage in more detail.

2.1.3 Properties

SMC shows a wide range of fibre volume fraction between 20% and 50% (Advani & Sozer, 2010) and consequently the properties vary as well. High modulus SMC can reach a modulus up to 15 GPa (45% fibre volume content) while low density SMC using hollow microsphere has a modulus just about 8 GPa but on the other hand enables lower part weight (Kenig, 2001). The European Alliance for SMC/BMC (2007) provides a broad list of various advantageous properties of Sheet Moulding Compound:

- Excellent mechanical properties even at very high and very low temperatures (Kenig, 2001) (Subramanian, 2012)
- Design freedom (Schuh, 2007)
- Low thermal expansion coefficient comparable to steel (Schuh, 2007)
- Low weight (McConell, 2008) (Subramanian, 2012)
- High temperature paintability (Schuh, 2007)
- Excellent dimensional accuracy and stability (Schuh, 2007)
- Low system costs through integration of parts and functions
- Favourable life cycle comparison
- Flame retardancy and low smoke emission, halogen-free formulations
- Speed to market and customization

Most of the named properties are supported by other authors while the favourable life cycle comparison results from a life cycle assessment (LCA) conducted by the organization. In LCA the environmental impact of a specific product from cradle to grave is assessed including manufacturing, use, and disposal or recycling. The study compared an automotive part made in steel, aluminium, and SMC and the latter variant turned out to be the most favourable in terms of ecoefficiency (European Alliance for SMC/BMC, 2007).

Nevertheless is has to be pointed out that unresolved issues of fibre orientation and residual void formation leads to anisotropic properties that are not fully understood (Subramanian, 2012). On the contrary the numerous properties and especially the potential customization by a change of fibre volume content and resin formulations pave the way for a vast amount of applications.

2.1.4 Applications

Sheet Moulding Compounds are mainly used in the automotive and aerospace sector, for household goods, and in the electrical industry. Applied in hoods, deck lids or door panels (Figure 2-4) some cosmetic problems are encountered. To avoid the necessity of painting vacuum is applied during the mould cycle (McConell, 2008). The majority of applications are in outer body and structural panels of commercial vehicles rather than cars where it is used in niche vehicles in small quantities only (Schuh, 2007).

A prominent example is the Mercedes-Benz SLR McLaren using a full CFRP monocoque. Traditionally deep-drawn parts with their geometrical complexities are manufactured in a single mould process in a scale of several thousand parts for the first time. An automated preform layup and the use of endless carbon fibres enable nearly net-shape production and tailored fibre orientations ensure excellent properties (Kim, 2007). The use of carbon fibres offers potential weight savings because of the higher stiffness and strength as well as a lower density compared to regular glass fibres. This allows reduced wall thicknesses of up to 38% and even adjacent parts can be designed lighter which increases the weight savings (European Alliance for SMC/BMC, 2007). The potential use of recycled carbon fibres makes the use of SMC even more attractive.

Figure 2-4: Sliding sun roof, class A spoiler and truck front lid manufactured in SMC (from left to right) (European Alliance for SMC/BMC, 2007)

An industry that makes use of another segment of SMC properties is mass transit such as trams and trains. SMC is an excellent electrical insulator and is used as spark guards and arc barriers. The wide variety of resin formulations allows the compounders to develop grades of SMC that fulfil the strict international FST (Flame, Smoke, and Toxicity) requirements and design a new tough and vandal resistant interior layout (European Alliance for SMC/BMC, 2007).

The aerospace industry which is interested in using SMC for interior applications uses high content epoxy resin to fulfil their requirements. Furthermore the goal is to replace aluminium as secondary structural parts in wings, control surfaces, or nose cones (Advani & Sozer, 2010). To widen the area of application, new technologies have emerged to combine glass and carbon fibres as well as metal sheets or inserts in the sheet moulding compound process which is called Hybrid SMC.

2.1.5 Hybrid SMC

The use of carbon fibres in SMC also called Advanced SMC is commonly known since the Mercedes SLR Silver Arrow (McConell, 2008) but the first recipes using epoxy resin with no filler for maximum weight savings (European Alliance for SMC/BMC, 2007) date back to the year 2004 (McConell, 2008). The produced panel was 60% lighter compared to its metal version but the price of carbon fibres was a major challenge to overcome (Mitschang & Hildebrandt, 2012). Similarly the aerospace industry was a first user of Advanced SMC, too. In this sector performance is rated higher than costs and C-fibres offer a modulus three times higher than E-glass (Palmer, Savage, Ghita, & Evans, 2010). While the initially used chopped random fibres led to decreased mechanical properties compared to parts produced in traditional CFRP technologies, unidirectional continuous strands could close this gap. Consequently the SMC process had to be modified. Due to the reduced flowability of continuous fibres 85% of the cavity needed to be filled and the complexity of the preform increased. This preform finally constituted of several thin and individual layers (Schuh, 2007).

To overcome the issue of high costs for virgin carbon fibres mats and fleeces of recycled carbon fibres as shown in Figure 2-5 were used. 10-30% of the annual carbon fibre production goes directly to waste and is not used in products. With the so called pyrolysis process already impregnated fibres as well as end-of-life parts are separated from their matrix. The result is fibres that have 90% of their initial tensile strength and can be further processed to the mentioned fleeces and mats. (Fette M. , Wulfsberg, Herrmann, Stöß, & Rademacker, 2015)

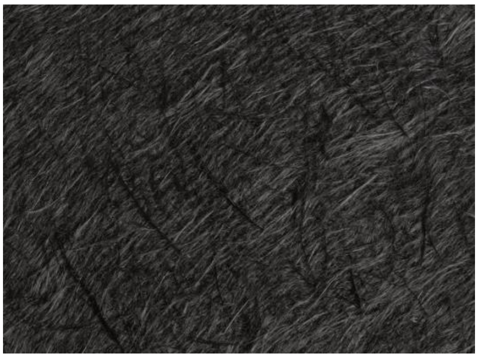


Figure 2-5: Needled airlaid fleece made of pyrolised carbon fibres (Fette M. , Wulfsberg, Herrmann, Stöß, & Rademacker, 2015)

The concept of hybrid SMC goes even one step further. With this approach, illustrated in Figure 2-2, conventional chopped fibres, continuous fibres, and metal inserts or sheets can be combined in a one shot process. The oriented fibres, used to produce cabin interior parts for aircrafts, ensure sufficient mechanical properties and metal inserts provide attachment points to the aircraft structure or system installations. Thereby the multi-material construction takes advantage of the different material groups. The mix of fibre types makes the adaption to certain mechanical characteristics possible and the integration of metal inserts allows saving assembly steps and therefore increases the productivity and lowers total production costs (Wulfsberg, et al., 2014). Nevertheless there are some drawbacks connected to residual stresses within the part due to different thermal expansion coefficients, a lack of bending stiffness and problems with the mechanical finishing (Fette M. , Wulfsberg, Herrmann, & Ladstaetter, 2015).

2.2 Aircraft Interior Parts

As aircraft interior are all parts considered that are situated between the cockpit wall and the pressure bulkhead in the rear fuselage. It is distinguished between the upper deck, where passengers are accommodated, and the cargo compartment. Typical examples are floor panels, sidewall panels, overhead stowage compartments, dividers, lavatories, and the seats (Figure 2-6). (Schaich, 1995)

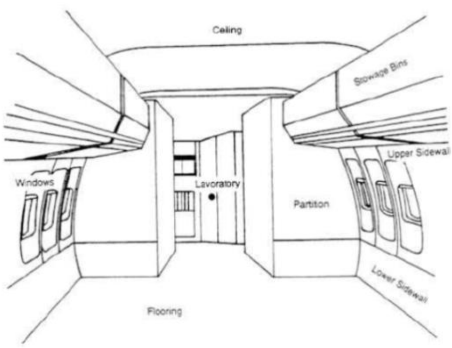


Figure 2-6: Aircraft interior cabin components (Committee on Fire and Smoke-Resistant Materials for Commerical Transport Aircraft, 1996)

2.2.1 Design and Requirements

During the flight several more functions than only transport the passenger from a place of departure to a place of destination must be performed. The interior furnishing of an aircraft needs to be designed in a way to fulfil the requirements of regulatory agencies, the airlines, their passenger and crew and the aircraft manufacturer (Committee on Fire and Smoke-Resistant Materials for Commerical Transport Aircraft, 1996). It has to accommodate passengers, protect them and provide service or entertainment. Each airline prefers a different arrangement which leads to an almost unlimited variety of design configurations. (Schaich, 1995)

Accommodation of passengers means a cabin layout that fits the needs of the passenger and the airline. There is a trade-off between maximum transport capacity and maximum comfort which changes with the flight time. It includes the arrangement of seats and aisles but also stowage space for hand luggage and escape routes. Trends for passenger service and entertainment are diverse. On the one hand is an increasing amount of service facilities at some airlines and on the other hand are inexpensive flights with almost no passenger service at all. (Schaich, 1995)

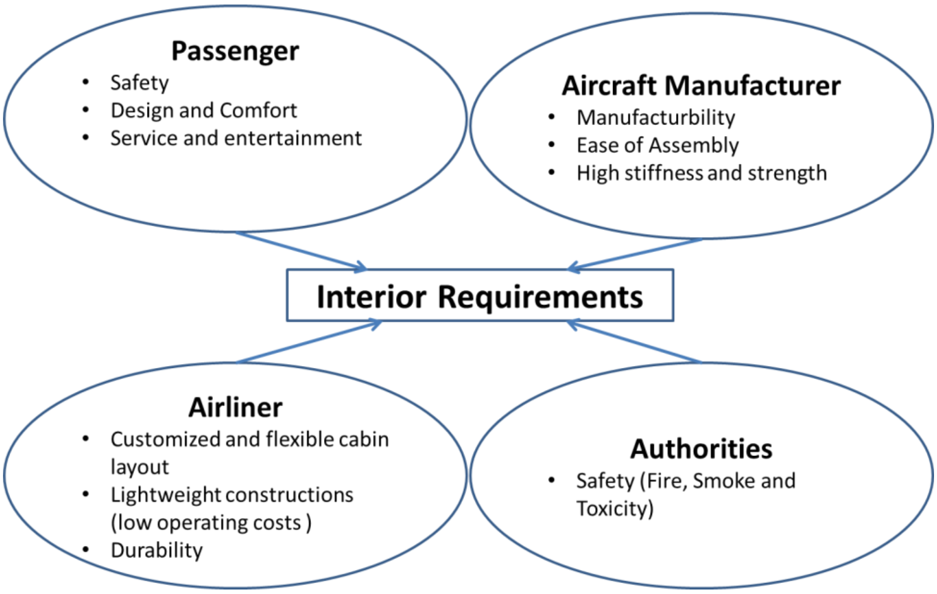


Figure 2-7: Aircraft interior requirements from the standpoint of different actors

The protection of the passenger is a primary requirement, both in normal operation and in emergency situations. The safety system comprise of several features. The lighting system and signs provide guidance and information regarding the use of certain facilities. Likewise the air-conditioning protects the passenger from temperature and humidity at flight altitude and the stowage compartments receive the hand luggage to avoid injuries caused by dropping luggage. Additionally all materials used inside the cabin must be FST (fire, smoke, toxicity) proofed. They are allowed to emit thermal energy, smoke and toxic gases only to a degree that is accepted by the FAA (Federal Aviation Administration) (Schaich, 1995). The three flammability requirements for a cabin liner for instance are ignitability, heat, and smoke release that are tested according to FAA procedures (Committee on Fire and Smoke-Resistant Materials for Commerical Transport Aircraft, 1996). Two types of fire scenarios can occur: in-flight and post-crash. The first results from a system or component failure while post-crash fires usually include the ignition of fuel released during a crash landing for instance (Tutson, Ferguson, & Madden, 2011). In general safety measures are classified in active features (e.g. fire extinguishers) and passive features (e.g. non-flammable materials) and should minimise the risk potential during use and the risk of accidents (Schaich, 1995).

This variety in requirements leads aircraft manufacturers to develop interior furnishing that allows a high degree of flexibility in configuration and design but keeps costs for manufacturing and operating in certain limits. (Schaich, 1995)

This ends up in specific requirements for the interior parts themselves. High strength and stiffness and a lightweight construction as well as fulfilment of safety requirements have top priority. But design and colour, durability, manufacturability and handling are important, too. The lightweight aspect is especially important because the weight of the interior has a direct influence on the payload that can be transported and in this way on the profitability of the whole aircraft (Schaich, 1995). Over the lifespan of an airplane one extra pound on the airframe results in up to $400 extra costs only for fuel. Regarding strength and stiffness cabin interior components need to withstand typical flight loads which are called limit loads. However abuse loads (e.g. bumping, pushing, and pulling handles) are design criteria as well. Under those only elastic deformation is allowed. The great cost pressure within the industry demands ease of manufacturing and assembly. The main driver for costs is processing labour. Part configuration and the chosen process determine the amount of labour; while hand lay-ups of sandwich structures (most common nowadays) are very labour intense, injection-moulded parts for instance have their advantage in this sense. After the components are installed in the cabin they are exposed to various environmental factors like vibration, water and moisture, corrosion or impact damage. Consequently all of them need to be resistant to those factors and mild abuse to avoid replacements that generate costs for the airliner or leads to annoyed customers in case of broken equipment (Committee on Fire and Smoke-Resistant Materials for Commerical Transport Aircraft, 1996).

2.2.2 Materials and Manufacturing

Composite and hybrid structures in particular sandwich structures are almost always used for interior parts while metals make a minor contribution. Most often the preformed parts are finished with decor foils, vanishes or textiles and temperature-resistant layers to enhance their fire resistance. To make the replacement of parts easy and avoid costs interior assemblies use simple principles like plug-in, snap or locking (Schaich, 1995). The FST behaviour of those systems is determined by the choice of material and the manufacturing process and both have to match the designated application area.

Thermosets such as unsaturated polyester and phenolic resins contain additives or are finished with coatings to meet the requirements. This can be aluminium trihydrate (ATH) imbedded in microcapsules. A high ratio of ATH in SMC formulation was used to limit stable processing. But recently the Polynt GmbH in corporation with Airbus managed to enhance the flame retardant additive ratio to an extent that makes cabin applications possible. It was realised by an optimised crystal size distribution (Stoess, Fette, & Schoke, 2015). Cyanate ester systems or bismaleimides are characterised by good fire resistance but long cycle times, high processing temperatures and costs hinder an extensive use. Nanomaterials reveal another opportunity. These materials with a grain size between 1 and 100 nm yield dramatically improved or altered properties but the mechanism behind those properties are not fully understood. (Committee on Fire and Smoke-Resistant Materials for Commerical Transport Aircraft, 1996)

Sandwich structures consist of a hexagonal honeycomb core covered by two fibre-reinforced plastic layers (e.g. phenolic resin) on the top and on the bottom. Decorative foils and paint are applied to meet the decorative requirements. Flat sandwich structures most often use one-shot curing in a flat press. The prepreg layers are bonded on the honeycomb using the resin as adhesive. Curved sandwich structures are produced in the crushed-core process. Similarly a press is used and all components including inserts are placed in the tool. The honeycomb is given an oversized thickness (up to 40%) and is inevitably crushed which results in an improved surface quality compared to conventional pressing. The pressure can exceed 20 bars and the curing time is approximately 10-15 minutes at 175°C. The process is very robust and produces consistent quality at reasonable costs (Gardiner, 2014). Afterwards the decorative varnish is applied in three steps: spray filler, apply smooth coating and finally the top varnish (Berg, 1995). This manual process is a major cost driver and initiatives to combine for instance moulding and application of the decorative foil would cut costs significantly. Furthermore the use of automation equipment for ply cutting and location has shown to be promising. Another trend is the use of continuous-fibre reinforced thermoplastics which provides significant cost benefits (Committee on Fire and Smoke-Resistant Materials for Commerical Transport Aircraft, 1996).

An aircraft fuselage can be described as a flexible tube and composite interiors need to be attached to it with a lot of hard to reach tie rods and attachment points requiring lots of manual labour (Gardiner, 2014). In the future the flow time for manufacturing needs to decrease by simplification and mechanization of assembly sequences to finally cut costs. From an ecological standpoint carcinogenic and mutagenic products that harm production workers especially during the resin production and the environment need a step by step substitution. Consequently replacements for phenolformaldehyde resins are necessary (Berg, 1995). Even some of the flame-retardant additives need examination regarding their impact on the environment. On the contrary the certification of new materials is associated with high costs and risks for the material supplier and the aircraft manufacturer (Committee on Fire and Smoke-Resistant Materials for Commerical Transport Aircraft, 1996).

2.2.3 The Overhead-Stowage-Compartment (OHSC)

The OHSC provides capacity for passenger carry-on baggage and other equipment (e.g. first aid kits, crew oxygen bottles). They are attached to the aircraft structure and are part of the visual and acoustic cabin concept. Depending on the number of aisles they are installed above the left, right and centre seat rows (Airbus S.A.S). There are three basic models of OHSC. The first and simplest one is the shelf bin (Figure 2-8 right). This type opens outwards and up and is still most often used. The second and third variant can be found in twin-aisle aircrafts, namely pivot (Figure 2-8 left) and translating bins. This hatrack has a controlled rate of opening and enables good visibility for the passenger because the door opens out and down (Simmons & Worden, 2001).

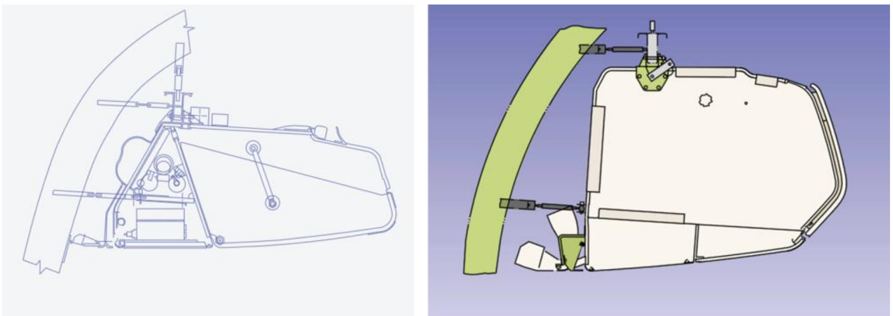


Figure 2-8: Illustration of a pivot bin in closed position (left) and shelf bin (right) used in Boeing aircrafts (Simmons & Worden, 2001)

The bottom of the pivoted (moveable) bin provides the load-carrying surface. The compartment is opened by pivoting the bin in vertical direction with the aid of two dampers that provides sufficient comfort for passenger regarding opening and closing the bin. The bin is secured in the closed position by latch mechanisms. An installed and opened OHSC loaded with baggage is shown in Figure 2-9 .Each OHSC consists of a housing and a bin while each of them in turn are built from sidewalls, bottom or top panel respectively and various attachments.

Figure 2-9: Pivoting Overhead Stowage Compartment loaded with bags (Airbus S.A.S)

2.3 Automation

The chapter of automation describes several aspects that are important or touched by this thesis starting with a definition. The terms cognitive and mechanical automation are introduced which are later used in the Level of Automation concept. The chapter continues with a quick overview about the reasons for automation to give a basic understanding. Next limitations of automation are presented which directly lead to human-machine interactions as some tasks cannot be solely by machines. The chapter concludes with examples of automation concepts and systems that are already used in the manufacturing of composite parts in general and can be considered as state of the art.

2.3.1 Definition

An automated manufacturing system performs operations such as assembly, inspection or material handling on the physical product with a reduced level of human participation both physically and cognitively (Electrical-engineering-portal.com, n.d.). Nof (2009) suggests that automation is the combination of four fundamental principles: mechanization, process continuity, automatic control, and rationalization. Robotics in particular focuses on autonomous or semiautonomous systems incorporating actuators and sensors which corporate with humans in one or the other way (Goldberg, 2012). The actual robot such as the one in Figure 2-10 can be programmed to perform a number of different tasks and in case of the displayed articulated robot is highly variable and flexible. Other types of robots can only be used for a specific set of tasks (Nof, 2009). Most automated systems are still semi-automatic consisting of combinations of automated and manual tasks. With the growth of the information technology system were in the centre of attention that combined information and mechanical technology covering both physical and cognitive labour (Frohm, Lindström, Stahre, & Winroth, 2008).

Figure 2-10: Articulated robots in an automotive painting line (Nof, 2009)

2.3.2 Mechanical vs. Cognitive Automation

In a production environment that gains in complexity, more and more information need to be handled and companies have to find ways to convey those information to their recipients, which are either human operators or machines and robots (Fast-Berglund, Akermann, Karlsson, Garrido Hernandez, & Stahre, 2014). This calls for cognitive automation which is defined as a computerised system that provides relevant information to operators. Most often the term automation refers to mechanization and the integration of environmental variables to replace the human operator with machinery in doing physical tasks. This is referred as physical automation and most often associated with manufacturing machines and robots (Frohm, Lindström, Stahre, & Winroth, 2008). If mechanization includes cognitive and decision-making function the modern term automation becomes appropriate (Nof, 2009). Physical automation still requires operators, even though a different type,, to perform cognitive work such as data processing, supervision, interpreting information, and decision making. Those cognitive tasks are usually divided in skill-based, rule-based and knowledge based types. To minimise the mental workload, which typically increases with the physical level of automation (LoA), and increase productivity well-designed cognitive automation solutions are necessary. (Choe, Tew, & Tong, 2015)

Choe et. al. (2015) investigated the effect of cognitive automation on manufacturing flexibility in a material handling system. An operator had to perform supervision, control, planning and decision making as cognitive tasks and loading/unloading materials and moving parts as physical tasks. The research team focused on cognitive automation. Because it is easier and less expensive to implement and although it does not affect the mechanical LoA or the number of tasks it does affect cycle times and downtimes which as a conclusion enhances flexibility. The adaption of the user-interface of the feeding robot to graphically present the operator the origin of a malfunction instead of providing only textual information is an example for a simple change of the system's interface which enhances the operator's ability to deal with a series of cognitive tasks. Another measure taken was to provide tactual and auditory information complementary to already existing visual aids that were rather complex.

2.3.3 Reasons for Automation

The reasons for companies to make an effort to automate their production processes can vary to a great extent. The benefits can be tremendous. One typically distinguishes between nine aspects that are influenced by automation:

Increase productivity	An automated manufacturing system usually increases production rate and labour productivity by reducing the time for repetitive tasks. Machinery can operate with high speed and capacity that would be impossible without automation
Reduce labour and capital costs	An investment in automation leads to a replacement of manual operations. Material waste, inventories and shop floor space savings are further effects.
Mitigate the effects of labour shortages	A shortage of labour in some countries drives the development of automated operations. Automation changes the nature of the work and therefore requires a different set of skills and training by the operator
Reduce routine manual tasks	The reduction of routine tasks has a certain social value and constitutes to the improvement of working conditions. Usual effects of repetitive routine tasks are a bored and slowed down workforce.
Improve worker's health & safety	Transferring the task of the operator from active participation to passive supervisory makes the workplace safer. Additionally the operator does not need to operator in hazardous environments and most often the ergonomics are improved as well.
Improve product and process quality	An automated system performs the task with greater uniformity and conformity to quality specifications and reduces the defect rate. Furthermore it reduces the room for human errors. Auditing processes are simpler which makes the analysis of the production system easier.

Reduce manufacturing lead time	Automation can reduce the time from customer order to product delivery and at the same time cuts work-in-process inventory.
Accomplish processes that cannot be done manually	A set of operations requires the use of machines due to precision requirements, the complexity of geometry, vast amount of data or enormous process speed.
Intangible benefits	There are a lot of intangible benefits that are difficult to relate to the introduction of automation such as higher sales, better labour relations, company image or increased customer satisfaction level

(Electrical-engineering-portal.com, n.d.) (Valuestreamguru.com, 2016) (Hed, 2015)

2.3.4 What can Be Automated and What Cannot?

In theory the limit of automation is set by its meaning which is about self-moving or self-dictating rather than self-organizing. People even think that self-organizing automation would not be a good thing. While one automates one mechanises some aspects of a system but only those aspects that are highly specialised or can be made highly specialised. In other words one extracts some portion of a system. If one cannot do so, one simply cannot automate the process. On the contrary it does not mean that one is limited to the mechanical metaphor used today but the next step would be to imitate aspects of how a system itself works (Patton & Patton, 2009). On the contrary an extreme degree of automation does not always achieve the desired objectives. Industrial robots for example reach their limit when a work task requires a great deal of perception, skill or decisiveness and cannot be realised in a cost-effective way. Developments in the machine-machine interaction and robotics made stationary or mobile assisting robots available which can work together with the human operator and form a hybrid production system (Spath, Braun, & Bauer, 2009).

The use of robots for handling operations is state of the art. They are used for loading and unloading machine tools, die-casting machines or simply transport components between stations. They reduce cycle times and even save valuable shopfloor space because the designer needs to seek for more compact layouts due to reach limitations. The aspect that robot handling systems can quickly be retooled and reprogrammed is another advantage. The most often performed task is “pick and place” with or without insertion. In case of machine unloading auxiliary tasks such as die cleaning and lubrication are carried out. If one robot is loading and unloading the machine the robots end effector has to be capable of handling the part before and after processing.

Automated assembly operations are not very widespread and limited to applications with large production volumes because of the immense hardware costs. The difficulty is that more than one workpiece needs to be located with respect to any associated tools in the workplace. Furthermore to be assembled they have to maintain certain orientations and relative positions while moving with respect to other objects (Appleton & Williams, 1987). Precision can be seen as an enabler of automation, especially for assembly. The interchangeability which means that parts are consistently produced to specification reduces fitting and rework. Modern manufacturing principles such as lean and agile manufacturing are highly dependent on it but automation can at the same time enable precision by minimizing variability and human errors at the production of the single parts (Donmez & Soons, 2009).

2.3.5 Human-Machine Interaction

The success of a human automation system depends on the quality of the support provided by the automation and the way the human makes use of the system. There are several attributes which are closely connected to and influenced by each other. The automation reliability and the perceived reliability (or trust) are two of them. The latter is improved as the automation reliability increases. But knowledge about reliability has an influence, too. As information about the casual nature of unreliable behaviour is available the trust towards automation rises. The more humans trust automation, the more likely they rely on it and a high LoA lead to an increase in overall performance. As a consequence the fact that the operators completely trust the system can end up in the situation that they are unable to detect automation failures or act as a backup system. (Sanchez, 2009)

The degree of automation affects the decision and action selection. As more tasks are allocated to machines the human operator has more of a supervisory function. In some domains such as inspection humans can still outperform machines. In other areas people and robots work in close collaboration which can lead to several issues. Some of them are safety, task delegation or authority. One solution to overcome part of it is establishing a thorough basis of trust in the automation especially in unanticipated or complex situations. If a system is not trusted operators tend to ignore alarm system or try to verify the existence of a failure by themselves which leads to productivity losses or dangerous events. An aspect always present in human-machine interaction is safety and the risk of injuries. Countermeasures are to use rigorous safety installations or to use remote control through teleoperations for instance and in this way keeping the human outside the dangerous zone.

An increasing rationalization and automation yields the risk to separate the human from its work. One has to realise that the human contribution will always influence the performance of a production system. A high amount of products is customised and the required production system needs flexibility and dependability. An entirely automated system cannot fulfil those requirements which call for hybrid automation to utilise the specific strength of humans and machines. This human-oriented design subordinates man to the technical-organizational conditions of a work process and helps to sustain humane conditions (Spath, Braun, & Bauer, 2009).

2.4 State of the art automation concepts for the production of composite parts

While in low to medium volume production of SMC products the cutting and placement of the plies is done manually high volume automotive applications use the aid of automation. This automation is critical to the competiveness of the technology towards injection moulding (Advani & Sozer, Overview of Manufacturing Processes, 2010). Especially if the preform constitutes of several individual strips and is rather complex automation should be introduced to achieve a highly uniform quality and also limit costs (Schuh, 2007). The European Alliance for SMC/BMC (2007) describes such a highly automated process chain. At the beginning the SMC material is peeled of its carrier film and slit into appropriate pieces by an automatic station. Afterwards the plies are stacked in predetermined charge patterns and the weight is checked to ensure it complies with the set tolerances. A robot equipped with a needle gripper accurately places the preform inside the mould at a determined position. The demoulding again is done by a manipulator. The de-flashing which is normally done manually can be automated as well to ensure consistency especially in areas of critical tolerances. The job of machining the parts afterwards is most often done by CNC machines even in low and medium volume production due to requirements for precision that the machines can provide. Besides conventional 5-axis milling machines waterjet and laser cutting is utilised.

One obstacle for the implementation of automated production system in the composite industry is the high investment per task. Therefore a feasible automation system should be able to carry out several tasks. Typical examples for such systems are "pick and place" solutions. They minimise the time-consuming manual work between the cutting table and the mould but at the same time preceding and subsequent processes remain unchanged. Furthermore the manual placement lacks accuracy that can be compensated only to a certain extent by laser projection systems and if fabrics exceed a certain size manual handling without damaging the plies becomes generally difficult. Automated gripping systems (Figure 2-11) using needles, vacuum or even frozen water can handle big plies, ensure that only a single layer is picked up and place it reproducibly into position. At the same time proper process documentation can be achieved. Rather advanced systems with specifically designed end effectors stitch dry fabrics to generate complex 2D or 3D-preforms and even integrate metal inserts. (Wittig, 2005)

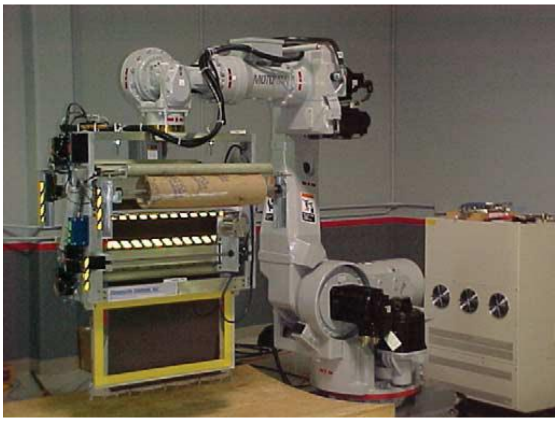


Figure 2-11: End effector for placing prepreg mounted on an industrial robot (Wittig, 2005)

Angerer et. al. (2011) developed a handling system for non-resinous dry carbon fibre textiles. The automatically cut plies are gripped, draped, and fixed in the mould. The system copes with small as well as large textiles. During the development the constructed end effector was integrated in an industrial robot (Figure 2-12). The process includes heating the vacuum-gripped ply to activate the binder and draping the textile into the mould to finally produce a 3-D preform. The work allows automating the most time-consuming step in CFRP manufacturing which is still performed manually in state of the art processes. The creating of the draping movements needs a high expertise and has to be considered semi-automatic rather than automatic.

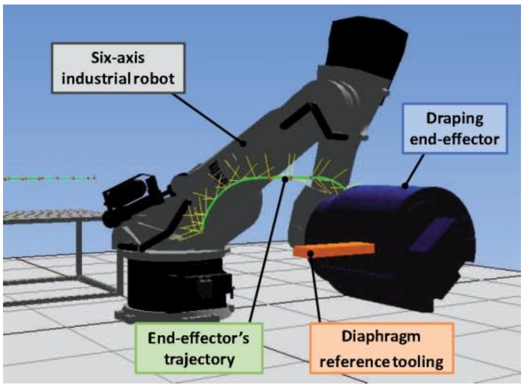


Figure 2-12: End effector for draping small and large dry textiles mounted at an industrial robot (Angerer, Ehinger, Hoffmann, Reif, & Reinhart, 2011)

A very sophisticated approach is done by Dieffenbacher. They developed a fully automated system to produce thermoset SMC components including a high-speed press, cutting and stacking tools as well as finishing machining. Loading and unloading is done by industrial robots as it can be seen in Figure 2-13. Furthermore the system can be expanded by cooling stations, conveyor belts or safety equipment if needed. The company goes even one step further and has got a so called "SMC Directline" in their portfolio. Besides all the above mentioned features, the system starts the process by producing the SMC semi-finished product using fibres, resin and fillers. This yields the advantage to bypass the costly and time consuming maturation step and avoids unnecessary logistics. (Dieffenbacher GmbH, 2015)

Figure 2-13: Fully automated SMC production line by Dieffenbacher (Dieffenbacher GmbH, 2015)

3 *Methodological Approach*

This chapter compiles all methods used throughout the thesis and in this way outlines the applied way of working. Each subchapter represents one step in the project and presents all the required tools within this step. First a thorough process analysis conducted with the aid of utilization charts and level of automation reveals automation potentials after the process is mapped. The second phase focuses on manufacturing automation approaches needed to design appropriate concepts. Finally, (to enable verification and validation of the automation concepts) discrete event simulation and evaluation methods are explained.

3.1 Process Analysis

During the process analysis two major methods are used. First of the process has to be mapped using a flowchart comprising of block diagrams. As the flow chart contains only the names of stations and activities the mapping is complemented with a table including detailed descriptions and pictures for every step. The second method is the *DYNAMO*++ including the theory of *Level of Automation*. DYNAMO++ has its starting point in the process analysis but the steps described apply to all following steps within the project such as design of future improvements or visualising them. The method concludes with a description of Squares of Possible Improvements (SoPIs). The future automation concepts are based on them.

3.1.1 Process Mapping

Process maps are generally used to ensure that the activities of a process are well understood and provide a basis of communication. They can vary in level of detail and appearance. One type of maps is a flowchart. A flowchart shows the sequence of activities (Accounts Comission, 2000). Among the vast amount of possible choices the block diagram is an easy to use and easy to understand type and gives a quick overview of the process sequence. Often the start is a macro-map that in case of a manufacturing process can be the sequence of workstations. To enhance the level of detail micro-maps are then created for each workstation and integrated into the flowchart (Kalman, 2002). Nevertheless those block diagrams can only visualise the logical flow of steps within a specific process. Hernandez-Matias et al. (2006) suggest complementing those information models, as they call them, with quantitative attributes gathered in an initial stage. In case of the overhead stowage compartment real data are not available because the physical process is not in place yet but data from similar SMC manufacturing processes can be used as a guideline. The processes share a lot of communalities and are comparable in many of their aspects. To cope with the alterations a workshop with experienced engineers and input data provided by suppliers are used. Cycle times, process times and set-up activities are crucial to determine as quantitative data. On the qualitative side quality requirements and ergonomic issues as well as safety concerns are important to determine.

After gathering the data for the single work tasks the logical sequence is developed. Similarly the manufacturing processes of SMC components in general are the basis. Variations are the result of a different design and a subsequent assembly process. To enhance the understanding and verify some of the estimated data the principle of *genchi genbutsu* (go, look and see), as it is suggested in the lean philosophy, is used (Liker & Meier, Background to the Fieldbook, 2006). Although a fully operational production line is not in place yet the operational steps associated to the sheet moulding compound process can be observed on a laboratory scale. This provides a thorough understanding of the most crucial and innovative steps which is necessary to evaluate their automation potential in the later process.

3.1.2 Level of Automation and Dynamo++

The easiest distinction between automation systems is complete automated systems, semi-automation and manual systems. The first system does not need any human support but reliefs the worker from any physical task. This could be necessary due to dangerous working conditions or a precision that cannot be achieved by an operator. Semi-automated systems need some human support. This could be start or end a program for instance (Spath, Braun, & Bauer, 2009). Finally there is the fully manual system without any help by automation technology, although the increasing complexity in production systems requires a more detailed distinction and the consideration of multiple aspects.

An efficient and flexible manufacturing system requires both an advanced technical system and skilled human workers and thus one needs a deep understanding of automation and ways to approach it to decide upon an appropriate level of automation. Aspects such as sharing of tasks, control and authority between humans and machines are in the spotlight, especially when it comes to human-machine integration. The level of automation concept is based on the assumption that a manual work task is performed without any tool or support simply by the human operator. With an increasing level the support is increased or the operator gets tools as an aid. The highest level is reached when full automation is in place. Thus automation is not an all or nothing decision but should be rather seen as a continuum from manual to fully automated. Furthermore automation is classified in physical and cognitive automation as a replacement for the respective human task. The difference between those types was already described in chapter 2.3.2. (Frohm, Lindström, Stahre, & Winroth, 2008)

Frohm et. al. (2008) reviewed existing level of automation taxonomies from several authors in the context of cognitive as well as physical automation. The majority of the suggested rankings are specific for either aspect of automation or only applicable in certain situations or industries. Therefore they suggested a classification that takes into account the interaction between the two types of tasks: physical tasks and cognitive tasks and is applicable in all kinds of manufacturing context. Each task can be assigned to one of seven steps from totally manual control to fully automatic and both scales (physical and cognitive) are independent from each other. The developed LoA scale is shown in Table 3-1.

Table 3-1: Level of Automation scales for physical and cognitive tasks within a production system (Frohm, Lindström, Stahre, & Winroth, 2008)

LoA	Mechanical and Equipment (Physical)	Information and Control (Cognitive)
1	**Totally manual** - Totally manual work, no tools are used, only the users own muscle power. E.g. The users own muscle power	**Totally manual** - The user creates his/her own understanding for the situation, and develops his/her course of action based on his/her earlier experience and knowledge. E.g. The users earlier experience and knowledge
2	**Static hand tool** - Manual work with support of static tool. E.g. Screwdriver	**Decision giving** - The user gets information on what to do, or proposal on how the task can be achieved. E.g. Work order
3	**Flexible hand tool** - Manual work with support of flexible tool. E.g. Adjustable spanner	**Teaching** - The user gets instruction on how the task can be achieved. E.g. Checklists, manuals
4	**Automated hand tool** - Manual work with support of automated tool. E.g. Hydraulic bolt driver	**Questioning** - The technology question the execution, if the execution deviate from what the technology consider being suitable. E.g. Verification before action
5	**Static machine/workstation** - Automatic work by machine that is designed for a specific task. E.g. Lathe	**Supervision** - The technology calls for the users' attention, and direct it to the present task. E.g. Alarms
6	**Flexible machine/workstation** - Automatic work by machine that can be reconfigured for different tasks. E.g. CNC-machine	**Intervene** - The technology takes over and corrects the action, if the executions deviate from what the technology consider being suitable. E.g. Thermostat
7	**Totally automatic** - Totally automatic work, the machine solve all deviations or problems that occur by itself. E.g. Autonomous systems	**Totally automatic** - All information and control is handled by the technology. The user is never involved. E.g. Autonomous systems

The presented scale is used in the DYNAMO++ methodology to assess the current level of automation and decide upon relevant min- and max values of a possible future state. In the following the DYNAMO++ is described which includes four phases: Pre-study, measurement, analysis and implementation, illustrated in Figure 3-1. Each phase consists of three individual steps. Steps 1-10 are in the scope of this thesis while the first three need to be altered due to the specific boundary conditions. Step 11 and 12 deal with the physical implementation of suggested changes and follow-up. (Fasth, Stahre, & Dencker, 2008)

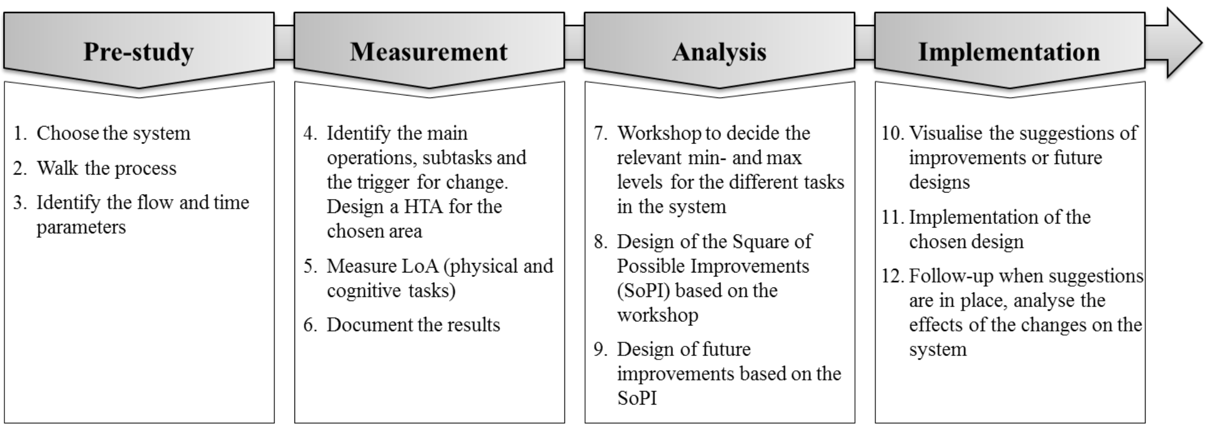


Figure 3-1: Dynamo++ methodology divided in the four main phases: Pre-study, measurement, analysis and implementation (Fasth, Stahre, & Dencker, 2008)

In general the methodology starts with choosing the system, which in this case is given by the topic of the master thesis. The next step would be to physically walk the process. This is only possible to a limited extent. While similar SMC production processes are accessible the actual production system to manufacture the OHSC sidewall is not in place. Therefore the available information will be combined with assumptions taken from the panel design and the designated production process. Those result in the flow and time parameters (step 3) which are visualised in flow diagrams and process time tables and finalise the pre-study phase. Subsequently a HTA (Hierarchical Task Analysis) (Sheperd, 1998) is designed as a preparation for the measurement of the current LoA which is the following activity (step 5). Step 6 is the proper documentation of all information gathered in previous steps and concludes the measurement phase. All information needs reprocessing to present them as introduction to the workshop with the aim to define the relevant min- and max levels of automation (LoA) for the chosen system. The HTA and the measurement are complemented with the trigger for change determined by the project team or the some kind of shareholder (the investigated company, the executive management etc.). These triggers can be singular or multiple and strongly influence the outcome of the workshop and finally shapes the suggested changes. Examples of triggers are increased output or quality, reduced throughput time or enhanced flexibility. The workshop is composed of people with different backgrounds and functions within the company (e.g. operators, engineers, external consultants etc.) to have multiple viewpoints. The relevant minimum LoA is equal to a solution where the work can be carried out at a sufficient speed at acceptable cost and working environment while the relevant maximum LoA is a possible technical solution without exceeding cost limits. It is important to keep in mind that automation should only be considered to a degree where it is justifiable regarding investment costs, rigidity and manual backup in case of fatal breakdowns (Frohm, Lindström, Stahre, & Winroth, 2008). The outcome of the described workshop is the Square of Possible Improvements (SoPI), a two dimensional matrix that contains the range of possible cognitive and physical LoA for each task. Inside the obtained area there are several possible solutions for each subtask. In the following the areas of the subtasks belonging to one operation are superimposed to get a higher level of SoPI and define the max and min LoA values for each single task belonging to one operation. Only the area where all subtasks overlap is considered. Figure 3-2 illustrates the step from a SoPI on subtask and operation level. (Fasth & Stahre, 2008)

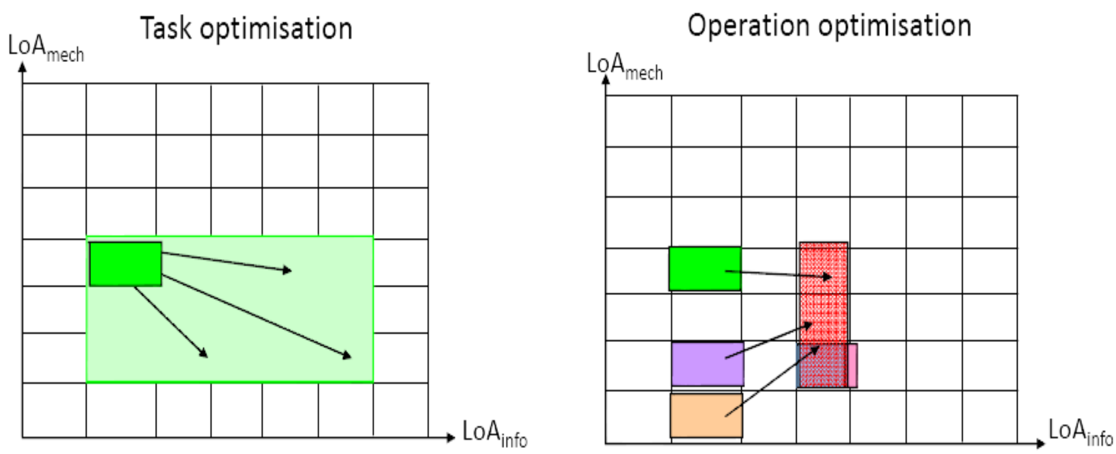


Figure 3-2: SoPI on task level with current level in intense green and on operation level with narrowed overlapping area (Fasth & Stahre, 2008)

At this stage of the method the dimension of time is added. Because one trigger of change is a reduction of cycle times for the individual stations only the operations or workstations are investigated that are considered critical to achieve the required takt time. Furthermore within a certain workstation the times per subtask are analysed to identify the most time consuming ones using the Pareto principle (consider the task that constitutes to 80% of the total time). The Pareto principle discovered by Vilfredo Pareto is a widespread principle to describe effects in different areas of application. It originally derives from the amount of income among the population. Pareto found out that 80% of the income in Italy is earned by 20% of the people and vice versa. In quality management it states that 80% of all defects can be explained by 20% of the causes. In the area of warehouse management it can mean that 20% of stocks takes up 80% of the warehouse's space (Ivancic, 2014).

The identified tasks are matched with their corresponding SoPI to view their automation potential. The result is a list of tasks that contribute most to the total production time and at the same time have a great potential of automation according to their SoPI. All other tasks are not completely neglected but considered as well. The analysis of their potential for automation can reveal that implementing a specific solution for one time-consuming task have a positive impact on another task and improves the overall system performance. Afterwards step 9 starts with designing appropriate solutions for these tasks using different manufacturing approaches described in a later chapter. The solutions are arranged in a matrix to be combined and build up complete production systems that are later evaluated by adequate methods. Finally in step 10 the systems are visualised and simulated to evaluate their expected benefits. The most promising are picked to suggest further improvements. The initial analysis is based on several assumptions concerning the operating hours and the design of the mould. After the best concepts are chosen an improvement loop shows further potentials to reduce production lead time and costs. To exclude the possibility that those improvement would have affected the initial evaluation the relevant calculation influenced by the changes are performed again for all concepts. Step 11 and 12 are the steps of implementation and follow-up and would exceed the scope of this thesis. (Fasth, Stahre, & Dencker, 2008)

3.2 Manufacturing Automation Approaches

In the following several automation approaches are introduced. They are applied to design different system solutions. The chosen approaches represent different strategies. They include commonly known strategies such as lean thinking or technocentric approaches which have already proofed their success. Especially human-machine systems which reveal great potential for an efficient automated production system are in focus. There are several approaches that commonly apply human-centred thinking but still show substantial differences in their ideas and criteria in focus. Many different approaches were chosen to cover all the different aspects of the topic and there could be the opportunity to combine several strategies after their strengths and weaknesses are assessed. The approaches are combined to five automation concept. Table 3-2 shows how the approaches influence the respective concept.

Table 3-2: Developed automation approaches and the authors they are influenced by

Automation Approach	Influenced by:
Technocentric Approach	(Lindström & Winroth)
Human-Centred Approach	(Lindström & Winroth), (Parasuraman, Sheridan, & Wickens), (Mital & Pennathur)
Lean Manufacturing Approach	(Seifermann, Böllhoff, Metternich, & Bellaghnach), (Liker & Meier)
Human-Machine Collaboration	(Shen, Reinhart, & Tseng), (Mital & Pennathur)
Human-Machine Task Allocation	(Säfsten, Winroth, & Stahre), (Rouse), (Sheridan)

The number of ways to implement automation is countless. Galen (2014) summarised a list of common patterns and anti-patterns for starting automation. His examples are from the software industry but are applicable to the manufacturing industry as well. To start with the anti-pattern he describes the groups that simply start to develop automation without any strategy and are meant to fail. On the contrary there are the people who make a detailed list before starting but never alter it while they make progress. A promising approach is to start with the so called low hanging fruits to get quick result. But many miss to take the step towards long-term gains and get stuck with short-term success. Others are afraid of taking risks by using new technologies and tools and thereby inhibit mutual progress in the development of automation. However there are some promising patterns. One pattern is driving with value. Fundamentally one has to compare the time and money it costs to automate against the time and money saved by the automation. If there is any value generated the automation seems suitable. (Galen, 2014)

Another approach is the allocation of physical and cognitive tasks to either humans or automation equipment. The most classical model is the so called Fitts' list (Figure 3-3). Fitts defined, for a set of tasks, if it fits men or machines best (MABA MABA list). This is similar to the comparative strategy, one of three strategies suggested by Rouse (1991). The two others are leftover allocation, applicable for situations where no technical solution is suitable and economic allocation. The last strategy describes that if the costs for automating a function are higher than the costs for hiring an extra operator the task remains manual even if it is technically possible. This is comparable to the driving with value pattern described earlier. (Säfsten, Winroth, & Stahre, 2007)

Table 3-3: The MABA MABA list by Fitts

Men are better at	Machines are better at
Detecting small amounts of visual, auditory, or chemical energy	Storing information briefly, erasing it completely
Perceiving patterns of light or sound	Applying great force smoothly and precisely
Improvising and using flexible procedures	Responding quickly to control signals
Reasoning inductively	Reasoning deductively
Storing information for long periods of time and recalling appropriate parts	
Exercising judgment	

The concept of *human-computer task allocation* (Sheridan, 1997) eliminates the presumption that tasks can simply be broken down into independent elements and assigned to either machine or human. On the contrary, task components interact in different ways depending upon the resources chosen from the infinite number of ways humans and machines can interact. The criteria for judging the suitability is often implicit and difficult to quantify. The previously introduced *Fitts List* gives a first guideline to choose either men or machine but is often criticised as it understands human as one type of machines. However, instead of neglecting the idea completely one should keep the basic idea about what humans and machines can do best but see them as complimentary to each other. Sheridan (1997) introduces a list of guidelines to design a system:

- Judge obvious allocations: easy tasks should be automated, non-repetitive tasks should be done by humans

- Look at the extremes: either fully automated or completely manual to widen the set of possible solutions

- How fine allocation makes sense: human mind prefers large chunks of information while machine are good at details

- Trading vs. sharing: trading means humans and machines perform tasks after each other while sharing means working on the task simultaneously. (Sheridan, 1997)

Human-Robot-Coexistence within a production system reveals the potential to create an effective collaboration of human and technology. Coexistence in contrast to other forms of collaboration is defined by a shared workspace without a common task. The robotic system needs to cope with time variations caused by different human skill level and task execution and alternating manufacturing tasks. This leads to different trajectories and sequences requiring an overall flexibility and results in more idle-time. The close proximity of human and machine makes the use of proximity sensors (attached to the robot or stationary) and robust master-slave relationships inevitable. Due to the mentioned varieties position-dependent hand-over tasks are most applicable in order to reduce waiting time. This can be realised by tracking systems and spatial relationships. The latter include human positions, object positions and human object movements considering time-sequential position information. (Shen, Reinhart, & Tseng, 2015)

Lindström & Winroth (2010) summarise a range of different approaches such as the *technocentric approach*. Automated operations in production are in the centre of interest and the systems are often characterised by a certain inflexibility and high sensitivity to disturbances due to the lack of human involvement. The counterpart is the *human-centred approach* keeping the human in the focus. One example is the sharing approach which means that operator and automated equipment complement each other. There are several degrees of sharing and the task allocation to either human or machine moves to focus. (Lindström & Winroth, 2010)

Parasuraman et. al. (2000) present a combined approach distinguishing types and levels of automation. Evaluative criteria allow the designer to decide which part of the system should be automated. They argue that automation does not simply replace a human activity by technology but rather change operator tasks in an unintended or unanticipated way. They distinguish between four functions in a human-machine system: Information acquisition, information analysis, decision selection, and action implementation. Every single function can be automated to differing degrees using a scale equal or similar to the one provided by Frohm et. al. (2008). To start with, appropriate levels of automation are identified and evaluated. As the authors use a human-centred approach mental workload, situation awareness, complacency and skill degradation are the main criteria. Data transformation using graphical information presentation is one example for reducing the mental workload while skill degradation due to less human involvement can lead to an increasing unfamiliarity and threat to safety. Those firstly selected levels of automation are evaluated with secondary criteria including automation reliability, cost of decision outcomes, ease of system integration, operating costs and efficiency/safety trade-offs. The final outcomes are levels of automation that are independent of their type (cognitive or mechanical) and can even vary giving particular situations. (Parasuraman, Sheridan, & Wickens, 2000)

Lean manufacturing has the objective to increase the efficiency of a production system and at the same time retain its flexibility. Therefore it is proposed to purchase several basic machines in a right-sized manner. The high manual operational effort which results from using those basic machines calls for the introduction of automated solutions. Contradictory to the often used complex and expensive solutions the purchased basic automation equipment should be adapted to the individual task and the tasks themselves should be well chosen. Consequently, identifying the potential manual tasks and quantifying the benefits is the first step in the analysis stage. (Seifermann, Böllhoff, Metternich, & Bellaghnach, 2014) The philosophy of lean automation is to meet the takt time by creating a low cost human-machine system. Therefore the technology needs to be put in proper perspective and should not be used as substitution for thinking. The value-adding process is in the centre of lean thinking. Consequently the technology should support the elimination of waste and must contribute to the value adding process or in other words: the technology has to support the people working. Traditionally engineers walk from station to station and evaluate automation potential that is most often purchased from the outside. The decision is justified by simple cost-benefit analysis and decrease of labour costs. But many other effects such as high capital costs, unreliable and inflexible technology and increasing waste are neglected. Applying lean thinking, total system costs and quality delivery are in the centre of focus and the philosophy provides tools like *poka yoke* (mistake-proofed), right-sized equipment and *SMED* (Single Minute Exchange of Die) to achieve those objectives. In contrast to traditional approaches lean automation requires customised solutions to fit the system. One example is the mentioned mistake-proofed equipment that is complemented with sensors to trigger an *andon* call if failures occur and draw the attention of an operator very quickly to minimise downtimes. (Liker & Meier, 2006)

Mital & Pennathur (2004) claim that there is an interdependent relationship between technology and humans that needs to be recognised when designing an automated production system. It is therefore not possible to simply mimic the work of humans by some sort of machine. Moreover a *human-centred approach*, already mentioned previously, is favourable to take advantage of the technology and the ability of humans, who are still the most versatile element in the manufacturing system. Nevertheless they admit that as technology advances machines will become more flexible. Recognizing the limitations of both is a key element to an efficient manufacturing system. Despite their flexibility humans tend to make errors with a variety of consequences and have limited capabilities of processing data and information. The technology should therefore aim to reduce the occurrence of errors and the workload of processing data. One way is to use error monitors. This means the operators stay fully in charge of the operation but the technology provides them support to detect their errors through an alarm system or similar. With increasing operator-machine collaboration machines can advise operators, mitigate their errors or assist them when the workload is overwhelming. Regarding the processing of data, technology should compensate for the shortcomings of humans in particular in terms of numerical operations and projection in time and space (need for visual space/time projections). In general an anthropocentric automated manufacturing system should aid humans in decision making by minimising information-processing load. This is achieved by an efficient human-equipment interface which is user and task oriented, flexible, responsive, error-tolerant and user-controlled. (Mital & Pennathur, 2004)

Säfsten et. al. (2007) on the other hand suggest that the degree of automation should be connected to the overall manufacturing strategy and is therefore a consequence of the company's demanded manufacturing capabilities. This strategic view on automation requires the consideration of different LoA and their respective advantages. The field of human factors engineering provides the knowledge to allocate functions between humans and machines and enables the selection of a variety of levels of automation. Furthermore, they point out that this choice is interlinked with other business areas such as the requirement for a certain set of operator skills, appropriate component supply, or a specific quality management. This interdependence as the significance of the right level of automation can be summarised as "rightomation" and is visualised by Figure 3-3. (Säfsten, Winroth, & Stahre, 2007)

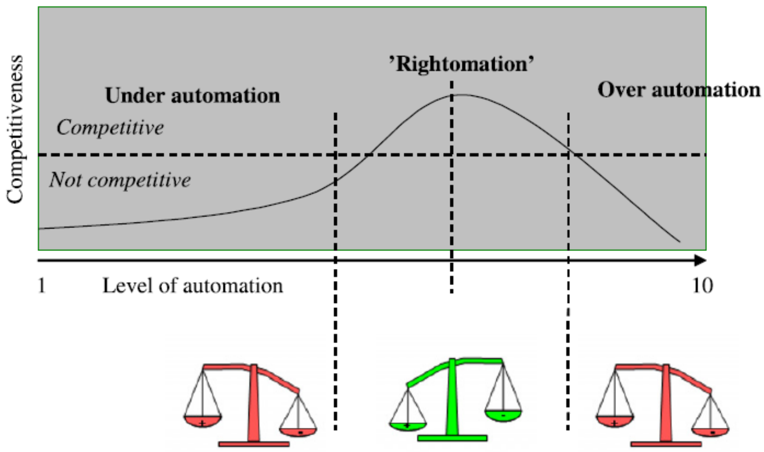


Figure 3-3: Appropriate level of automation and the effect of the company's competitiveness (Säfsten, Winroth, & Stahre, 2007)

3.3 Discrete Event Simulation

"Simulation is the imitation of a real-world process or system over time. Simulation involves the generation of an artificial history of the system and the observation of that artificial history to draw inferences concerning the operating characteristics of the real system being represented." (Banks, 2004).

Discrete event simulation is a collection of events that happen in chronological order and change the system's state. It is used to study a system over time and do capacity calculations, analysing throughput and lead times or do layout planning in the automotive industry, at airports or in the aerospace industry. Beginning in the 1960s simulation was used in the mining industry. Today several simulations programs are available such as ProModel, Automod, Quest or Arena. (Gingu & Zapciu, 2014)

Simulation provides advantages as well as disadvantages. One of the benefits is making correct choices because the system can be tested before acquiring expensive hardware. Moreover one can speed up or slow down the system to observe specific phenomena more closely. Furthermore constraints can be identified by bottleneck analysis which can detect causes for delays. Using CAD layouts and animation features one can visualise layout plans and build consensus as a basis for decision making. Applied inappropriately simulation is sometimes used for cases where analytical solutions are preferable. Furthermore it is time-consuming and requires special training and the result might be difficult to interpret as specific behaviour can be caused by interrelationships or simply randomness. (Banks, 2004)

Most often simulation is used to describe and analyse a system and answer the question "what if" about the real system. Both real and conceptual systems can be modelled. The area of simulation has some specific nomenclature that will be presented hereafter. A *model* is the representation of the actual system while an *event* is the occurrence of changes of the state of the system. Discrete-event models are *dynamic* and *time-based* and in contrast to mathematical models they are not solved but *run.* Each model contains *entities* which need explicit definition and can either be dynamic (products move through the system) or static (machines with a fixed location). In this thesis the software Delmia Quest by Dassault Système is used. Consequently the nomenclature specific for this software is used. In Delmia *parts* are used to represent the products and travel through the system. *Resources* provide service to those parts. They can serve one or more parts in parallel. Services provided by resources can be *activities*. Those last for a period of time which is known prior to commencement of the actual activity which means the end can be scheduled when it begins. The duration can be constant, random or following statistical behaviour. A *delay* on the other hand has an indefinite duration. A part waits for a resource and the time in the waiting line is unknown as other events can occur that effect it. (Banks, 2004)

To perform a simulation project Banks (2004) suggests a model containing necessary steps which is shown in Figure 3-4. First the problem is formulated with specific emphasis to state it as clearly as possible. Afterwards one has to agree on the objectives of the project. Those are the questions answered by the simulation. The first step towards the actual simulation is building the conceptual model containing all relationships and other necessary information such as cycle times, maintenance efforts etc. The quality of the conceptual model has a direct effect on the final output of the simulation. In parallel to the conceptual model input data is collected and analysed. After those two stages the actually coding or building the model within the software begins. While coding the simulation is verified concurrently. Verification means that the model performs as designed by the conceptual model. In the end of the coding stage a validation phase follows. Herein it is determined whether the model works as the real world production system does. Finally the simulation can be run after the run time and number of runs are determined in the experimental design phase. The results of those runs are documented and interpreted. The way the Banks model is followed in the DES of this thesis is described in chapter 6. (Banks, 2004)

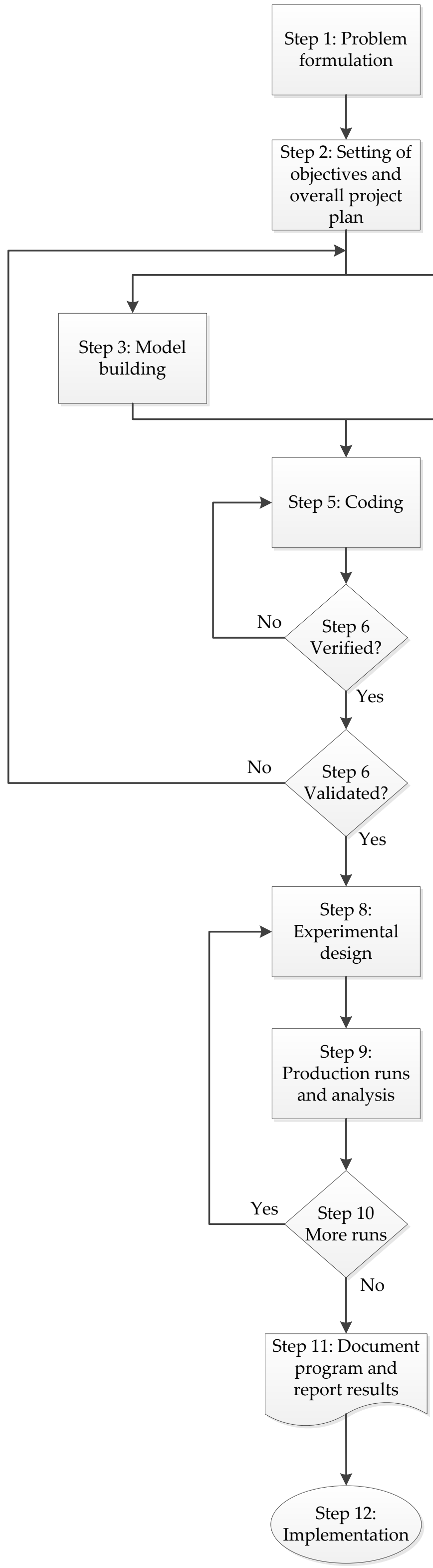


Figure 3-4: Banks model: Steps in a simulation study (Banks, 2004)

3.4 Evaluation Methods

This thesis uses three different evaluation methods which complement each other to assure the identification of the most suitable production system. The *pairwise comparison* ranks the chosen evaluation methods according to their relevance while the *utility analysis* evaluates the quantitative and qualitative criteria to result in a final ranking. The most promising concepts can be further assessed by a *SWOT* analysis to identify their strengths and weaknesses. The evaluation criteria as well as the results of the respective evaluation are presented in chapter *6 Evaluation of Automation Concepts*

3.4.1 Utility Analysis and Pairwise Comparison

The basic idea of a *utility analysis* (or *concept scoring method*) is the quantification of originally qualitative criteria by a multifunctional team which does a subjective assessment. The method is one of the most commonly used to perform a concept selection. Before the assessment can be done the criteria influencing the performance of the system has to be chosen by the system designer and ranked according to their relevance.

To do so, the method of *pairwise comparison* is used. Each of the chosen criteria is compared to each other one-by-one. If a criterion is less important it gets 0 points and if it is more important it gets 1 point. In the end the points per criteria are summed up and give the total score representing the weight for the subsequent utility analysis, called W factor. An example of a pairwise comparison is shown in Figure 3-5. (Lindemann, 2009)

than/as more/less/ equally important	Criteria 1	Criteria 2	Criteria 3	Criteria 4	Sum	Weight in %
Criteria 1		0	0	1	1	17%
Criteria 2	1		1	0	2	33%
Criteria 3	1	0		1	2	33%
Criteria 4	0	1	0		1	17%

Figure 3-5: Example of a pairwise comparison with weight in percent as the final result

As the criteria are chosen and weighted they are assessed for the different variants by a multifunctional team by determination of their utilities. A scale from 1-5 or 1-10 is most often used to quantify the utility which is also called the “Rating” factor (R). A reference design should be selected as a reference. This could be a state of the art design or the current design in place. R is multiplied with the previously determined “Weight” (W) to take into account the relevance of the specific criterion. All utilities are added up and the result is an overall utility for each variant. A final evaluation reveals the variant with the highest score to have the best qualification or suitability. (Hartel & Lotter, 2006) (Haag, Schuh, Kreysa, & Schmelter, 2011)

Selection Criteria	W (%)	Concepts					
		A (reference)		B		C	
		R	Weighted Score	R	Weighted Score	R	Weighted Score
Criteria 1	8	3	0.24	2	0.16	5	0.4
Criteria 2	42	3	1.26	5	2.1	1	0.42
Criteria 3	33	3	0.99	3	0.99	2	0.66
Criteria 4	17	3	0.51	3	0.51	2	0.66
Total Score			3.00		3.76		2.14
Rank			2		1		3

Figure 3-6: Concept scoring matrix or utility analysis which ranks different concepts according to their rating

A utility analysis offers a number of advantages which justify their use. First of all it supports the fuzzy nature of concept selection by quantifying it. As the results of the analysis are plain numbers it is easy to communicate them to others not involved in the assessment process. Furthermore the method has the ability to treat non-technical (costs, ergonomics etc.) as well as technical (cycle time, quality etc.) requirements. Once the *concept scoring matrix* is created it can be adjusted very efficiently to cope with a changing environment and shifting priorities while most of the information can still be used. The result of a *utility analysis* can not only be used to choose the best concept design but can help the designer to identify strengths and weaknesses, combine different designs and come up with an improved design at the end of the process. Although the method provides several advantages it has to be noted that the assessment is purely subjective and depends highly on the involved team members but however it allows to assess qualitative criteria in a more structured way. (Xiao, Park, & Freiheit, 2007)

3.4.2 SWOT Analysis

SWOT stands for strengths, weaknesses, opportunities, and threats. The method evaluates those four elements and can be applied to a company, product, industry, or person. The objective of a *SWOT Analysis*, as it can be seen in Figure 3-7, is to identify internal and external factors that are seen as important to achieve a goal. In this thesis the *SWOT analysis* is used to evaluate the most promising concepts, according to the previously described *utility analysis*, further and include aspects that are not captured by it. (Lindemann, 2009)

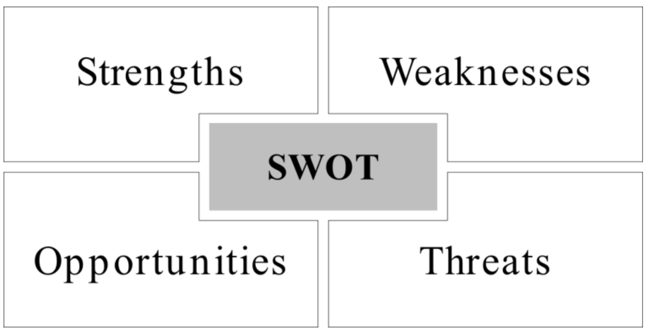


Figure 3-7: Schematic appearance of a SWOT analysis

4 *Analysis of the SMC Process with Manual Handling*

The introduced process analysis methods are applied and the results are presented in this chapter as a starting point for the concept design. The design of the sidewall panel leads to the process flowchart and process step description. Underpinning the description with sufficient numerical data based on a number of assumptions enables a thorough analysis which shows weaknesses and potentials for improvement by automation.

4.1 Process Description

The process description is the starting point of the analysis and includes the sidewall panel design and the process chain. The first describes the design of the actual panel manufactured in SMC technology and the downstream assembly with the tailored sandwich panels. The second part describes the process chain as a whole and the single process steps

4.1.1 The Sidewall Panel Design

The sidewall panel is illustrated in Figure 4-1. The inside of the panel (not shown) which is visible for the customer and therefore need to fulfil strict surface quality requirements. The SMC surface is grinded and filled and gets textured paint afterwards. The outside on the other hand accommodates the ribs represented by the thin walls inside the panel geometry.

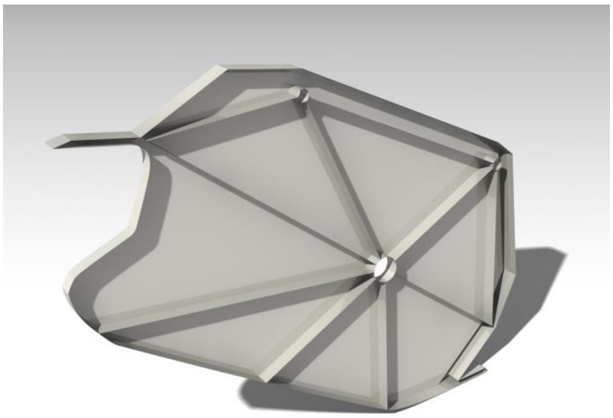


Figure 4-1: Sidewall panel design with circumferential fillet and outer dimensions (CTC GmbH)

The two upper holes are attachment points to the aircraft structure. Therefore inserts are brought in. The centre hole where most ribs originate is the position point for further parts that are added during the assembly step. Again, inserts are placed at this position during the production process. Furthermore at the position of the later latch (not drawn in this case) inserts are used. The circumferential fillet, which is better shown in Figure 4-2, is mounted further downstream with the tailored sandwich panel to generate the final component shape. Surface preparation for bonding both parts is needed in advance. Each assembly consists of two mirrored sidewall panels and one tailored sandwich panel. Therefore two moulds or one modular mould is necessary to produce both sidewalls within one production system. The moulds need to be exchanged or adapted in a predefined manner.

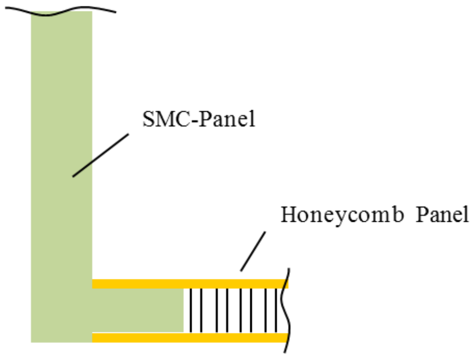


Figure 4-2: Schematic drawing of the sidewall panel assembly (CTC GmbH)

4.1.2 The Process Chain

The process of producing the sidewall panel and the downstream assembly is divided in five main steps plus the additional painting which is out of scope for this thesis. The flowchart in Figure 4-3 visualises the chain while in the following the single tasks are described. The chart combines the earlier mentioned macro and micro map. While the rectangular boxes are part of the micro map the frames represent the macro map. Information about the safety and ergonomic situation are included in the description of the single process steps.

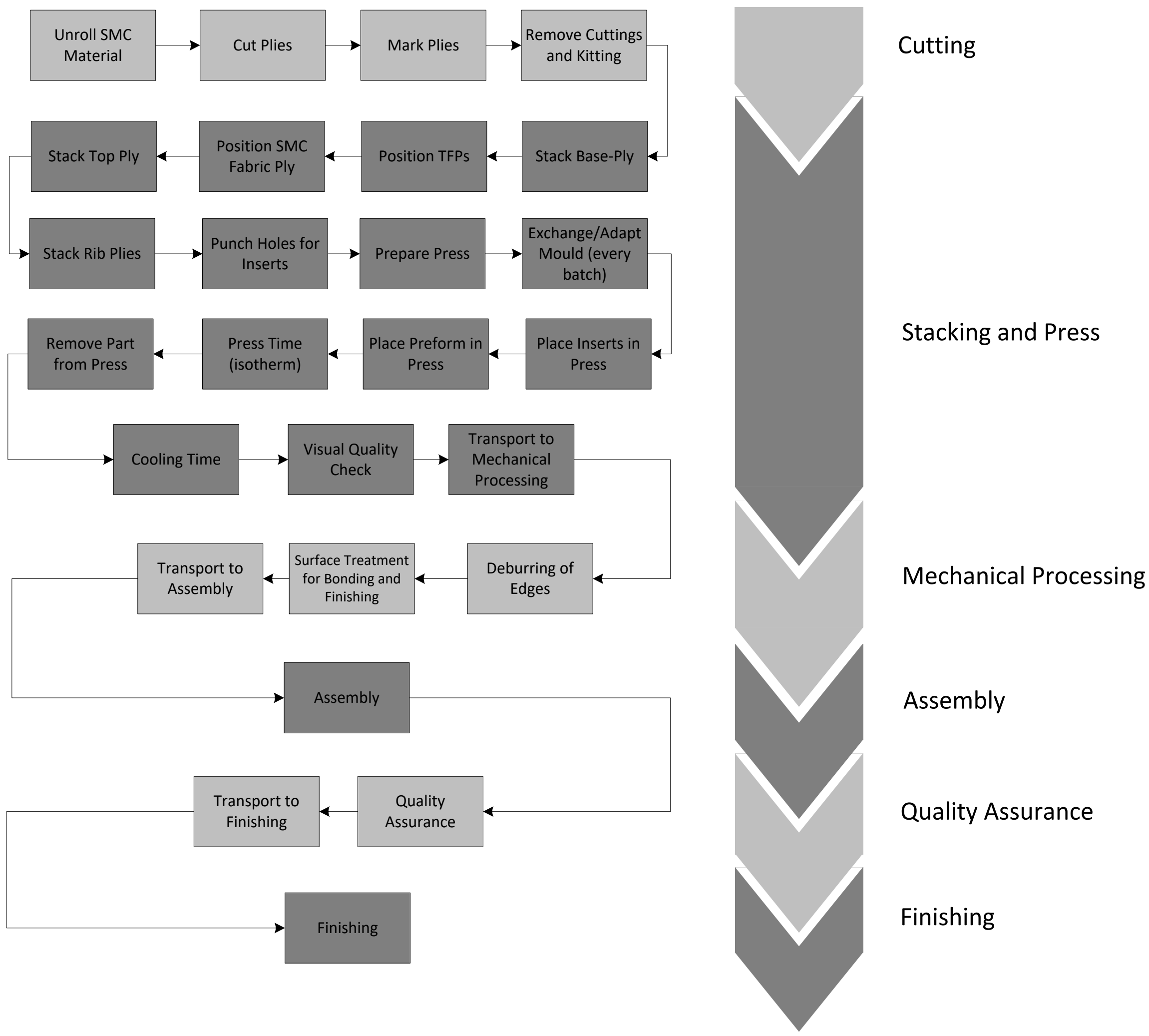
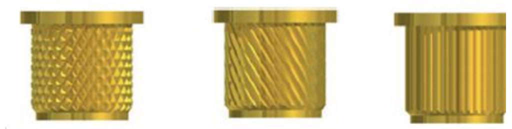


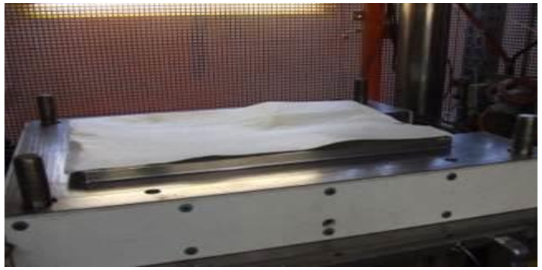
Figure 4-3: Flowchart of the sidewall production chain including assembly and paint

Table 4-1: Detailed process description of the sidewall panel production including assembly and finishing

<table>
<tr><td colspan="3">Cutting</td></tr>
<tr><td colspan="3">At the first station the SMC semi-finished material is cut into plies. Coils are unrolled, cut and an operator marks the plies and prepares kits as a preparation for stacking.</td></tr>
<tr><td>Operation</td><td>Description</td><td>Notes/Images</td></tr>
<tr><td>Unroll SMC Material</td><td>The SMC coils (typical values: weight: 500 kg, width 1.3 m, linear meter: 100-150 m) are placed in a roll holder and unrolled. After cutting, the waste material is cut and scrapped and the coil unrolled again.</td><td>
Figure 4-4: Glass fibre SMC on a roll holder ready for being cut
• Handling of the rolls only possible with handling aid
• Step place the coil in roll holder is not regularly performed but only if the material roll is empty or a change of material is necessary (compare to batch size) – CT negligible</td></tr>
<tr><td>Cut Plies</td><td>The single plies are cut with a cutter and templates, specific for each geometry. The top, base, and middle ply as well as rib plies need to be cut for one component before performing the next step.</td><td>
Figure 4-5: Cutting of prepreg with cutter and templates (Easy Composites Ltd)
• Appearance of SMC similar to traditional prepreg material but considerably thicker
• Base, middle and top ply: geometry identical to final part
• Rib plies: 200x50 mm
• Middle ply: continuous, oriented fibres → cutting direction important</td></tr>
</table>

		• Top, base and rib plies: chopped, random fibres → only edge distance needs consideration
Mark Plies	Plies for one part are marked with a consecutive number that corresponds to the ply book.	• Makes clear allocation of each ply possible
Remove Cuttings and Kitting	The plies are removed and placed aside as a kit. All kits are placed in a dedicated area for easy access to the next operator	• Each kit contains plies necessary for one part and is marked with corresponding part number.
Stacking and Press		
At this station the preform is stacked. The cut plies are complemented with prefabricated TFP patches. The stacked preform is placed in the prepared press, cured and de-moulded. The removed part needs to cool down before an operator will transport it to the next station.		
Operation	**Description**	**Notes/Images**
Stack Base Ply	First ply forms the basis of the preform. One of the cover foils is removed and ply is placed on separating foil attached to lay-up table. Operator presses on layer.	• Base ply covers 90% of the final component area • Press on avoids wrinkles and creates smooth basis for TFPs
Position TFPs (Tailored Fabricated Patches)	The delivered TFPs have got a carrier fabric. The patch including the carrier fabric is placed at a defined spot (definition by ply book or drawing). The patch is pressed against the SMC ply. This procedure is repeated with all required patches.	 **Figure 4-6:** Carbon fibre TFP patch ready for usage (Walther, 2015) • TFP patches are tailored elements made of carbon fibre and used as local reinforcements • Position of each of the patches needs to be exact because of their load bearing functions
Position SMC Fabric Ply	The stacking of the fabric ply is similar to the stacking of the base ply. The cover foil is removed and the ply	• Ply has to be placed carefully because position of TFPs must not be altered

	placed exactly on top of the previous one. Afterwards the ply is pressed on.	
Stack Top Ply	The stacking of the last SMC ply follows the same procedure as the first and previous one (cover foil is removed and ply placed exactly on top of the previous one). Afterwards the ply is pressed on.	• SMC material is characterised by a slight tack • If gentle pressure is applied plies stick together very firmly • Particularly important when placing the preform in press because it ensures the position of all plies and TFP patches
Stack Rib Plies	The stacking of the smaller rib plies follows the same scheme as the plies before. At the end all cover foils need to be removed.	• Like TFPs, plies need to be placed in certain predefined locations
Punch Holes for Inserts	Holes at the position of the later inserts are punched using a punch and a hammer. Previously the positon is marked. The punched out material is removed and scrapped.	
Prepare Press	The tooling and the press are cleaned from component or SMC residues with compressed air. The dies are checked for damage and contamination. The tooling temperature and press programme are checked.	• External release agent not necessary because SMC formulation contains internal release agent which ensures a proper removal of the part.
Exchange/Adapt Mould (every batch)	If two different moulds for the left and right-hand side are used they need to be exchanged defined by the batch size. If a modular mould concept is used only movable elements are exchanged.	• Two operators perform the step (shorter downtime)
Place Inserts in Press	The inserts either with or without thread are placed in the upper mould before moulding. Before they can be placed a strip of sealant tape is applied.	 **Figure 4-7:** Metal inserts with different surface texture used in SMC applications (Stanley Engineered Fastening, 2015) • Holding fixtures are built in tooling to accommodate inserts • Position of the holding devices correlates to punched holes in the preform.

		• Sealant tape necessary to ensure insert functionality after compression moulding
Place Preform in Press	The final step before compression moulding is to place the preform on the predefined position in the mould.	 **Figure 4-8:** Glass fibre SMC preform placed in press before mould is closed (Airbus Operations GmbH) • Preform handling needs extreme care to prevent damage or relocation of layers/TFPs. • Position of preform influences flow of the material and properties of the final component.
Press Time (isotherm)	The curing cycle is started by closing the mould. The preform heats up, the viscosity of the resin drops and fills the mould under great pressure. The matrix cures and the press opens again so the part can be removed.	• Operator only starts cycle and can be occupied by other activities afterwards
Remove Part from Press	After the curing cycle the part is de-moulded. The part is placed in a rack or on a table to cool down.	• Operator needs to wear protection gloves or use handling tool because part's temperature is about 140°C • Component needs proper storage during cool down to avoid any distortion, due to different thermal coefficients
Cooling Time	The time to cool down the part depends on the curing temperature and part thickness. During this phase the part should not be moved.	• Step considered as process time because no operator needed • Appropriate space necessary to cool down several parts at the same time
Visual Quality Check	The operator performs a basic visual quality check and comes to a go/no-go decision.	• Check of surface quality and enclosed foreign objects • Avoid further processing of non-quality parts

Transport to Mechanical Processing	The components are transported to the mechanical processing department in batches.	

Mechanical Processing		
After cooling the sidewall is prepared for assembly and painting. The preparation includes deburring and surface treatment. Finally it is transported to the assembly stations.		
Operation	**Description**	**Notes/Images**
Deburring of Edges	The SMC compression moulding process only leaves a tiny burr at the edges of the part which is removed manually.	• No contouring necessary to generate the final geometry • Deburring with abrasive paper • Dependent on the tool tolerances and part geometry deburring can be superfluous
Surface Treatment for Bonding and Finishing	As a supplement to deburring the fillet surfaces on the one hand is prepared for bonding and the outside surface of the panel on the other hand is filled and grinded. Afterwards the surfaces are cleaned with an organic agent and preserved.	• Outside surface visible to the customer → therefore strict surface requirements • Cleaning required as precondition for proper bonding • Preservation only necessary if considerable time gap between grinding and assembly
Transport to Assembly	The prepared components are transported to the assembly in batches.	
Assembly		
After mechanical processing the sidewalls are assembled with the housing panel and the chute and transported to the quality assurance.		
Operation	**Description**	**Notes/Images**

Assembly	The final assembly consists of two SMC panels, a tailored sandwich panel (housing) that is mounted in a technique called "cut and fold". Using this technique, strips of skin layers are removed while the core remains intact. Adhesive is applied to the core; the panel is folded to the desired shape and clamped until the adhesive cures completely. In this case the tailored sandwich panel is clamped in the fixture. Adhesive is applied to the inner radii of the sandwich and the open edges. Afterwards the sandwich is bended to the desired shape and the SMC panels are mounted to the front side. All parts are clamped to restrain them from moving until the adhesive is fully cured. Finally the assembled part is removed from the fixture.	 **Figure 4-9:** "Cut and Fold" technique; adhesive applied to a cut sandwich panel that is afterwards folded to the desired shape (ACP Composites, 2011) • Width of the removed strip depends on the desired radius angle → tighter fold requires wider gap
Transport to Quality Assurance	The ready assembled components are transported to the quality assurance one by one.	
Quality Assurance		
Each SMC component is checked by a quality inspector against several requirements.		
Operation	**Description**	**Notes/Images**
Quality Assurance	The inspector checks the weight of the component, the surface and edges, and checks for the appearance of foreign objects. The checks are complemented by proper documentation.	• Weight: must not exceed a maximum value • Surface quality: need to fulfil strict requirements, non-conformance leads to rework • Foreign objects: leads to scrap • Every component is examined
Transport to Finishing	The checked components are transported to the finishing in batches.	
Finishing		
Finishing is the final step of the process. As this process is out of the scope of the master thesis it will not be described in detail.		

4.2 Time Estimation

Although the production of the investigated sidewall panel is not in place yet the process times can be estimated. Assumptions of two kinds form the basis. The design assumptions which originate from the part itself include among others the number of rib plies or the total cutting length. The second group are the process assumptions. They include cutting speed or lay-up time per SMC ply, for instance. The values are taken from experience with similar production technologies or other SMC production processes which include comparable process steps. In case of the cutting speed of SMC plies the prepreg process forms the basis. This process is well understood and both semi-finished products show similar properties as mentioned earlier. The lay-up time of SMC plies could be observed on site within the *genchi genbutsu* initiative. Although the geometry of the cuttings varies from part to part the overall time needed is insignificantly different. All assumptions used are listed in Appendix A.

With the aid of those assumptions the cycle time for each process step is quantified and shown in Figure 4-2. All process times such as cooling of the part after compression moulding or the curing time for the adhesive within the assembly are excluded because no operator is required for those activities and therefore they have no influence on the total cycle time. On the contrary for calculating the lead time the process times are added to the total cycle time to receive the duration for one part to pass through the whole process chain from raw material to finishing the assembled part.

Table 4-2: Cycle times based on previous assumptions for stations cutting, stacking and press, mechanical processing, assembly, quality assurance and finishing and respective total cycle times

Work Station	Process Step	Baseline Process (Manual)	
		Time [h]	Remarks / Assumption / Calculation
Cutting	Unroll prepreg material	0,01 h	Time to change roll neglected
	Cut Plies	0,27 h	Place and remove template: 0.5 min/ply
	Mark Plies	0,04 h	Estimation: 0.25 min/ply
	Remove Cut-offs and Kitting	0,04 h	Estimation: 0,25 min/ply
Stacking and Press	Lower SMC Ply	0,02 h	Includes removal of cover foil
	Position TFP Patches	0,09 h	
	SMC Fabric	0,02 h	Includes removal of cover foil
	Upper SMC Ply	0,02 h	Includes removal of cover foil
	Rib SMC Plies	0,06 h	Includes removal of cover foil
	Punch Holes for Inserts	0,13 h	
	Preparation of Press	0,03 h	Cleaning, application of release agent and intensive at start of production day (20 min)
	Exchange/Adapt mould	0,04 h	Estimation: 60 min, at the end of every production day, heating during night
	Position Inserts	0,13 h	
	Place Preform in Press	0,02 h	Estimation: 1 min
	Press Cycle	0,07 h	Estimation: 4 min, includes close press, curing part and open press
	Remove Part from Press	0,02 h	Estimation: 1 min
	Visual Quality Check	0,01 h	Estimation: 0.5 min
	Part Cooling	0,00 h	Estimation: 15 min process time, no operator required
	Transport to Mechanical Processing	0,01 h	Transport in batches
Mechanical Processing	Deburring of Part Edges	0,04 h	
	Surface Treatment for Bonding and Finishing	0,20 h	Preparation for bonding: 5 min + 8 h Drying Time Filler
	Transport to Assembly	0,01 h	Transport in batches
Total Cycle Time		1,24 h	Cycle time refers to one sidewall left/right
Assembly	Assembly	0,25 h	4-6 h curing time (process time), 0.5 h/OHSC, 0.25 h/sidewall
	Transport to Quality Assurance	0,004 h	Transport in batches
Quality Assurance	Quality Assurance	0,04 h	Estimation: 5 min/OHSC, 2.5 min/sidewall
Surface Finishing	Surface Finishing	0,50 h	Estimation: 1 h/OHSC, 0.5 h/sidewall
Total Cycle Time		0,80 h	

To enable the analysis of the all manual process the necessary takt time for different scenarios is calculated. The calculation is based on the number of parts per aircraft and produced aircrafts per year. Part in this case relates to the final component that is assembled from two sidewalls and one sandwich panel. The available operating hours per year are found out by taking an 8 hour working day as a basis at 220 days per year. The consideration of an OEE of 80% leads to the final figures. The whole calculation can be reproduced with the aid of Table 4-3.

Table 4-3: Takt time calculation for the scenarios single aisle and A350

Takt Time Calculation	SA+A350		Single Aisle (SA)		A350	
Parts per Aircraft A350	112	56 OHSC/AC			112	56 OHSC/AC
Production Rate A350	13	AC/Month			13	AC/Month
Parts per Aircraft SA	48	24 OHSC/AC	48	24 OHSC/AC		
Production Rate SA	60	AC/Month	60	AC/Month		
Running Hours 1 Press or 1 Operator / 8h Operation per Day (one shift) / 220 days/a / 80% OEE	1408	h	1408	h	1408	h
No. of Parts per Year	49864		33120		16744	
Takt Time	1,69	min	2,55	min	5,05	min
	0,03	h	0,04	h	0,08	h

4.3 Analysis of Manual Baseline Process

The previous process description including the process times is used to conduct a thorough analysis. First of all the cycle times per station are plotted against the required takt times for certain scenarios. Thereby the A350-900 (hereafter called A350) as well the single aisle aircraft family scenarios are most significant and will be considered in particular. The second part of the analysis will deal with the results of the LoA workshop to identify the relevant min- and max values.

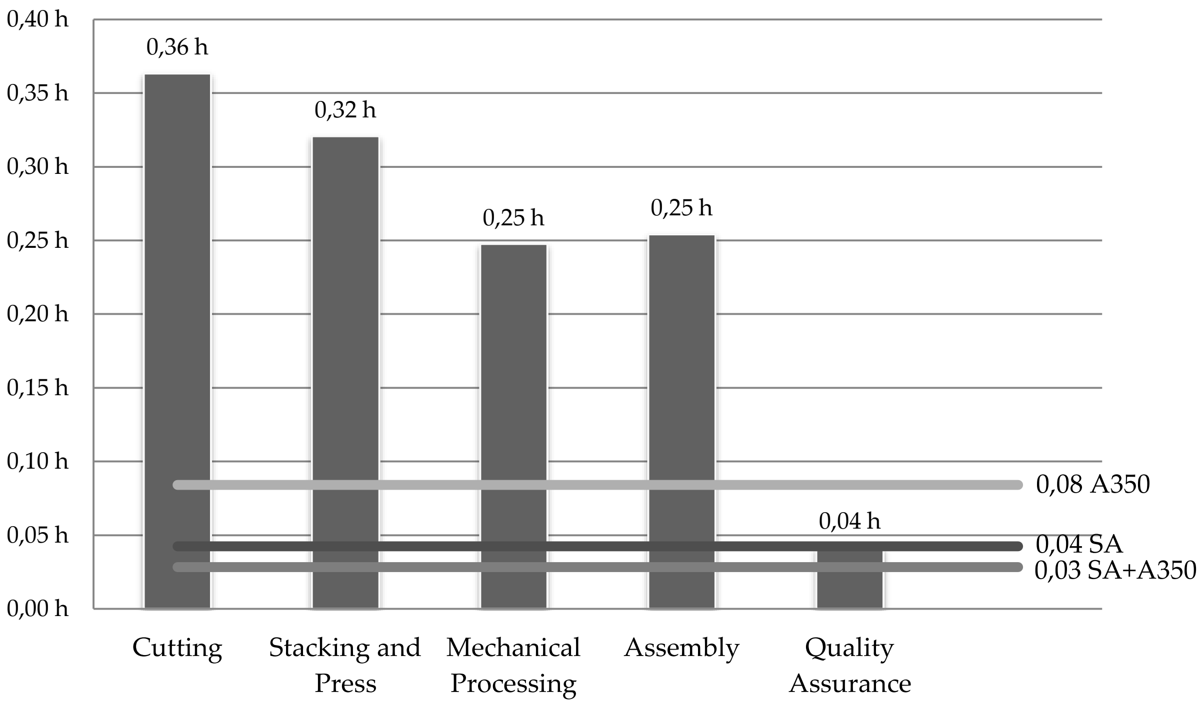


Figure 4-10: Plot of cycle times (bars) against the required takt times for A350, SA and SA+A350 (horizontal lines)

Figure 4-10 shows the cycle time for each station as bars and horizontal lines referring to the required takt times to match the production rate of the particular scenarios. The finishing station is not plotted because it will not be considered any further.

One can conclude that stations need to be multiplied to match the takt time. The number of presses is particularly important because they relate to huge investments or non-recurring costs that influence the production costs. Further calculations about the exact number of presses, RC and RC will be done in the chapter 6 (Evaluation of Automation Concepts). Figure 4-11 shows a possible layout of the production system with 1 press and 2 cutting and stacking stations feeding the presses which would correlate to a takt time of 9.6 min.

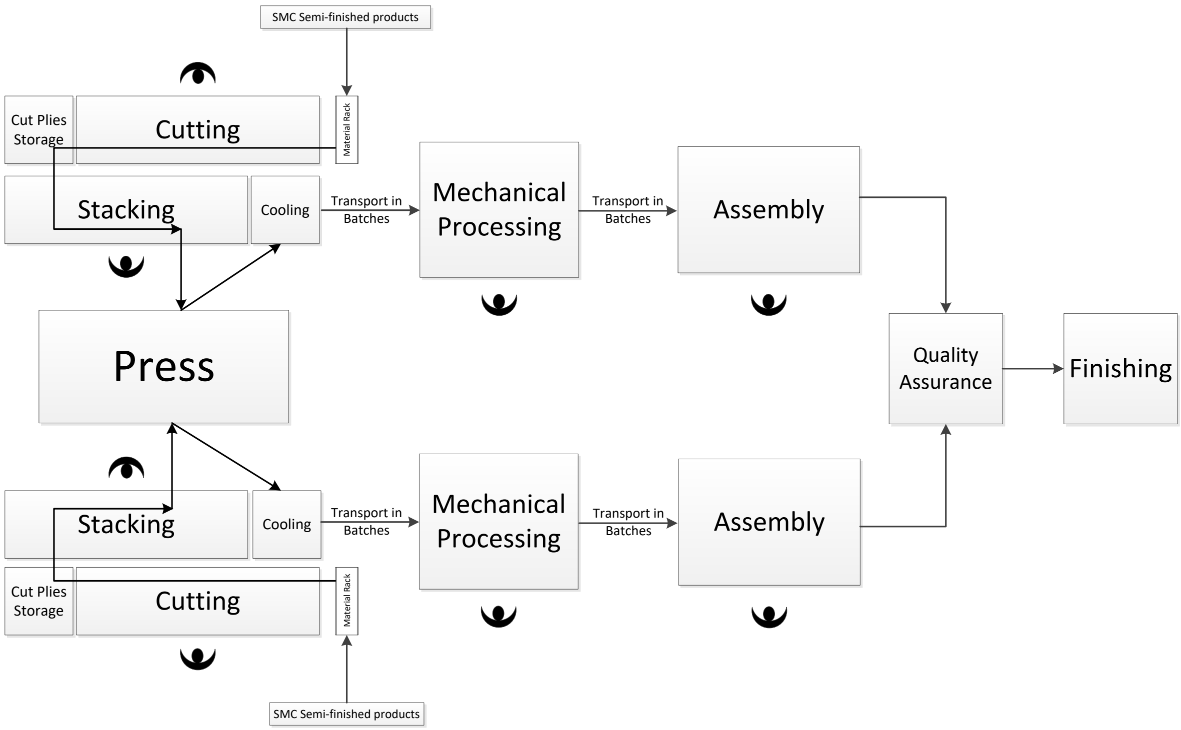


Figure 4-11: Possible layout for the baseline process based on previous

Although the cycle time diagram gives an impression which station exceeds the required takt time most, the situation within each station remains unclear. Consequently the cycle times within each station need further investigation. The times are plotted in percentage to the total cycle time of the station (Figure 4-12). On the first glance one can detect that a minority of tasks make up for the majority of the cycle time. This is especially noticeable for the stations cutting and mechanical processing.

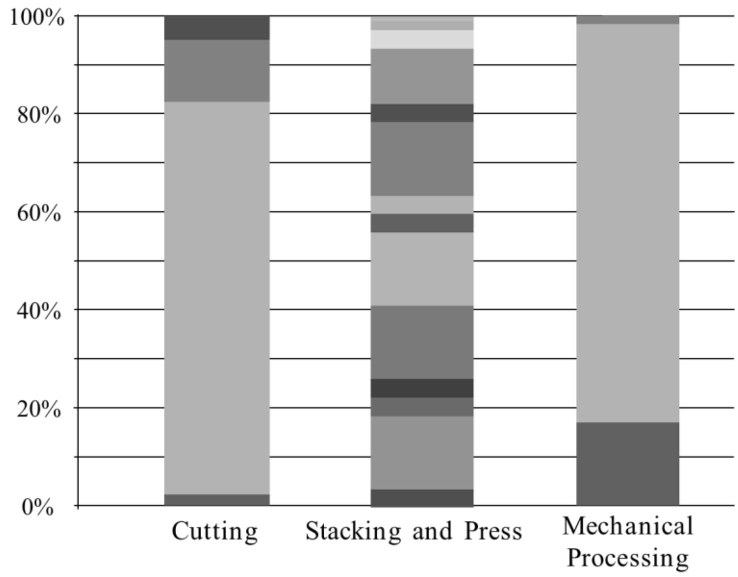


Figure 4-12: Cycle times per task as percentage of operation's total cycle time

To narrow down the tasks one should focus on automating from the lead time perspective the Pareto principle is applied. The Table 4-4 summarises the tasks that constitute to 80% of the station's cycle time. As it is possible that in a future production process stacking and press can be done in individual stations (e.g. one manual and one automated station) they are already considered separately.

Table 4-4: Identified most time consuming tasks per operation

Station	Tasks accounting for 80% CT
Cutting	Cut Plies
Stacking	Stack Rib Plies & TFPs, Punch Holes
Press	Place Inserts, Press Time, Place/Remove Preform
Mechanical Processing	Surface Treatment for Bonding & Finishing

After analysing the cycle times of the production process the LoA workshop is conducted. As a preparation of the workshop the process flow chart was modified into a HTA. The HTA consists of several levels from manufacturing process via operation down to individual process steps. The resulting HTA can be seen in Figure 4-13. The next step in the measurement phase of the DYNAMO++ methodology is to determine the current LoA for every process step and document them. Figure 4-14 exemplifies the minimum and maximum LoA for the steps within the cutting station. "M" represents the measured current level. Those charts are developed for every operation. Finally they are transferred to SoPIs, first on single process step level and afterwards they are superimposed to obtain squares on operation level. The whole series of charts can be found in Appendix B.

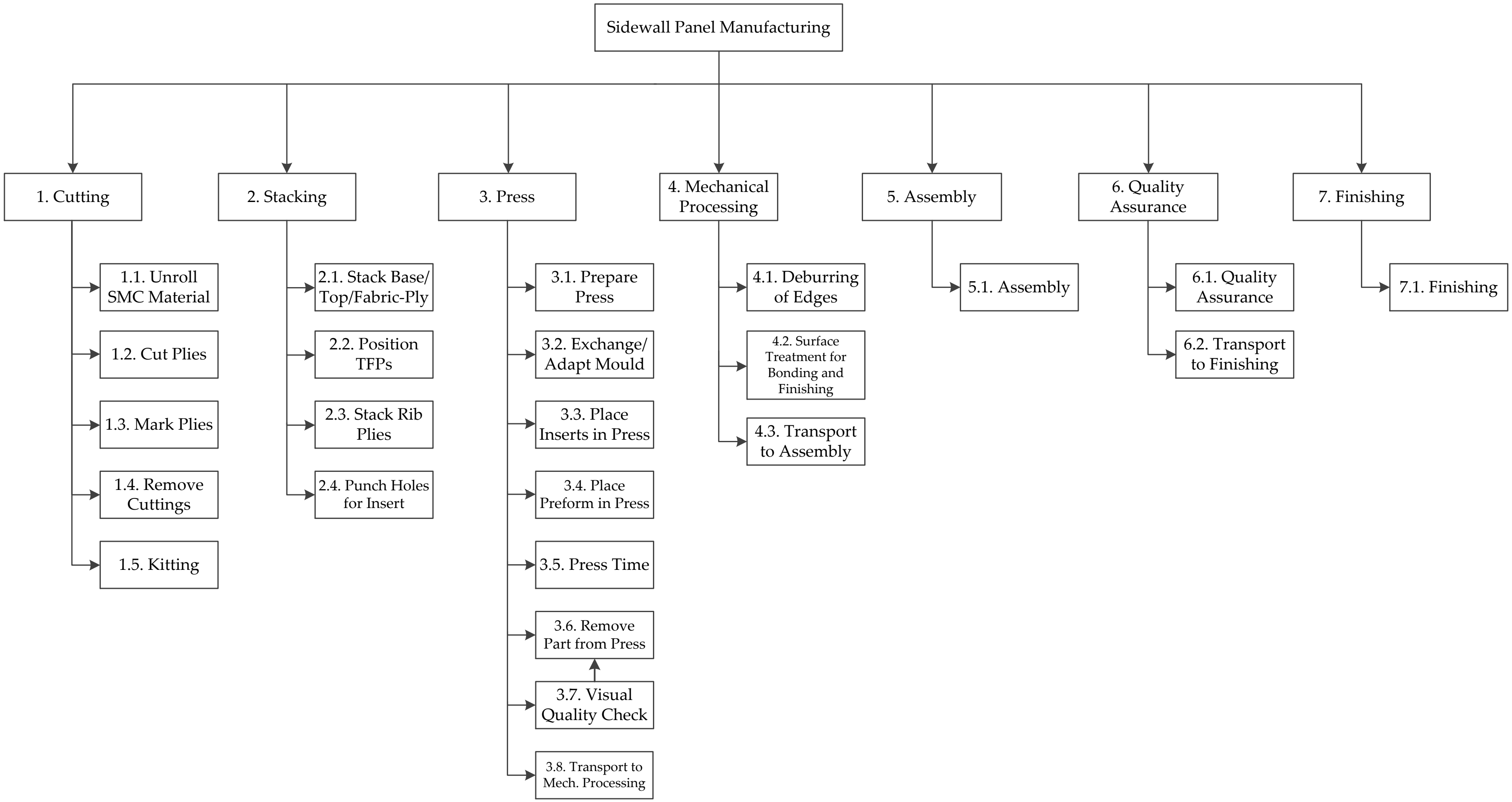


Figure 4-13: Hierarchical Task Analysis (HTA) of the sidewall manufacturing process

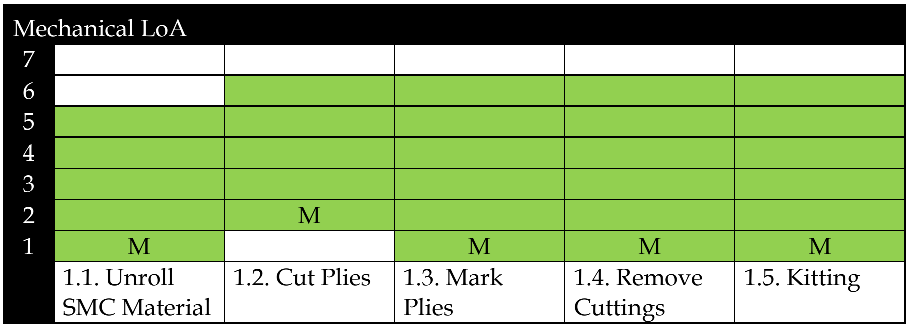


Figure 4-14: Min- and max LoA_{mech} of the cutting operation with current levels marked with "M"

The generated SoPIs, especially the one of cutting and press, reveal a limited solution space (compare to Appendix B). The reasons are that the tasks within an operation are sometimes very different to each other. Thus the maximum and minimum LoA are different as well. Therefore assumptions are made to widen the possible automation solutions and make use of the full potential of the method. Within cutting the task "unroll the SMC" has got a maximum mechanical level of 5 which limits the whole operation to this level. If one considers the device/module of unrolling the material as part of a more complex machine such as a NC-cutter it becomes LoA_{mech}=6 and the SoPI is extended to this. Furthermore the maximum cognitive level of kitting should be set to 5 as this activity is crucial to the whole operation. At this point errors made by previous steps can be detected and waste prevented. The adjusted SoPI is shown in Figure 4-15.

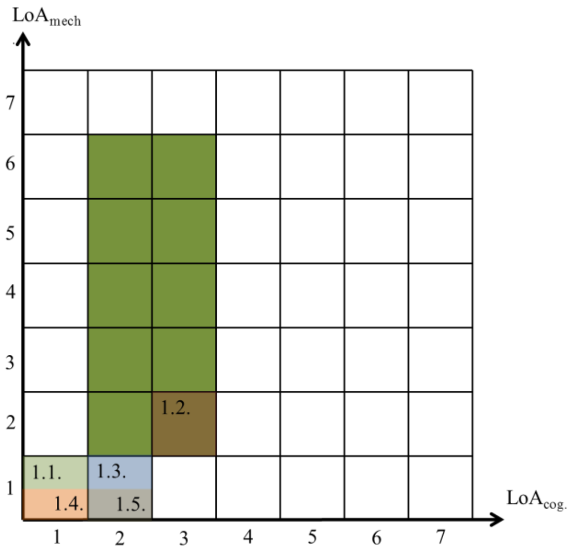


Figure 4-15: SoPI of cutting taken into account previously made assumptions

In contrast to the press operation there are no assumptions made connected to stacking. Pressing on the other hand is characterised by the tasks being very different. Exchanging the mould to switch between the different variants should be excluded from the analysis and considered differently by performing a SMED analysis for instance as it is not performed at every cycle but only once per batch. Similarly the visual check at the end of the operation should be considered as a downstream process outside the boundaries of the press operation because it is very different to the previous processes and therefore requires a different solution. Pressing is the core activity within this operation and all other tasks are placed around it. But at the same time the use of a press and the technology to control it results in a very high mechanical LoA (5-6) for the whole operation although other tasks can be performed with less mechanical aid without jeopardizing an efficient system solution. Consequently the LoA_{mech} of the task is neglected for creating the SoPI. The task that limits the cognitive axis is de-moulding the cured part because no high cognitive LoA is necessary. On the contrary it is justifiable or even necessary to have a higher LoA_{cog} for other tasks so the solution space should be extended under the precondition that it does not add extra costs to the demoulding task. The resulting adjusted SoPI of pressing and the one of stacking are shown below.

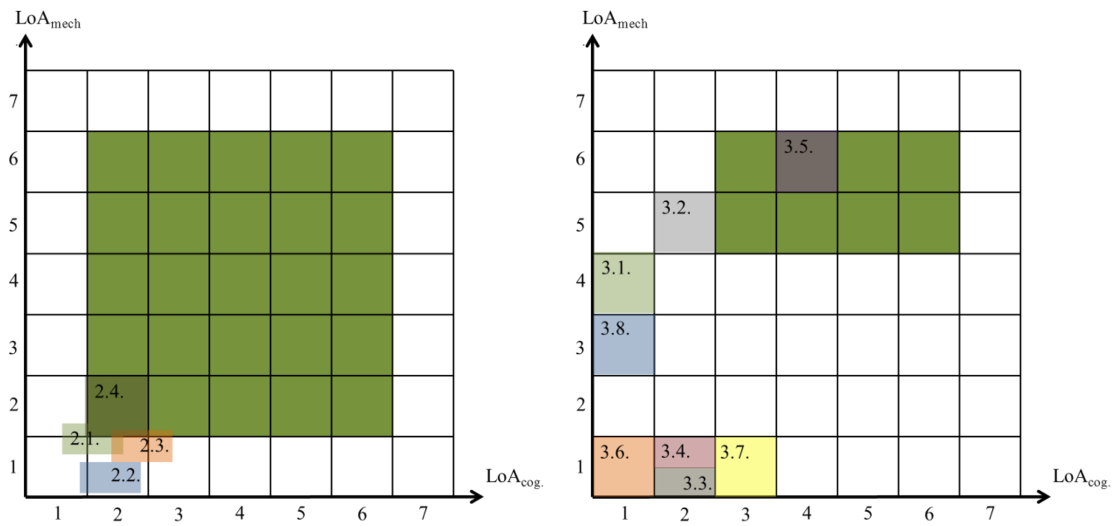


Figure 4-16: SoPI of stacking (left) and SoPI of press taking into account previously made assumptions (right)

There are no assumptions made for the final mechanical processing (Figure 4-17). But generally transporting is done from station to station. If the preconditions such as distance between the stations and amount of parts to transport are comparable a uniform solution should be found to benefit from synergy effects. As the SoPIs conclude the analysis phase future concepts with different LoAs based on various automation approaches are developed and described in the next chapter

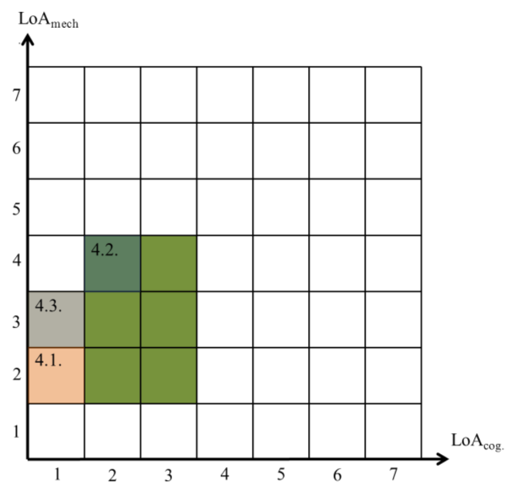


Figure 4-17: SoPI of mechanical processing.

5 *Development of Automation Concepts*

The result of the previous analysis chapter is used together with manufacturing automation approaches to develop suitable automation concepts. Before the different automation concepts are described single solutions for each major production step are collected. They are combined to automation concepts later on. The concepts are described in a coherent manner: The general concept is described with focus on the identified crucial process steps. Key elements such as machines are visualised with images or drawings. Afterwards a 2D-layout is presented and finally necessary investments are listed. The investments relate to the A350 scenario. Moreover, effects on other process steps that are not major cycle time contributors in the productions system are mentioned. In the later progress each concept needs to be evaluated and compared with each other. Process times, savings as well as costs of the respective concepts are estimated.

5.1 Single solution

In a first step the SoPIs are transferred into a solution matrix. The identified most time consuming process steps are listed in one dimension and all possible combinations of cognitive and mechanical LoA on the other axis. Initially the fields that are not relevant for a specific task are crossed out which is visualised by a dash. Secondly, areas without a reasonable technical solution are excluded and marked orange. Reasons for this assessment could be:

- High of level of cognitive automation (e.g. intervene) not suitable if task is done with simple hand tool
- Technical realisation is feasible but would exceed cost limits
- No intermediate solution between manual performance (LoA_{mech}=1-3) and programmable machines (LoA_{mech}=6)
- Low level of cognitive automation possible but would reveal great potential for errors

All leftover fields within the matrix are filled with a solution that represents the respective cognitive and mechanical LoA. The solution matrix is complemented with suggestions out of bounce of the LoA matrix. The complete matrix is shown in Appendix C and an extract can be found in Table 5-1.

Table 5-1: Extract of single solution matrix, the solutions for the relevant stacking tasks are shown (LoA_{mech}=2)

(LoA_{mech};LoA_{cog})	(2;2)	(3;2)	(4;2)	(5;2)	(6;2)
Rib SMC Plies	Possible but lower LoA_{cog} than current state	LoA_{mech}: Cover foil peel off aid and template LoA_{cog}: Templates (pins and holes in plies)	LoA_{mech}: Cover foil peel off aid and template LoA_{cog}: Laser projection system and hand device	LoA_{mech}: Cover foil peel off aid and template LoA_{cog}: Camera and signal system, image recognition assistance system	no technical solution possible
Punch Holes for Inserts	LoA_{mech}: Current solution (hammer and punch) LoA_{cog}: Work order (risk of bad positioning)	LoA_{mech}: Current solution with hammer and punch LoA_{cog}: Template (foil with hole positions)	LoA_{mech}: Current solution with hammer and punch LoA_{cog}: Laser projection system and hand device	LoA_{mech}: Current solution with hammer and punch LoA_{cog}: Camera and signal system	
Position TFPs	Possible but lower LoA_{cog} than current state	LoA_{mech}: Static Tool to preload TFPs while placing LoA_{cog}: Templates (pins and holes in plies)	LoA_{mech}: Static Tool to preload TFPs while placing LoA_{cog}: Laser projection system and hand device	LoA_{mech}: Static Tool to preload TFPs while placing LoA_{cog}: Camera and signal system, image recognition assistance system	

5.2 Technocentric Approach

The technocentric approach puts technology in focus and the overall goal is to perform as less manual work as possible. Applied to the DYNAMO++ methodology the upper right corner of the respective SoPIs is most interesting. Figure 5-3 shows the chosen line type layout with robots (SCARA and articulated robot) as handling devices. The NC-cutter (Figure 5-1) creates the initial ply geometries which are removed and stacked by a SCARA robot in one step (remove plies and kitting be omitted).

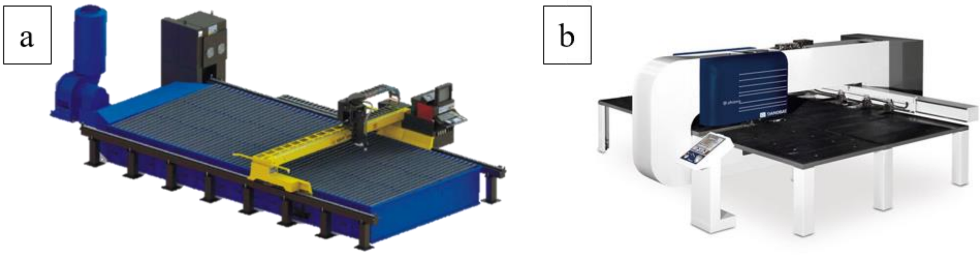


Figure 5-1: (a) Typical NC-cutter used to cut SMC material and (b) Punching machine (Danobatgroup, 2016) (Ajanusa, 2016)

The stacked preform is picked up by a robot, moved forward to a punching machine (Figure 5-1) and is finally placed in the mould. A second robot de-moulds the cured part and a cooling tunnel with included visual inspection system reduces the part's temperature for the subsequent mechanical processing done by an operator using an electrical hand grinding tool (Figure 5-2). The final quality assurance is again performed by an automated system using various kinds of cameras to detect even small errors. A similar system is visualised in Figure 5-2.

Figure 5-2: (a) Automated visual inspection system including several cameras to assess parts and (b) electric hand grinder for several grain sizes (ZBV Automation, 2016) (Handwerker Versand, 2016) (Pomati Chocolate Technology, 2016)

If this solution is compared to the SoPIs or the single solution matrix one can recognise that the mechanical LoA for most tasks is 6 and also the cognitive LoA is rather high to avoid human involvement as much as possible. Only one operator is needed to operate all machines up to mechanical processing (maximum $LoA_{mech=4}$). The presented solution will most likely reduce the lead time and avoid any ergonomic issues connected to cutting, stacking and the compression moulding process. The necessary investments are listed in the table below. Extending the presented approach to other activities within the process chain would mean to implement an automated tool changer and a robot endeffector which can clean the mould as well as handle the preform. This increases the complexity for necessary investments and would otherwise be done by the mentioned operator which increases RC. There are two sources of input for the estimated investments costs. One are the actual costs paid by the company for similar or equal equipment. For the investments those prices are not known interviews with manufacturing experts within the company are performed.

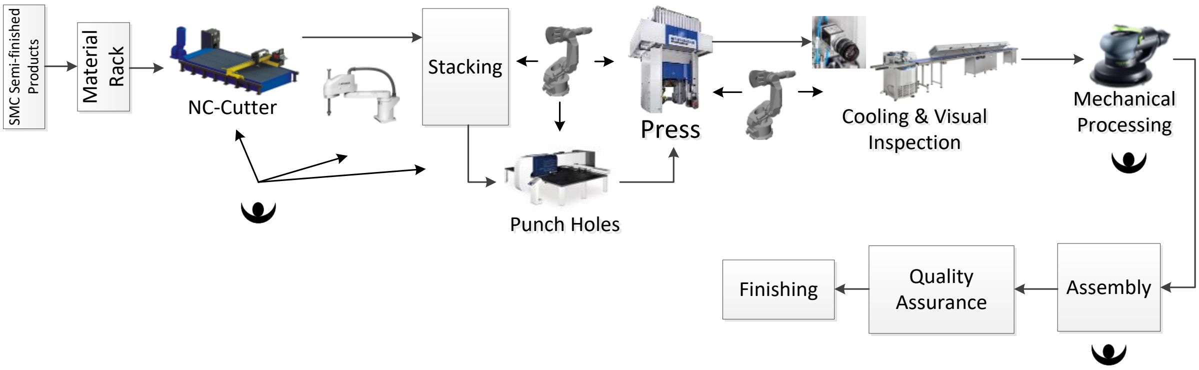


Figure 5-3: Conceptual line type layout for technocentric approach

Table 5-2: Investments costs for technocentric approach

Equipment	No.	Price
NC-cutter	1	100 000 €
Articulated robot (incl. endeffector)	4	450 000 €
SCARA robot	1	50 000 €
Peripheral and safety equipment	1	150 000 €
Punching machine	1	100 000 €
Cooling tunnel	1	75 000 €
Stacking table	1	1 000 €
Automated visual inspection	2	250 000 €
Press	3	3 000 000 €
Press tool	4	1 200 000 €
Assembly and commissioning	1	200 000 €
Total Investment		**5 576 000 €**

5.3 Human-Centred Approach

The human-centred approach puts the human in focus. Parasuraman (2000) describes the reduction of mental workload, increase in situation awareness and the graphical presentation of data and information as the most important aspects. Consequently cognitive automation is mainly used to implement the approach. However, operating costs, lead time, ergonomics and safety are evaluation criteria as well which leads to some mechanical aids where applicable. Therefore the manual cutter is replaced by an electric one (LoA_{mech}=4) which reduces the operator's physical burden and speeds up the process (Figure 5-5). Templates to guide the operator are inevitable as cognitive help. Stacking places the highest mental workload on the operator since a lot of decisions have to be taken and the placement requires the processing of much information. Therefore an innovative assistance system shown in Figure 5-4 is suggested, representing a cognitive LoA=5. It combines guidance to perform the operation and quality assurance. The core is an industrial image recognition module which detects objects on the table. A touchscreen shows the current situation, the desired situation when the task is performed and verbal instructions. The cameras can detect if the task is performed correctly and goes on to the next step while it sets an alarm if errors occur. The system can be combined with a laser projection system which shows the correct ply position on the work table. An integrated scale can determine if all plies are stacked and the preform weight is within the set tolerances. This is one quality criteria checked after compression moulding.

Figure 5-4: Innovative image recognition assistance system ("Der schlaue Klaus") (Optimum GmbH, 2016) (handling online, 2016)

After the preform is stacked inserts and the preform are placed inside the mould. For better accessibility a tool slide is used to move the lower mould out of the press. This makes a laser projection system similar to the one presented in Figure 5-5 for the exact preform position possible. It increases the situation awareness and assures consistent part quality. In this case the LoA_{cog} is 4.

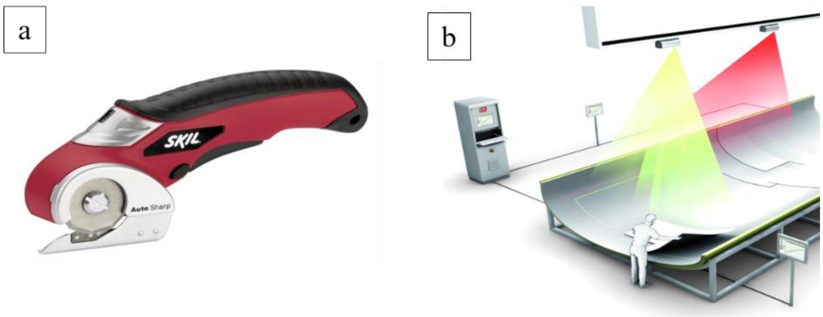


Figure 5-5: (a) Electric cutter and (b) laser projection system to assure correct placement of plies or preforms (focus.com, 2016) (ToolGuyd, 2016)

The de-moulding of the part is done by a robot (LoA_{mech}=5) due to the risk of burn injuries when de-moulding the hot part and ergonomics issues while working close to the press. The subsequent mechanical process is done similarly to the process described in the technocentric approach. Nevertheless, it is important to ease decision making for the operator by using boundary samples (LoA_{cog}=3) to assess the right surface quality. The use of the image recognition system can be extended towards less time-consuming tasks such as mark plies and kitting. Although the tasks were not identified as crucial regarding their cycle time such a system can contribute to the overall reduction of mental workload and an increase in efficiency and quality by reducing errors. The final layout and necessary investments are shown below. There are two sources of input for the estimated investments costs. One are the actual costs paid by the company for similar or equal equipment. For the investments those prices are not known interviews with manufacturing experts within the company are performed.

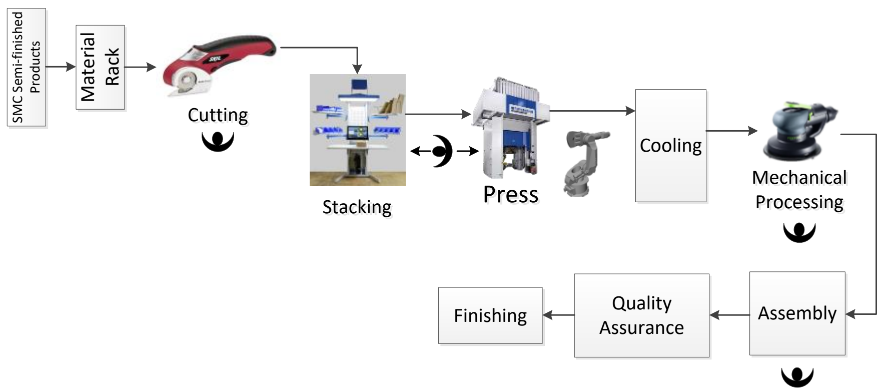


Figure 5-6: Conceptual line type layout for human-centred approach

Table 5-3: Investments costs for human-centred approach

Equipment	No.	Price
Image recognition assistance system	7	525 000 €
Articulated robot (incl. endeffector)	2	150 000 €
Laser projection system	3	90 000 €
Peripheral and safety equipment	1	75 000 €
Electric cutter	3	1 500 €
Cutting/Stacking table	7	7 000 €
Press	3	3 000 000 €
Tool	4	1 200 000 €
Tool slide	3	150 000 €
Assembly and commissioning	1	150 000 €
Total Investment		**5 348 500 €**

5.4 Lean Manufacturing Approach

The main idea of a lean production system is increase the efficiency of the system and keeps its flexibility. This is achieved by right-sized machines and a human-machine system. Most often standard machines are purchased and customised to fit the need of the production system and they are continuously improved while in use. Machines and tools have the task to help the human worker to perform the task with high quality but the actual value-adding activity is still performed by the operator. Another aspect of lean are evenly distributed cycle times among the stations as lean focuses on a smooth production flow. Stacking and press needs particular recognition because it has the longest cycle time in the baseline process and includes a lot of waste activities. First of all, the step of punch holes for inserts can be shifted towards cutting. As the operator is unable to cut the holes with sufficient precision and speed a NC-cutter is used. Furthermore it saves time to cut the plies compared to the manual process. The concept of *poka yoke* (mistake proofed) is used to reduce time for stacking and fulfil the strict quality requirements which are as well part of the lean strategy. Figure 5-7 shows the realisation of *poka yoke*. The template uses the integrated previously integrated holes to position the plies correctly. Additional holes are included to use this principle for the rib plies which are closed during compression moulding.

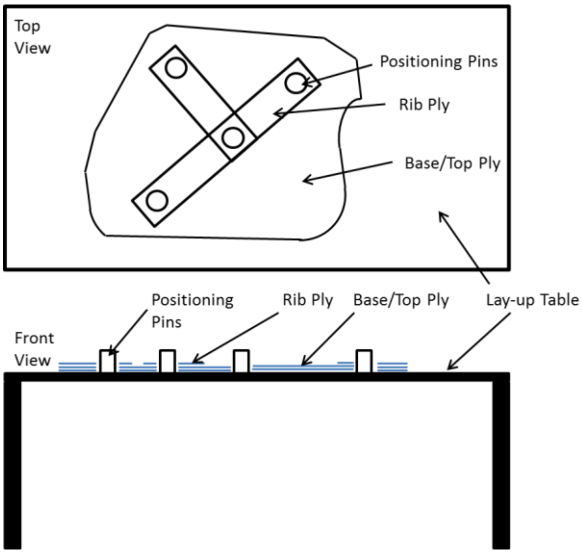


Figure 5-7: Template with pins to position plies and TFPs via holes cut during NC ply cutting

To reduce the cycle time even further the station is split. A handling robot performs the tasks of placing the preform and de-moulding the cured part whereas the operator prepares the next preform. Moreover, the robot assures a proper preform placement which influences part quality and the time for the operator to work close to the hot tools is reduced which improves his/her work environment. The robot is equipped with one simple endeffector that enables handling the part before (needle gripper) and after (vacuum gripper) compression moulding. Both types are shown in Figure 5-8.

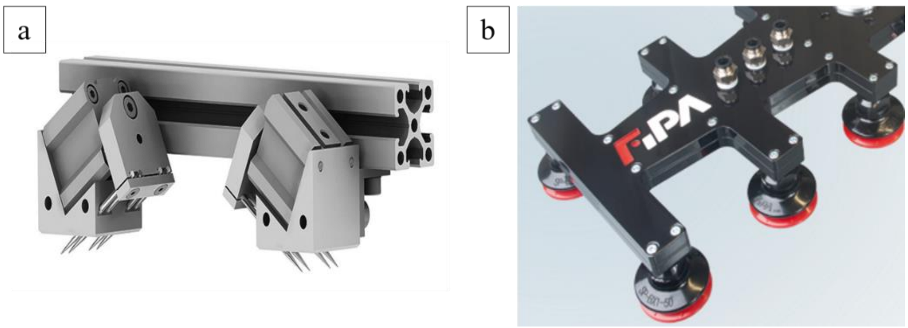


Figure 5-8: (a) Needle gripper which can be attached to robot to handle preform and (b) Vacuum gripper to handle part after compression moulding (ASS, 2016) (FIPA, 2016)

The downstream mechanical processing is performed in the same way as described in the previous concept saving some time for deburring as an electric hand tool is used. The final layout and necessary investments are shown below. There are two sources of input for the estimated investments costs. One are the actual costs paid by the company for similar or equal equipment. For the investments those prices are not known interviews with manufacturing experts within the company are performed.

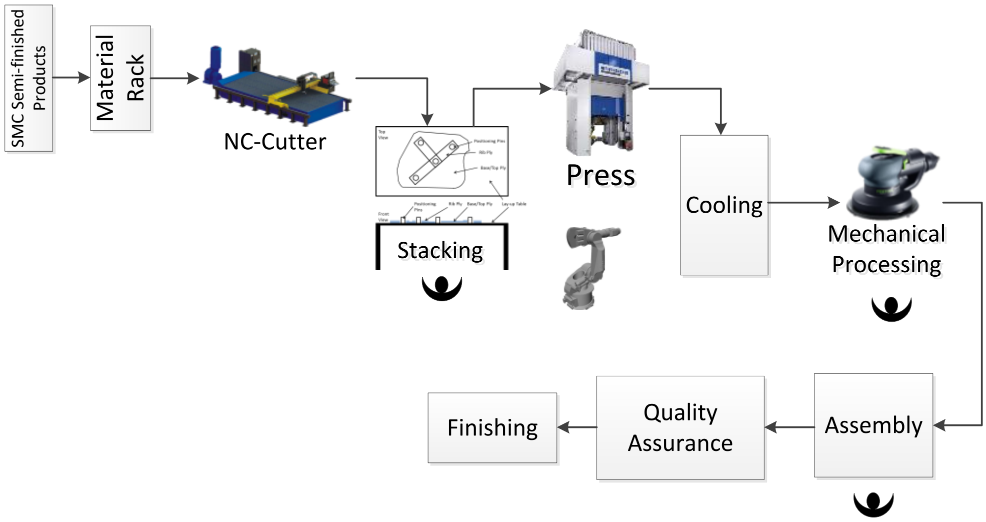


Figure 5-9: Conceptual line type layout for lean manufacturing approach

Table 5-4: Investments costs for lean manufacturing approach

Equipment	No.	Price
NC-Cutter	2	200 000 €
Stacking table	3	3 000 €
Articulated robot (incl. endeffector)	2	200 000 €
Peripheral and safety equipment	1	100 000 €
Press	4	4 000 000 €
Tool	4	1 200 000 €
Stacking template	3	30 000 €
Assembly and commissioning	1	150 000 €
Total Investment		**5 883 000 €**

5.5 Human-Machine Collaboration

The aim of human-machine collaboration is to reduce the occurrence of errors and workload. If the concept of collaboration is even further extended the machine can assist the operator or mitigate errors. Sheridan (1997) introduced the concept of sharing vs. trading which is one aspect in this concept. Sharing goes even one step further than collaboration as machine and human work simultaneously on the same task and in close proximity. Thus one can talk about human-machine-coexistence. In the given context it is applied to operations connected to the press. The sealing of the inserts requires much dexterity and is very difficult to be done by a robot. But the placement of the inserts on the other hand is rather easy to automate as a pick and place activity. Consequently the human prepares the insert and hands it over to a robot which does the placement. This requires collaborative robots as shown in Figure 5-10, proximity sensors and spatial relationships to hand-over the task position related rather than time related because the task execution time can vary due to different operator skills or natural variations. The placement of the actual preform and its de-moulding can be done by the robot as well such as it is described in previous concepts.

Figure 5-10: (a) Collaborative articulated robot and (b) SCARA robot (Robot Worx, 2016) (Softpedia, 2016)

The concept of trading is used for the cutting of plies. A NC-cutter cuts the ply geometry while afterwards the operator marks, removes and kits them. To reduce error potential the holes used for the integration of inserts are already cut by the NC-machine. Another activity suited for trading is stacking of the plies. While the large base and top plies are placed manually the smaller TFPs and rib plies are placed by a SCARA robot (Figure 5-10) which is characterised by high speed and precision. Especially the latter characteristic is important as the correct positioning influences the final part performance. While the SCARA robot performs its tasks the operator is free to interact with the second robot and to prepare the inserts. The downstream mechanical processing is performed in the same way as described in the previous concept saving some time for deburring as an electric hand tool is used. The final layout and necessary investments are shown below. There are two sources of input for the estimated investments costs. One are the actual costs paid by the company for similar or equal equipment. For the investments those prices are not known interviews with manufacturing experts within the company are performed.

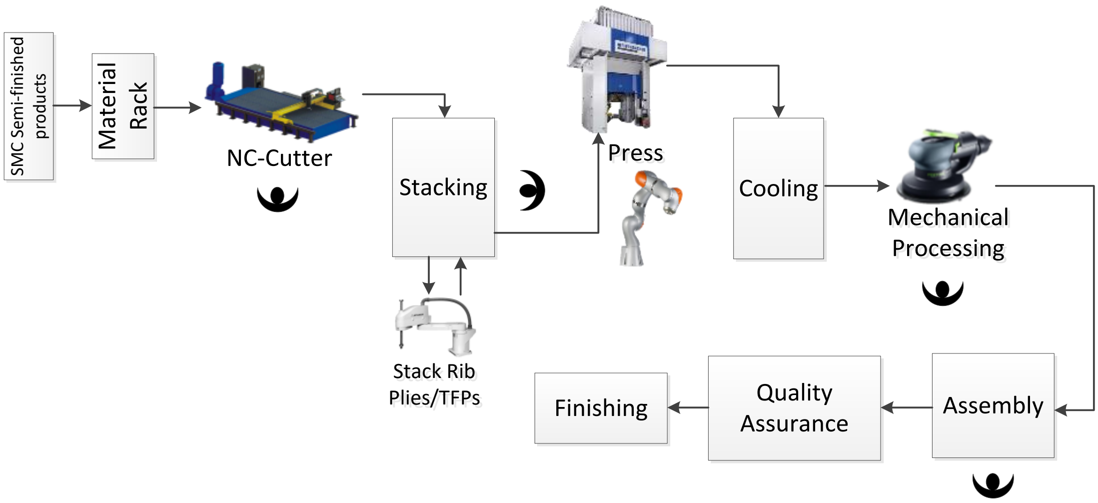


Figure 5-11: Conceptual line type layout for lean manufacturing approach

Table 5-5: Investments costs for human-machine collaboration approach

Equipment	No.	Price
NC-Cutter	2	200 000 €
Collaborative robot (incl. endeffector)	3	300 000 €

Peripheral and safety equipment (proximity sensors)	1	150 000 €
SCARA robot	1	50 000 €
Stacking table	2	2 000 €
Press	3	3 000 000 €
Tool	4	1 200 000 €
Assembly and commissioning	1	150 000 €
Total Investment		**5 052 000 €**

5.6 Human Machine Task Allocation

The concept of human machine task allocation is based on the assumptions that tasks can either be allocated to humans or machines depending on the characteristic of the task. The famous *Fitts List* is used as a guideline by stating which tasks humans or machines respectively can do better.

Applied to the given production system the cutting of plies would be performed by a machine, in this case a NC-cutter, as considerably great force needs to be applied precisely and fast movements are required. The opposite applies to the stacking station where flexible procedures and exercising judgment are required. This qualifies a human worker who can be guided by templates if applicable. As the methodology demands a strict separation of human and machine no technology is used in this process. Punching holes for the integration of inserts requires great force, so and a punching machine (compare to technocentric approach) should be chosen to perform this task. The placement of the inserts on the other hand requires a great amount of dexterity and some improvising. Thus a human operator is best chosen for the process step. The subsequent press cycle including loading and unloading the press calls for quick responding to control signals and precision. Therefore a robot (Figure 5-12) is used instead of a human.

Figure 5-12: (a) Dieffenbacher press and (b) articulated robot by Kuka (Dieffenbacher, 2016) (Kuka, 2016)

The last task of visual inspection requires again features that suite humans best. Reasoning inductively is only one of them. The downstream mechanical processing is performed in the same way as described in the previous concept saving some time for deburring as an electric hand tool is used. The final layout and necessary investments are shown below. There are two sources of input for the estimated investments costs. One are the actual costs paid by the company for similar or equal equipment. For the investments those prices are not known interviews with manufacturing experts within the company are performed.

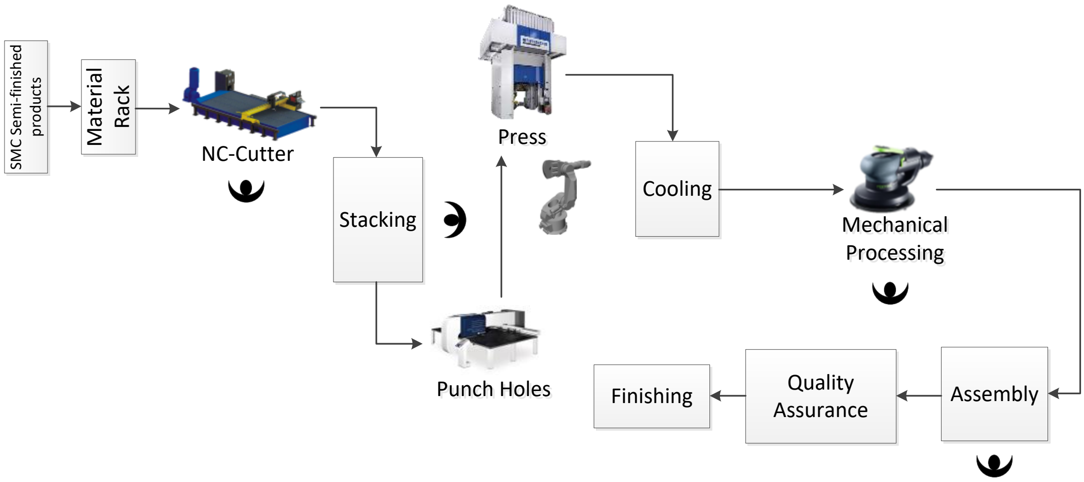


Figure 5-13: Conceptual line type layout for human-machine task allocation

Table 5-6: Investments costs for human-machine task allocation approach

Equipment	No.	Price
NC-Cutter	2	200 000 €
Articulated robot (incl. endeffector)	2	200 000 €
Peripheral and safety equipment (proximity sensors)	1	100 000 €
Punching machine	1	100 000 €
Stacking table	1	1 000 €
Press	4	4 000 000 €
Tool	4	1 200 000 €
Assembly and commissioning	1	150 000 €
Total Investment		**5 951 000 €**

6 *Evaluation of Automation Concepts*

The previously developed concepts are evaluated with the aid of the presented methods (Chapter 3). The aim of the evaluation is to identify the most suitable solution for a specific set of requirements and build the basis for a later discussion. First, evaluation criteria are presented and weighted by the paired comparison according to their relevance. Those weights serve as input to a utility analysis whose results are presented in the later part of the chapter. Other inputs are cost calculations, time estimations and lead time calculations which are presented one by one. The latter is underpinned with a discrete event simulation to take into account effects of unbalanced cycle times, idle and starve times as well as downtimes of machines and operators. The conclusion of the chapter is a SWOT analysis of the two top ranked concepts based on the utility analysis.

6.1 Evaluation Criteria and their Weighing

In the following the criteria for evaluation are described. In total 9 criteria are taken into account: NRC, RC, production lead time, quality, safety, ergonomics, technical complexity, required operator skills and flexibility. After the description the result of the paired comparison is presented.

Non-recurring Costs (NRC)

The non-recurring costs are the investments that have to be made to implement the respective production system. To achieve comparability between the considered scenarios with different production volumes the costs are broken down into costs per part. A payback period of two years is assumed based on the company's policy. Regarding the assessment the least expensive concept gets the highest score and consequently the most expensive one gets the lowest possible score. The intermediate scores are distributed evenly with regard to absolute values.

Recurring Costs (RC)

The recurring costs constitute of operator costs, maintenance and material costs. The detailed calculation of those costs is described later part in this chapter. Electricity costs and the cost for the occupied shop floor area are neglected because they are small compared to major the contributors material and operator costs. The assessment of points is done as described for the NRC.

Production Lead Time

The production lead time is the conglomerated time of all process steps from cutting to the finished product ready for delivery. The cycle times for assembly and finishing including their process times (drying of paint and adhesive) are not affected by the use of different concepts but are included in the calculation as constants. In a first step the times are simply added to calculate the production lead time. Afterwards the discrete event simulation is used to verify the times or adjust them according to the simulation results. In contrast to the basic calculation the simulation takes into account time variations and unforeseeable breakdowns which lead to dependencies of processes and unexpected waiting times. The scoring follows the same principle as previously used for NRCNRC and RC.

Quality

The criterion quality does not refer to the part quality per se but how features within the production system assure a consistent quality and avoid errors. Those features can be systems which detect errors or false parameters and give an alarm signal or templates which help the operator to stack plies or place the preform correctly. Mistake-proofed designs are another option. The assessment is qualitative and refers to the expected improvement by a particular feature or the sum of them. The absence of quality assuring elements results in a low score while a score of 10 does not need to be given to the best solution if sources of failures still exist.

Safety

Safety is a basic element of every production system. In this case the risk of injuries is assessed. Elements that can lead to a great risk potential are the hot press and moulds, robots within the working environment of humans or other machines which can harm people. The baseline manual process gets a score of five and other concepts can be assessed better or worse in comparison to the baseline process.

Ergonomics

The ergonomic working conditions of operators are an often forgotten aspect when designing a production system. But the long-term consequences can be huge. An ergonomically designed work place can lead to less absence, higher operator motivation and little staff turnover which finally improves the performance of a production system and leads to less overall costs. In this regard ergonomics is assessed for every concept on a qualitative base. Factors that can lead to bad ergonomics are among others working close to the hot press, very short cycle times (great number of repetitions) and the application of great force.

Technical Complexity

An increased technical complexity can result in errors while operating machines. This can lead to downtimes of machines or component quality issues. Furthermore, a high technical complexity can lead to increased maintenance costs (spare parts and staff costs) that might not be expected during the concept phase. Both, the risk of errors due to the incorrect use of machines and the potential for increased maintenance effort is qualitatively assessed.

Required Operator Skill Level

The increased use of machines and especially the application of many different machines require training of operators. Although this can be seen as one-time costs a more qualified operator gets a higher payment. Moreover, the company is more dependent on a highly trained operator. Thus in case of an operator leaving the company the recruitment of a new employee becomes more difficult or expensive if a less qualified operator is recruited and needs again excessive trainings. As the minimum amount of machines is used in the baseline process the score is set to 10. All other concept gets higher scores according to their complexity.

Flexibility

Flexibility has two dimensions. The first one is the ability to shift between different products or cope with a change of variant mix within an existing product line. This should be possible with minimum effort and adjustments. The second dimension could be seen as scalability. This refers to the ability to cope with changes in production volume. This criterion is affected by the costs associated with producing more or less products per year. Influencing factors can be fixed costs, increase with a decrease in production volume and the utilization of equipment. A high utilization leads to investments when increasing production rates while a low utilization can cope with a higher demand avoiding additional investments. The assessment is done qualitatively while more focus lies on scalability.

The identified evaluation criteria are ranked according to their relevance by the method of *paired comparison*. To minimise the effect of a subjective judgment by one individual person the paired comparison was done in a group of three engineers who were all familiar with the topic of SMC and the automation concept. It turned out that RC is the most important criterion having a weight of nearly 25%. Production lead time and quality with nearly the same result follow on rank two with a weight of ca. 18%. The other criteria fall in place behind the top three as it can be seen in Table 6-1. The weights are input for the subsequent concept scoring matrix. Each performance value will be multiplied with them to take into account their respective relevance. The criteria safety, generally considered as very important, gets a score of 11%. One have to state here that a minimum level of safety is always necessary before putting a production system into service. Furthermore, the level of safety is addressed in DIN EN ISO 9001 and 9100 which are mandatory as an aircraft supplier. The NRC are weighed lower than production lead time, quality and RC which makes perfectly sense. Otherwise the initial investment costs would influence the final decision to a large extent although they are calculated with a short payback period of 2 years.

Table 6-1: Result of the paired comparison includes all chosen criteria

than/as more/less/equally important	Production Lead Time	Non-recurring Costs (NRC)	Recurring Costs (RC)	Quality	Safety	Ergonomics	Technical Complexity	Required Operator Skill Level	Flexibility	Weight in %
Production Lead Time		1	0	0	1	1	1	1	1	17%
Non-recurring Costs (NRC)	0		0	0	1	1	1	1	1	14%
Recurring Costs (RC)	1	1		1	1	1	1	1	1	22%
Quality	1	1	0		1	1	1	1	1	19%
Safety	0	0	0	0		1	1	1	1	11%
Ergonomics	0	0	0	0	0		1	0	0	3%
Technical Complexity	0	0	0	0	0	0		1	0	3%
Required Operator Skill Level	0	0	0	0	0	1	0		0	3%
Flexibility	0	0	0	0	0	1	1	1		8%

6.2 Time Estimation

The basis of the time estimation for all concepts is the estimation performed during the analysis phase. The major process steps remain the same but the work content changed slightly for tasks. One example is the cutting operation where the use of template is redundant when using a NC-cutter. This saves some cycle time for the cutting operation. Likewise the basic analysis, the times are estimated based on machine parameters, information given by machine vendors, own experience or experience of colleagues and assumptions. Some of the times could be verified during the prototype production of similar SMC components.

The savings achieved by the use of cognitive or mechanical aids and their reasons are stated in the remarks column. Process steps can be either performed by humans or machines which is relevant for the subsequent cost calculation as only tasks performed by an operator generate operator costs (noted in the cost calculation). The times for assembly and surface finish remain unchanged because they are out of the scope of this thesis. Similarly the times for mechanical processing and quality assurance change only slightly for some concepts because no great changes are made in the way they are performed.

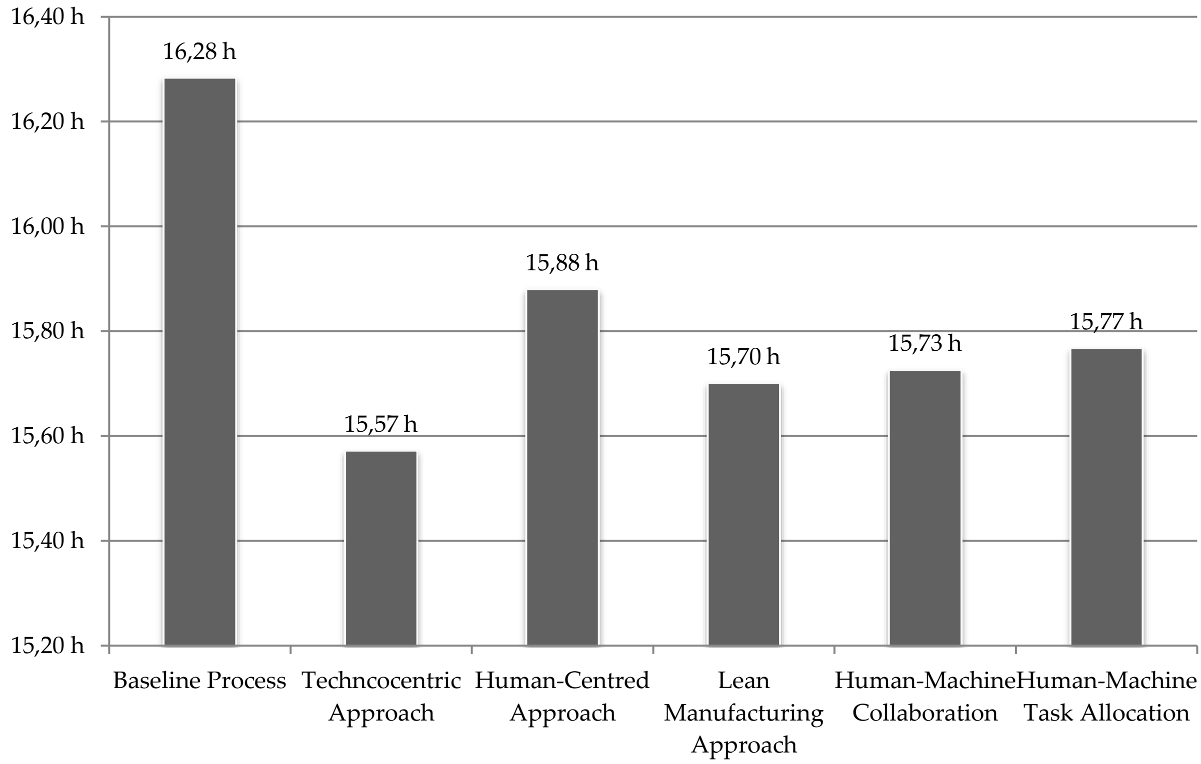


Figure 6-1: Result of the static production lead time calculation

The time estimation of the single steps is concluded by a production lead time calculation. At first all cycle times and process times (cooling, drying times etc.) are summed up and compared to each other. This static calculation of the production lead time does include effects that occur in reality such as random stoppages and breaks of operators. To consider those effects the DES was performed and the production lead time was calculated as the sum of the average residence time per station or buffer. The times are input for the concept scoring matrix. While the result of the production lead time calculation can be seen in Figure 6-1 the complete time estimation table including the actual production lead time calculation can be found in Appendix D.

6.3 Discrete Event Simulation

The DES is performed to verify the production lead time and include effects that cannot be covered by the static analysis. Delmia Quest was used as simulation software. Those effects include variations in cycle times, unforeseen stoppages that interrupt the product flow and unbalanced stations that causes waiting times. For each concept all three scenarios are built according to the layout presented in the previous chapter. The layouts can be seen as conceptual models. Buffers are included where applicable (between cutting and stacking and where drying and cooling time is necessary). The model is built as a pull system as the sink pulls parts according to the required takt time and the request is propagated through the system. Figure 6-2 displays the model of the baseline manual process for the A350 scenario.

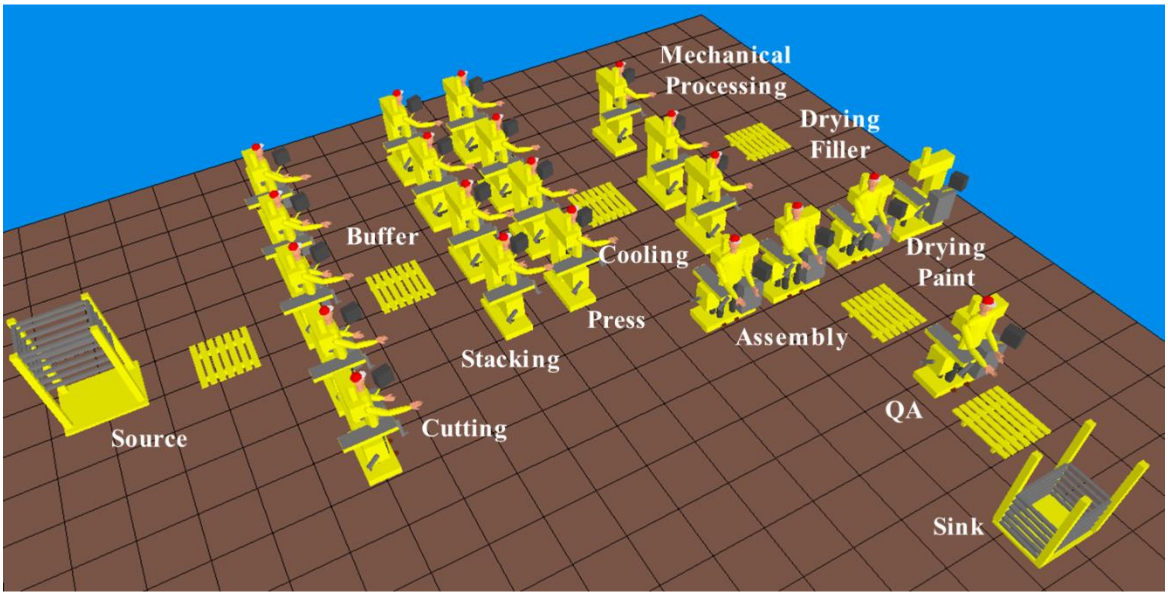


Figure 6-2: Delmia Quest model of manual baseline process for the A350 scenario

The source and sink are starting and end point respectively. The pallets represent buffers. Some buffer forward parts with a delay to mimic drying and cooling times. Others have limited capacity to reflect a realistic environment. A list with the most important assumptions applied to this and other models can be found in Table 6-2. In this case human operators are placed at every station throughout the system. As no real data are available the behaviour is estimated by crude assumptions. Cycle times for manually performed tasks are assumed as normally distributed while tasks performed by machines are constant. Machine failures follow the Poisson process and an exponential distribution is assumed.

Table 6-2: Assumption included in the DES

Entity	Assumption
Manual operations	Normally distributed CT acc. to time estimation (σ=CT/6)
Machine operations	Constant CT acc. to time estimation
Operators	Breaks every 4 h (n 4h, σ= 10min) lasting 5 min (n 5min, σ=50sec)
	Team meeting once a week (c 39h) lasting 55min (t 50min, max=55min, min=45min)
Machines	Failures that require maintenance (MTTF: e 18h; MTTR: n 20min, σ=200sec)
	Minor stoppages (only valid for technocentric approach) that require operator attendance (MTTF: e 24min; MTTR: n 50min, σ=50sec
Press	Clean mould and change tool every 39h (c 39h) lasting 75min (n 75min, σ=12.5min)
Cutting	Change SMC roll every 100 parts lasting 5 min (n 5min, σ=50sec)
Buffer before press	Capacity 10 parts per press
Buffer before stacking	Capacity 20 parts

The simulation runs for one month time. But instead of using the available production time considering an OEE of 80% as it was done in the static calculation the full available time is used. This means that the run time is 146 h (1760 h/a). A warmup time of 20 h is added to fill the system with parts and represent an already running production system. To calculate the production lead the average residence time of parts per station/buffer is evaluated and summed up. Ten runs with random variables are performed and the mean values calculated to cope with the variation introduced by manual operations for instance. Throughout the modelling the model is verified to assure its correct behaviour. Two concepts are used to do this. First the model's animation are watched to detect if parts are piled up in buffers as a consequence of unexpected behaviour or deadlocks. Moreover the takt time at the sink was altered and the output values observed to ensure the model behaves reasonable. The final validation is difficult to perform as no real system is in place yet. Nevertheless a face validation and sensitivity analysis is performed. The built model could not be compared to a real counterpart but as similar production systems exist the model can be compared to those. The sensitivity analysis is very similar to the described verification method of varying the takt time at the sink. But here more input parameters are altered segregated from each other. The statistics, especially the utilization and waiting times, give information if the system react as it would do in the real world.

First it can be recognised that all concepts can achieve the desired takt times with varying utilization of the stations. Those utilization are not further analysed in this context. The calculation provides three lead times per concept because of the three scenario. To be conservative the worst case was picked to be the input for the evaluation. Figure 6-3 shows the result production lead time results for all concept. It can be stated that the absolute values change but in relation to each other the times stay nearly the same.

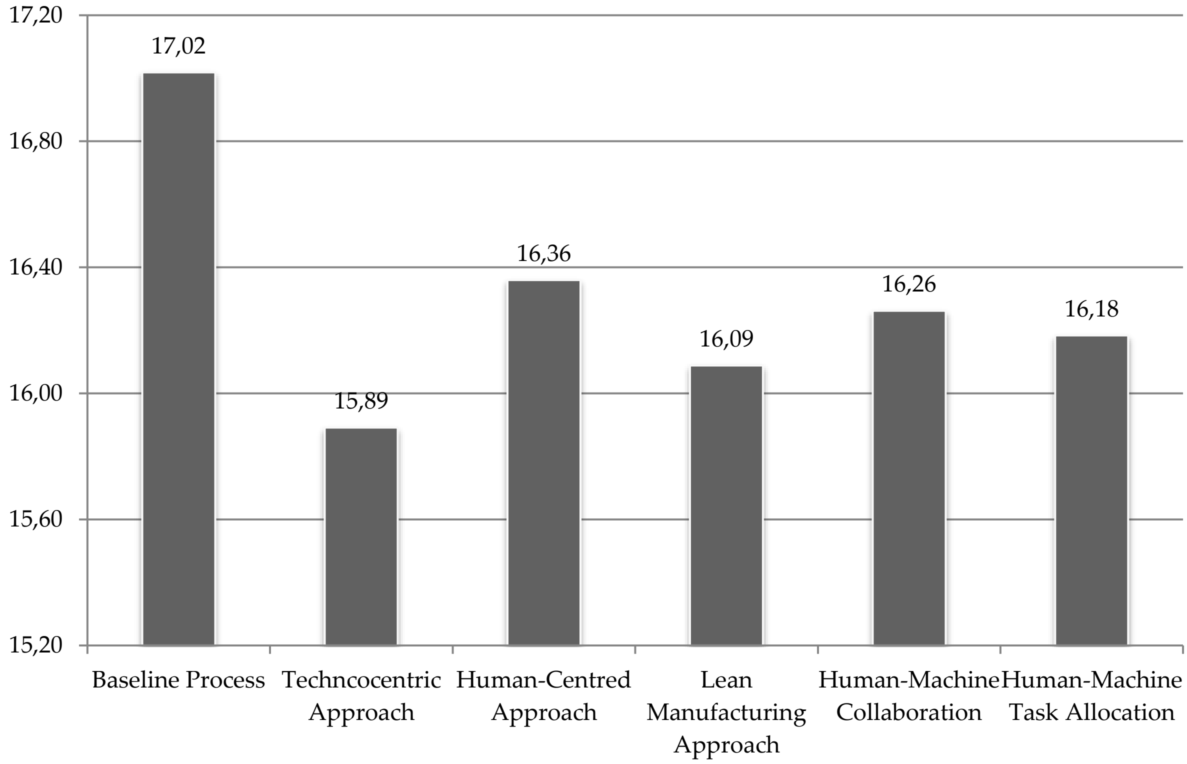


Figure 6-3: Production lead time according to the DES as input for the concept scoring matrix

6.4 Cost Calculation

Based on the estimated times of the single steps a thorough cost calculation is performed. The final results are RC and NRC shown in Figure 6-4 and

Figure 6-5. The savings are calculated with respect to the baseline process. As different production scenarios are considered (A350, SA, SA+A350) the savings vary in a certain interval revealing different concepts as favourable. Before the results can be presented several pre-calculations are performed. At first the number of presses is calculated (Appendix E). To do so, all process steps occupying the press such as place inserts, prepare press or the press cycle itself are summed up and divided by the takt time for the respective scenario. The cycle times for each station and automation concept are previously shown in the number of presses calculation. As some stations are condensed for a certain concept the number varies between the concepts. Cycle time charts are drawn to show the cycle time distribution and their relation to the required takt times (Appendix F).

The final pre-calculation deals with the material costs of the SMC part. The bases are costs per kilogram or piece of the different materials. A buy-to-fly ratio is defined which states the material usage. The NC-cutter leads to less waste because a thorough nesting can be performed as the cutter can cut the plies very exactly. After all the material costs per part are calculated multiplying the material needed with the price per kilogram. The material costs are one part of the recurring costs and presented in Table 6-1. Furthermore the table shows other assumptions necessary for the cost calculations. The operator costs of 80 EUR/h are a typical value for the German aerospace industry and used internally as basis for calculation. The input for OEE and maintenance costs were given by lean experts within the company.

Table 6-3: Assumptions made for calculation of costs

Assumptions	
Operator costs per hour	80,00 €
OEE	80%
Payback Period	2 years
Maintenance Costs in percentage of total investment	3%
Available operator hours per year (220 days*8h/day*80% OEE)	1408
Material Costs per part (manual cutting)	144,10 €
Material Costs per part (NC-cutter)	142,70 €

The cost calculation is divided in recurring and non-recurring costs and finally both values are combined. RC constitute of operator costs, maintenance costs and material costs. Each of them is scaled down to costs per part. The operator costs are calculated by multiplying the cycle times with the operator costs per hour. Only stations with a permanent operator are considered. In case of the fully automated system one full operator per NC-cutter is assumed who operates other machines including the press as well. The operator only has to deal with minor stoppages such as residues in the press that cannot be handled by the automated cleaning device or material rolls that need to be fed to the NC-cutter. The maintenance costs are calculated by the investment costs and the assumptions of 3% of the investment costs are needed for maintaining the machines. The material costs are taken from the previous calculations. Other costs such as electricity or costs for the occupied shopfloor area are neglected due to their minor contribution to the total RC. The RC between the different scenarios within one concept differ only slightly because operator and material costs per part are equal. The difference is only caused by the maintenance costs which make up for 3% of the total RC.

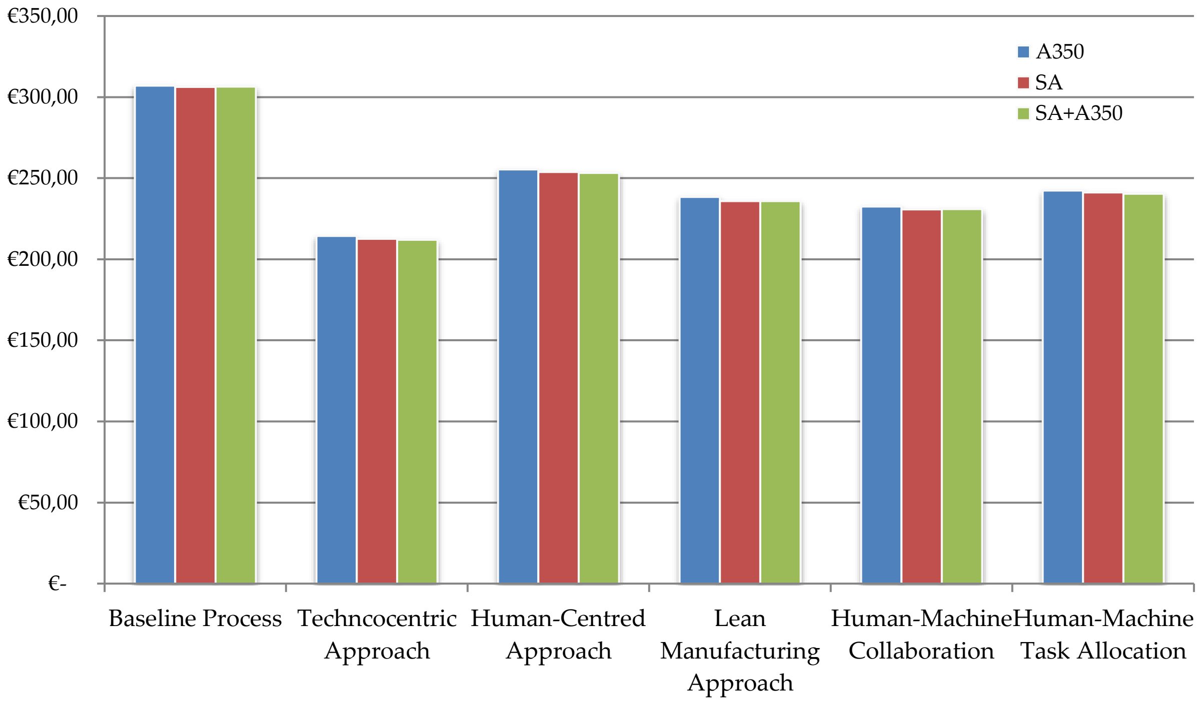


Figure 6-4: Comparison of recurring costs between chosen concepts for the considered scenarios

NRC are calculated by the investment costs divided by the number of parts during the payback period of two years. To determine the necessary investments the number of stations is calculated using the cycle times and the required takt time in each scenario. Afterwards the number of stations is multiplied with the costs for the machines necessary for the respective stations. The complete calculation is shown in Appendix G.

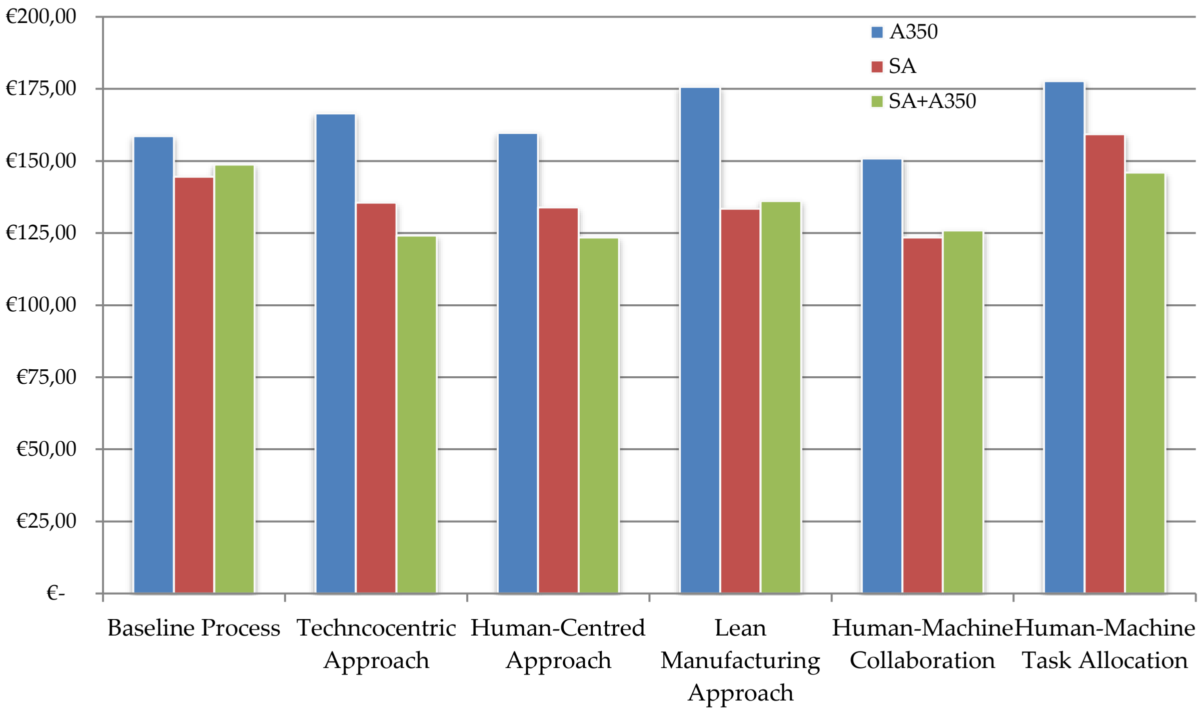


Figure 6-5: Comparison of non-recurring costs between chosen concepts for the three considered scenarios

6.5 Concept Scoring Matrix

The cost and production lead time calculations are the major input parameters for the utility analysis resulting in the concept scoring matrix. The three values are scored as described in the beginning of this chapter. All other criteria are assessed qualitatively from 1 to 10. The reasoning behind the respective values is summarised in Appendix H. Hereafter only the most promising concepts are elaborated more on. The following figure shows the result of the utility analysis for all three investigated scenarios. The scores vary between 3.0 for the manual process in the scenario of SA+A350 and 8.1 for the technocentric approach in the same scenarios.

In the following the scenarios are interpreted independently. The manual process and the human-machine task allocation approach show the worst results for the A350 production rate with a value of 4.1 and 5.2, respectively. The human-centred approach gets a final score of 6.7. However, all other approaches reach a score close to 7 or even higher. To guarantee a better evaluation the scores of lean manufacturing (6.7), technocentric (7.3) and human-machine collaboration (7.8) are investigated closer by a radar diagram Figure 6-7.

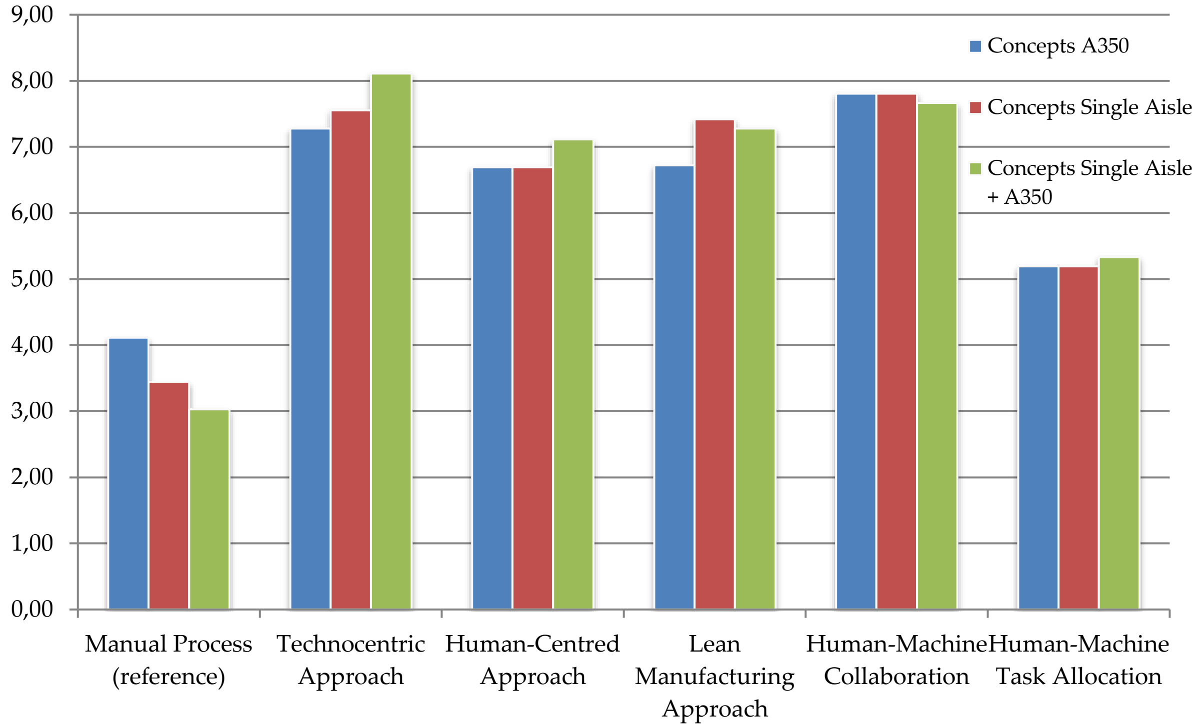


Figure 6-6: Final result of the utility analysis containing the score for all investigated scenarios (A350, SA & SA+A350) in the respective colour

The diagram reveals that the human-machine collaboration approach gets the highest score for the criteria NRC, safety and ergonomics (same score as technocentric approach) while the technocentric approach has its major advantage in production lead time and recurring costs. The lean approach on the other has the best results for the lower weighed aspects of flexibility, required operator skill and technical complexity but also quality.

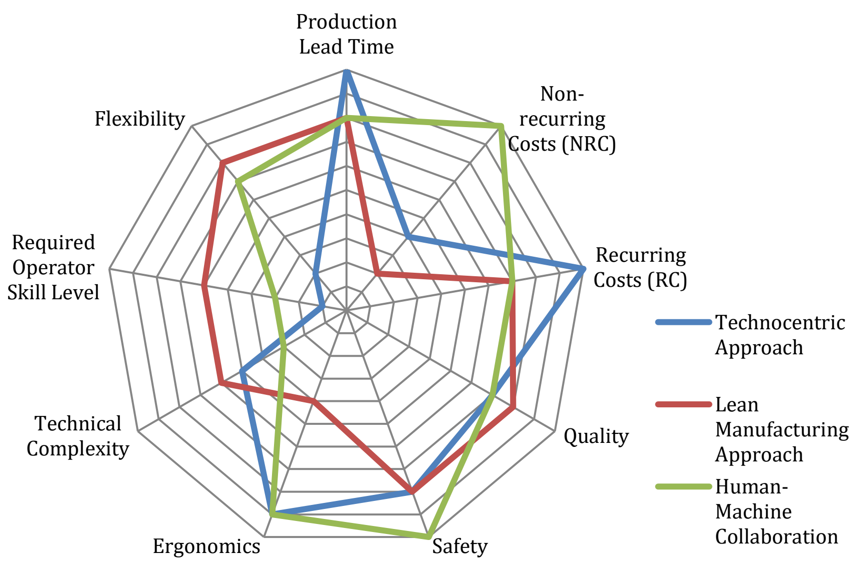


Figure 6-7: Radar chart of top-three ranked concepts for the A350 scenario

Regarding scenario two (single aisle) again the baseline manual process (3.4) and the human task allocation approach (5.2) get the lowest scores followed by the human centred approach (6.7). The latter one scores very high (8-9 points) in the criteria quality, technical complexity, required operator skill level and flexibility. The radar chart (Figure 6-8) compares the three best scored concepts (lean manufacturing: 7.4, technocentric approach: 7.6 and human-machine collaboration: 7.8) in more detail. The criteria flexibility, required operator skill level, technical complexity, ergonomics, safety and quality remain unchanged by the shifted production volume. Consequently, as the same approaches score best, the radar chart is identical to the one previously presented. Production lead time, recurring costs and non-recurring costs are affected due to different investments but the technocentric approach stays the top scored for the first two. The human-machine collaboration gets a score of 10 for the latter criterion. The lean approach improved significantly from 6.7 to 7.4 points compared to the initial scenario due to reduced NRC (Score: 7 points).

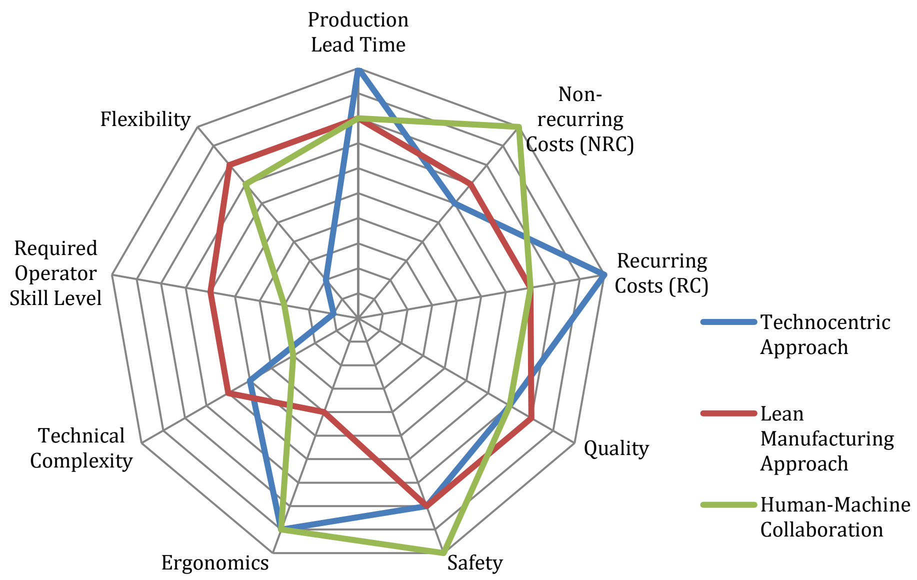


Figure 6-8: Radar chart of top-three ranked concepts for the SA scenario

The final scenario is a combination of the first two and includes the production sidewalls for single aisle and A350 aircraft. Human-task allocation and the baseline manual process get a final score of 3.0 and 5.3, respectively. The human centred approach shows a considerable increase to 6.8 points compared to the previous scenarios. The other three concepts remain the top-ranked ones but in a changed order. Lean manufacturing stays in position three with 7.3 points while human-machine collaboration approach is ranked as 2nd. with a drop in points down to 7.7. The technocentric approach on the other hand gets top points for the three changing criteria (NRC, RC and production lead time) and increases the final score to 8.1. The detailed comparison of the three best results is shown in Figure 6-9.

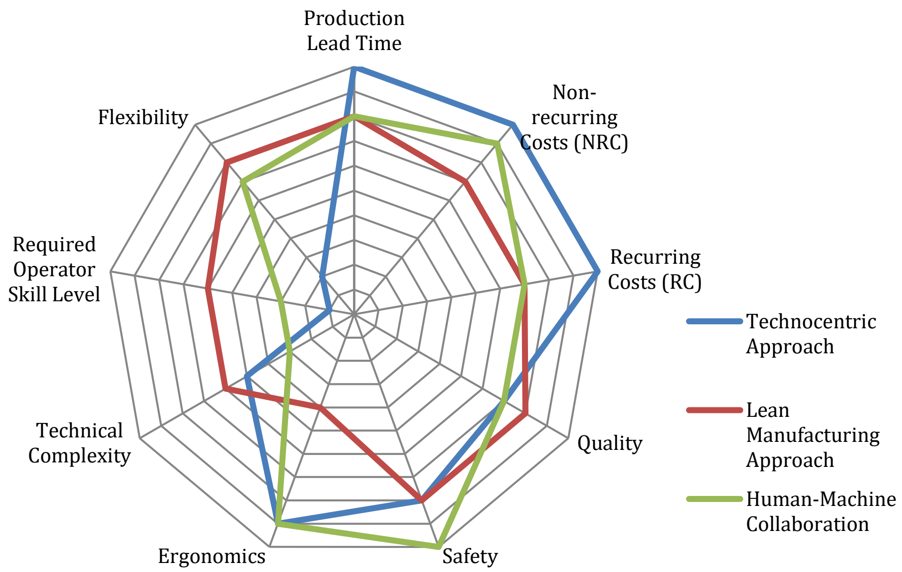


Figure 6-9: Radar chart of top-three ranked concepts for the SA+A350 scenario

6.6 SWOT Analysis

The previous evaluation by the concept scoring matrix identified three concepts as most promising: technocentric, lean manufacturing and human-machine collaboration approach. The SWOT analyses summarizes the strength and weaknesses of this particular concepts and adds aspect that were so far not considered. The concept scoring matrix and the SWOT analyses are together the basis of the subsequent discussion.

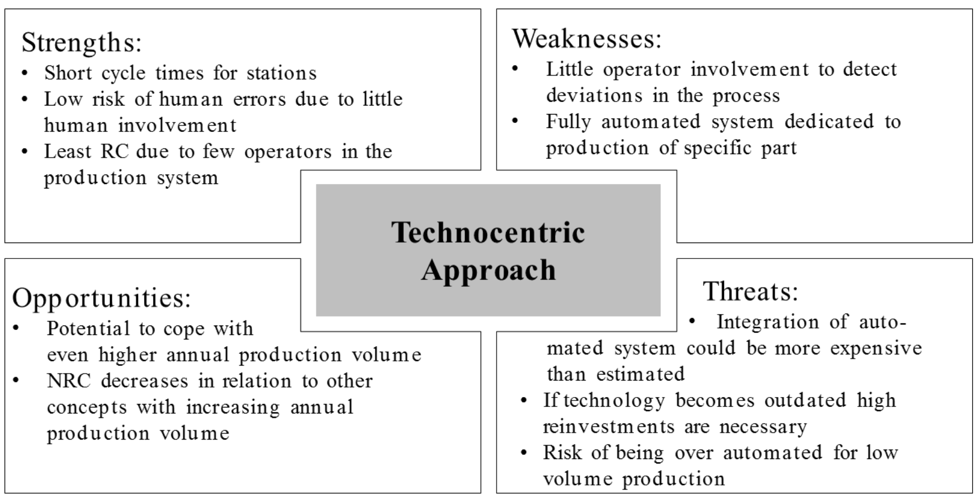


Figure 6-10: SWOT Analysis of technocentric approach

The technocentric approach is characterised by very short cycle times as its biggest strength. Opposite to this little operator involvement can lead to undetected systematic errors. The implementation of such a technocentric system could be more expensive than expected in the first place due to the complexity of the system. On the other hand with an increasing annual production the NRC decrease in relation to other concepts. This together with the general potential to cope with higher production volumes are the opportunities of the production system.

The lean manufacturing approach has a number of strengths such as avoiding of quality issues by the application of the poka yoke principle. But on the other hand the manual insertion of the inserts is one threat which has to be considered. To eliminate this the issue the robot can perform the task which yields the opportunity to reduce lead time simultaneously. A weaknesses of the concept is its extensive use of the press resulting in a great difference in utilization between the stations.

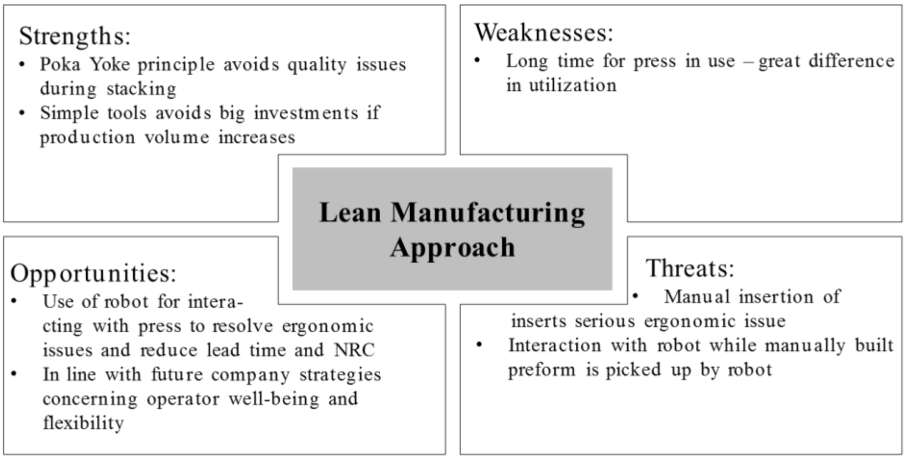


Figure 6-11: SWOT Analysis of lean manufacturing approach

The human-machine collaboration approach demands a certain shift of paradigms as the used collaborative robot is considered as a co-worker rather than a machine. The could lead to resistance among the human operators as they are used to this way of working. However, the strength of the concept is the ability to shift tasks dynamically between robot and human and even out the workload distribution. Furthermore most of the machines are multi-purpose which makes the production system flexible towards new products or changing designs. Nevertheless there are weaknesses to be stated. The savings in production lead time are not as high as the ones for the other top-ranked concepts. Also, the use of collaborative robots adds to the systems complexity and required operator skill.

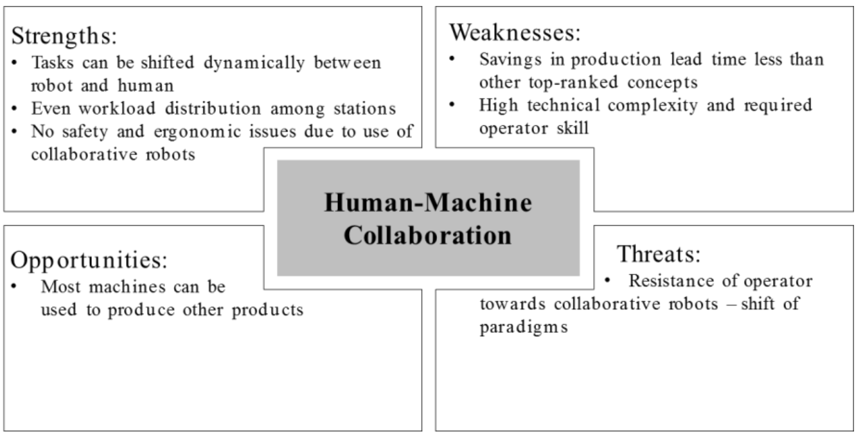


Figure 6-12: SWOT analysis of human-machine collaboration approach

7 Discussion

The previous chapter presented the results which shall be discussed hereafter. The overall result as well as aspects of each concept are discussed. Furthermore improvement potentials are emphasised. Finally, the decision upon the most desirable concept is taken and it is analysed with regard to the concept of "rightomation".

The evaluation results show that the top three concepts (technocentric, lean manufacturing and human-machine collaboration approach) score best in the top five criteria which make up for 83% of the total points according to the paired comparison. On the contrary the manual baseline process gets top scores in three categories (flexibility, required operator skill and technical complexity) but as those criteria contribute little to the overall result the concept remains with a poor final evaluation. Additionally, the top three concepts score very equally for quality and safety with a difference of maximum 1 point. Consequently, only three criteria are left to distinguish the performance of the concepts which are production lead time, NRC and RC.

The technocentric approach achieves the best result for lead time. This result was expected as the use of advanced technology assures the shortest times for the individual steps. Moreover the RC are lowest as well due to the fact that operator costs are the main driver for this criterion and the approach has the lowest number of operators (1 operator per cutter for the whole line). Although one has to state that the DES could come to the conclusion that this number is not sufficient. The last criterion is NRC which refers to the investment costs. In fact, the differences between the scenarios are not as big as expected. The top three approaches are in a range between 125 € and 175 €. This leads to a fairly good score (4) for the technocentric approach even at lower production volumes. The result improves with an increasing volume. The reason for the small differences in NRC is the composition of costs. Press and mould make up for around 75% of the total investment. Consequently, a great number of presses caused by long cycle times at the press station leads to big investment costs. Thus, the rather expensive equipment within the technocentric approach is compensated by the fewer presses needed due to the short cycle times.

The human-machine collaboration approach is characterised by excellent NRC. The concept achieves considerable savings in production lead time and therefore needs only few presses. In contrast to the technocentric approach the costs for other investments are less, leading to very good scores. The weakness of this approach is the high technical complexity and required operator skill. Furthermore, there is a certain risk that operators would resist the use of collaborative robots as it requires a certain shift of paradigm.

The human-machine task allocation approach is basically an all or nothing decision for each task which leads to the extensive use of machines at one station and complete manual work at another. This results in a high technical complexity and required operator skill level. The RC and quality cannot fully benefit from the use of machines as the stacking remains fully manual without supervision and long cycle times. The score for NRC is very low because a considerable amount of presses is necessary. The reason is that process steps connected to the press are more or less unchanged compared to the baseline manual process.

Comparable to the human-machine collaboration approach, the human-centred approach is characterised by a good quality score due to quality measures in the stacking process. This process is most crucial to the final part quality and the source of many errors. The suggested supervision system minimises the occurrence of errors and at the same time limits the technical complexity resulting in a good score for that criterion as well. On the contrary, the rather expensive equipment does not lead to savings in the production lead time (score: 6) that justify the investment. The RC (score: 5) stay still high as many operators are in place.

The biggest advantage of the lean manufacturing approach is the aspect of quality. A poka yoke principle is used for the quality critical step of stacking the preform. A deeper analysis of the lean manufacturing approach's lead time showed that the concept is greatly influenced by the manual handling of the inserts. This leads to a long cycle time for stacking and preparing the press as the process remains unchanged to the baseline process. Furthermore the constant interaction of the operator with the hot press results in a low score in ergonomics. In fact, the manual placement of the preform is another aspect here. Finally, the investment costs are rather high although the equipment, specific for the concept (e.g. stacking template and table and articulated robot), is less expensive than the one for the technocentric or human-machine collaboration approach. The reason is the long time for the press in use (0.25h) and thus a large number of presses. The other two top ranked approaches achieve 0.21h (human-machine collaboration) and 0.18h (technocentric approach) as press interaction time. As a result of the identified effects the adjustment of one production step can have an immediate effect on the final evaluation. Assuming a solution involving handling by the insert by a robot can be implemented, the final evaluation score would change as following:

- Ergonomic score goes from 4 to 9 as no interaction with the press is present (assuming handling the preform is automated as well)
- The time for the insertion of the inserts is reduced from 0.13h to 0.07h (production lead time score: 9)
- The number of presses is reduced to 3 (A350), 5 (SA) and 7 (SA+A350), respectively
- As one robot per press is necessary for loading and unloading the press plus handling the inserts the number or articulated robots increases by 1 (A350), 2 (SA) and 2 (SA+A350), respectively
- Lead time is reduced to 15.65h which means savings of 0.64h compared to the baseline
- Total investment costs considering number of presses and robots: 4 958 000 € (A350, savings: 925 000 €), 8 005 000 € (SA, savings: 836 000 €), 11 152 000 € (SA+A350, savings: 2 422 000 €)

The investment costs result in a NRC score of 10 and a final evaluation of 8.14 for all scenarios and puts the concept in top rank. Moreover the concept gets 6 or higher for all evaluated criteria and therefore showed no considerable weaknesses with very high scores for the top weighed criteria.

The presented production lead time calculation reveals that the savings are within 4%-7% compared to the baseline process. Consequently, one could easily jump to the conclusion that the lead time is of minor importance and should not be rated high in the paired comparison at is was done. Moreover, this suggests that the influence of the automation concepts on lead time is rather small which does not reflect reality. A closer look exposes that only a small portion of the total lead time is actually affected by the suggested savings. The production steps assembly, surface finishing, cooling and drying time make up 88%. The first two remain unchanged because they are out of scope of this thesis. Cooling as well as drying does not need operator attendance or excessive shop floor space and thus, it is not considered as the limiting factor in the production system. The parts can be stored in simple racks if sufficient space is available. So, the mentioned process steps should be neglected for the lead time analysis. The steps assembly and surface finishing are not altered within this thesis and should be excluded from the calculation as well. Although one have to keep in mind that future investigations should include the steps as their lead time is considerably large and changes could include alternative adhesives or fillers with an effect on their process times, too. Leaving only the operations that can actually be influenced by the automation concepts in place the lead times calculations reveal savings up to 65% compared to the baseline process. The concept scoring matrix is not affected by the changes as a relative scale was used. This means the longest lead time got 1 point and the shortest lead time 10 points. The scores in between were distributed evenly.

After discussing the results, the methodological approach shall be discussed. The distribution of workload among the stations is not considered as one of the evaluation criteria. However, especially in the lean philosophy it is important to consider as an even utilization results in an even workflow. The baseline process is characterised by a very even workload distribution as it can be seen in Figure 4-10 (chapter 4.3). Among the three top rated concepts the human-machine collaboration and technocentric approach show good results. In both cases the press process causes the highest single cycle time due to the curing process which makes up for 40% of the total cycle time and cannot be changed. The remaining option to reduce the cycle time is to separate the handling of the inserts from the press cycle. This is associated with major changes in the process and as the inserts are integrated in the mould it could lead to the need of an extra tool with non-acceptable investment costs. In contrast, the lean manufacturing approach shows a high cycle time for stacking the plies. In line with the mentioned emphasis on even cycle times within the lean philosophy this concept should fulfil those requirement more than other concepts. The automated handling of inserts releases the stacking operator from this production step. This finally concludes in a better workload distribution.

The creation of the different SoPI is done by using a number of assumptions. This is necessary because the individual processes within the operation are characterised by varying properties. Consequently it leads to min and max value that differ a lot. After the superimposition the solution space appears to be very small (compare to diagrams in Appendix B). However, the general idea of the DYNAMO++ methodology is to have a homogenous level of automation within a certain operation. The assumptions are necessary to widen the solution space otherwise the full potential cannot be used. Instead of those assumptions the set of processes within the operation could be altered. In case of the performed analysis the HTA was built on the basis of the physical stations in the baseline manual process and not based on the characteristics of the process steps. The press operation is one example. The operation constitutes of the steps connected to the press such as preparation, load press and press cycle. In general those share the same characteristics but the visual inspection and transportation activity are totally different and should therefore be separated from the operation right from the start. The effect of this strategy is that the solutions are much specialised for a limited set of process steps and the division of labour is very strong leading to stations with very different cycle times. A station which only performs visual inspection has a much shorter cycle time than a press station. The presented strategy only works if processes that should be excluded from operation are in the beginning or at the end. If they are between process steps that belong to one operation such as exchange or adapt the mould another strategy is necessary. In this case as done in the analysis the operation should be considered separately. Generally one have to state that the DYNAMO++ methodology is most often used in an assembly context (e.g. in the automotive industry) which is characterised by stations with distinctive process steps. Consequently, the methodology needs to be adapted to the circumstances of a production process in a composite industry environment.

The DES which was used to verify the lead times revealed that some scenarios need extra operators to cope with peaks in the workload. In the human-machine task allocation and the baseline process more operators than stations are necessary to achieve the desired output. The reason for this phenomena is the adapting and cleaning of the mould which occupies the operators so they cannot be used for stacking during this time. As using extra operators shortens the production lead time the RC are not affected because they are calculated based on the time an operator works on a product. Nevertheless using more operators has a monetary effect. If they are only needed temporarily they have to be seized from other production systems leading to production losses there. If this is not possible the company needs to be overstaffed to cope with the alterations which leads to higher staff costs in total. This is not considered in the evaluation of the concepts in this thesis but need to be taken into account before implementing a production system. Moreover, the simulation showed that the number of operators in the technocentric approach is not sufficient. Two operators per cutter are necessary to handle the change of SMC rolls and cope with minor stoppages. In contrary to the previous mentioned approaches in the case of the technocentric more operators affect the RC because they are considered as full time employees in the production system. The DES shows that the calculated production lead time is slightly higher in a dynamic environment although one has to constitute that the scores in the evaluation does not change because the proportion of the lead times, which are the basis of the calculation, are very similar.

The cost calculation as well as the takt time calculation are based on the assumption that a single-shift system is in place. Instead, a two-shift or even three-shift system can be used as this is often found in industry. It would lead to higher takt times and consequently to less stations necessary. The greatest effect is the reduction of the number of presses. Consequently the NRC would drop significantly and the total costs per part would decrease as well. Nevertheless, the change of shifts would affect all investigated scenarios in the same manner and would not lead to a different evaluation result. Another reduction of NRC can be achieved by using dual cavities. This means that instead of one part two parts per press stroke are cured at the same time. Thus, the time of the press cycle per part would be halved. Prerequisites for the use of dual cavities are sufficient press forces and a press table big enough to accommodate two tools. To show that both changes does not affect the evaluation results but only change the NRC as well as RC for all concepts the production lead time and cost calculation is performed again and a concept scoring matrix is created considering the changes in the lean manufacturing approach, shift system and the dual cavity. The result is shown in Figure 7-1. The diagram shows the scores of the SA scenario and the lean manufacturing approach appears to be the best concept with a score of 8.14 points. The total cost per part are 281.78 EUR/part while the RC make up for 80% of those costs. The other 20% are allocated to NRC. As a result of the evaluation the lean manufacturing approach is suggested as the right production system to produce the SMC sidewall panel. Finally the concept will be viewed from the perspective of “rightomation”.

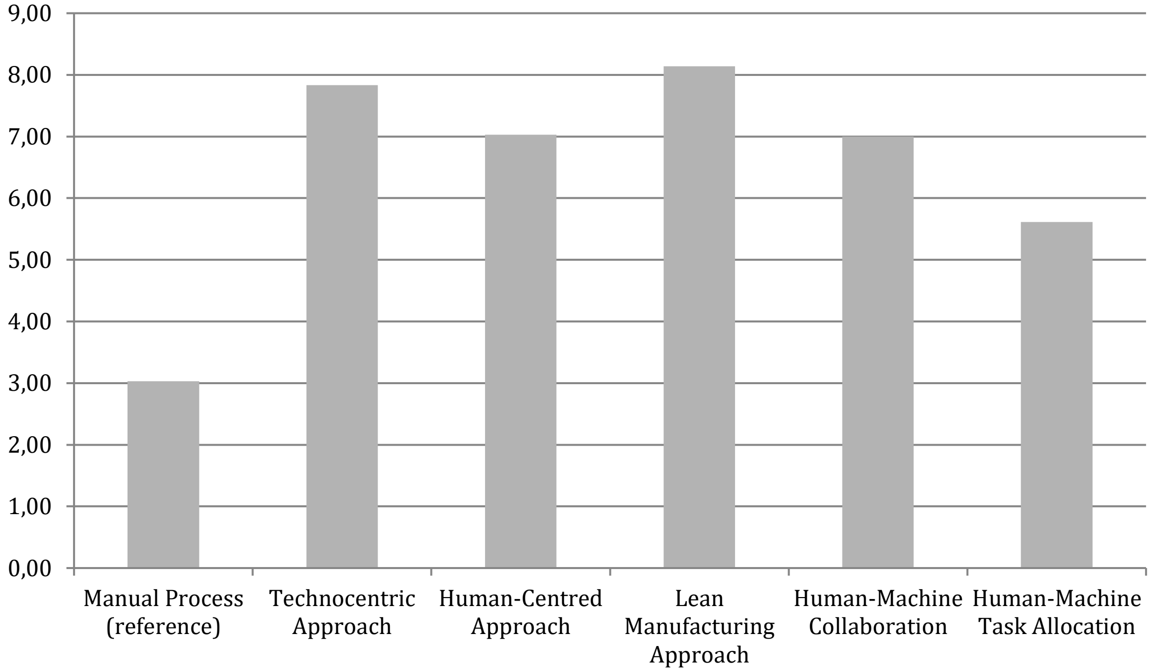


Figure 7-1: Re-evaluation of concepts with described changes in shift system, cavity and lean manufacturing approach for the SA scenario

Previously the term “rightomation” was introduced meaning that only a specific degree of automation leads to the highest competiveness and both under and over automation should be avoided. Furthermore the authors state that the level of automation should be linked to the company’s capabilities and strategy (Säfsten, Winroth, & Stahre, 2007). As currently SMC products are produced manually the operators are not familiar with a great amount of technology. Among the three best rated concepts the lean manufacturing approach shows the best ratio between the use of technology to shorten the production lead time and reduce costs and keep the required operator skill moderate. This avoids that operators feel overstrained. In terms of “rightomation” the lean manufacturing approach delivers the best results as well. Hereby the production lead time, RC, NRC and quality constitute most to the competiveness. The manual baseline process underperformance in all of the mentioned criteria which results in the production system being not competitive at all. The technocentric approach with its extensive use of technology lead to advantages in production lead time and RC due to less operators in the production system. But those savings are jeopardised by the enormous NRC due to over automation. The lean manufacturing approach can be a happy medium between those extreme cases. Adding up all four criteria it performs best and shows no weak points. Nowadays the strategy of most companies exceeds goals for costs, quality and lead time. Shorter product life cycles demand flexible production systems. The lean manufacturing approach is ideal to cope with those changing conditions due to the use of standard machines which can be customized as needed. Furthermore companies have to deal with demographic developments. An aging work force and the limited availability of highly qualified workers sets new demands on the workplace of the future. One aspect are the ergonomic conditions which make a workplace attractive for workers and assures that the existing workforce can stay on the job. The lean manufacturing approach promises the best conditions among the suggested concepts to deal with those challenges.

8 Conclusion

Commercial aviation's goal of fuel-saving and environmentally friendly aircraft involves the use of CFRP as material for structural and interior parts. The desired ramp-up in production to cope with an increasing demand of aircraft all over the world makes efficient production processes necessary. The Hybrid SMC technology is one of those promising technology with the potential to automate production. The purpose of this thesis was to analyse the process chain of an aircraft interior part manufactured in such a technology. The analysis revealed that a limited number of process steps make up a big amount of the total production lead time and operator costs such as cutting of SMC plies, stacking rib plies and TFPs and punch holes and place the inserts. Moreover the DYNAMO++ methodology and the concept of LoA showed great potential to automate most of the mentioned production steps.

The objective of the thesis was to evaluate possible automation concepts and make a decision about the most favourable approach. Three different scenarios with varying production volumes were considered. A paired comparison identified NRC, RC, quality, and production lead time as most important criteria to consider when evaluating the designed concepts. The conducted literature study led to several approaches which were used to answer the first research question:

What are suitable concepts to automate the production of the chosen aircraft interior part?

Five concepts were developed combining different approaches found in the literature. The human-centred approach focuses much on the application of cognitive aids to help the operator to perform its work. The human-machine task allocation and human-machine collaboration approach are closely related but still different from each other. While in the first approach an all-or-nothing decision is taken for each task to either perform it manually or by some sort of machine the collaboration approach suggests that human and machine work closely together. They should share the workplace and shift tasks dynamically to cope with shifting workload situations for instance. The fourth concept follows the better known technocentric approach and focuses on the application of machines and technology as much as possible to achieve the desired output. The last concept is based on the famous lean manufacturing approach. Most characteristic is the use of customised standard machines and principles like poka yoke (stacking template) or SMED. All designed and visualised concepts are rated in a concept scoring matrix to make them comparable to each other and the baseline manual process that was evaluated as well. The final evaluation led to the answer of the 2nd research question.

What is, according to the selected criteria, the most favourable of the developed concepts?

The concept scoring matrix indicated three concepts as most favourable with results very close to each other. These were the technocentric (8.1 points), the human-machine collaboration (7.8 points) and the lean manufacturing approach (7.4 points). Before the final decision was taken a SWOT analysis was done to identify opportunities and threats that were not covered in the previous evaluation but can have an influence on the system's performance. The first two showed the threat that the integration of large number of machines into an automated system can be more expensive than expected in the first place and the use of collaborative robots can lead to resistance by the operators as it means a shift of paradigms. The lean manufacturing approach on the other hand revealed the great opportunity to use the already intended robot to handle the inserts as well (manual task in the suggested concept). This would lead to savings in production lead time and RC and would improve the ergonomic situation significantly. These aspects were considered in the evaluation matrix and a new result was gained stating the lean manufacturing concept as the most favourable concept after all with a final score of 8.1 points. But the performance of the already improved solution can be further enhanced which leads to the last of three research questions.

Is there any potential for optimisation that further enhances the performance of the previously chosen concept?

The aspects that contribute most to an improved performance are the shift system and the tooling concept. In the general assumptions a one-shift system is assumed with 8 hours of production every day. A two-shift system would almost double the available production time (15 hours per day) and reduce the number of presses, the major contributor to NRC. Moreover a two-shift system represents a more realistic scenario as it is often used in such settings to utilize the expensive press more efficiently. The time during the night can still be used to heat up the tool if a tool change is necessary. Finally the tooling concept can be changed towards a dual cavity tooling which means that one stroke of the press produces two parts. This halves the time for the press cycle, one of the most time-consuming production steps that could not be changed by any automation concept so far. Both measures led to a reduction of NRC by ca. 115 EUR and RC by ca. 10 EUR per part. The overall costs per part constitute to 281.78 EUR including RC and NRC.

Furthermore the lean manufacturing concept proved to be the right candidate with regard to the concept of "rightomation". Most current SMC production systems use manual labour to a great extent comparable to the baseline process presented in this thesis. However, the previously performed evaluation showed the non-competitiveness of those systems in the given context. Lean manufacturing forms a compromise between the reduction of production lead time and costs by technology and keeping the required operator skill within limits. This prevents companies to implement a production system beyond their capabilities. Moreover, strategies of most companies today exceed cost, quality and production lead time goals but include flexibility and ergonomic conditions to cope with shortening product life cycles and demographic changes. The chosen approach represents the best choice to deal even with those challenges of the future.

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10 Appendices

Appendix A

Table 10-1: Design assumptions of sidewall panel

Design Assumptions	Value	Unit	Remarks
Number of Material Types	3	-	GF SMC, CF SMC, TFPs
Number of Tools	2	-	One per sidewall type (right, left)
Total Number of Plies	10	-	Full coverage plies and rib plies
Number of Ribs	7	-	
Number of TFP Patches	7	-	One TFP per rib
Lower Ply (SMC)	2,25	m	Including cut-outs, mould coverage: 90 %
Middle Ply	2,25	m	Mould coverage: 90 %
Upper Ply (SMC)	2,25	m	Including cut-outs, mould coverage: 90 %
Rib Plies - Cutting Length	0,65	m	
Total Cutting Length	11,30	m	
Circumference of Final Part	2,50	m	Including cut-outs, for deburring
Number of inserts	10	-	
Part Surface	1,00	m²	Relevant for grinding

Table 10-2: Process assumption of production of sidewall panel

Process Assumptions	Value	Unit	Remarks
Transport from Station to Station	0,17	h	Due to contamination issues the cutting and lay-up area needs to be separated from mechanical processing, QA most often separate location -> 10 minutes assumed
NC Cutter Speed	480,00	m/h	Typical value: 8m/min max cutting speed
Manual Cutting Speed	60,00	m/h	Estimation: 1 m/min
Manual Deburring	60,00	m/h	Estimation: 1 m/min
Lay-up Time per Rib Ply/TFP	0,01	h	Estimation: 0,75 min/ply or TFP, including exact positioning
Lay-up Time per Full Coverage Ply	0,02	h	Estimation: 1 min/ply, including exact positioning
Punching Time per Insert	0,01	h	Estimation: 0,75 min/insert
Set-up Time per Insert	0,01	h	Estimation: 0,75 min/insert
Surface Grinding and Filling	8,75	m²/h	Assumption: only 1 grinding and filling step needed; estimation: manual filling 16min/m² / manual grinding 12min/m²; 8 hours drying time (not process-time relevant)
Batch Size	20		Relevant for transport

Appendix B

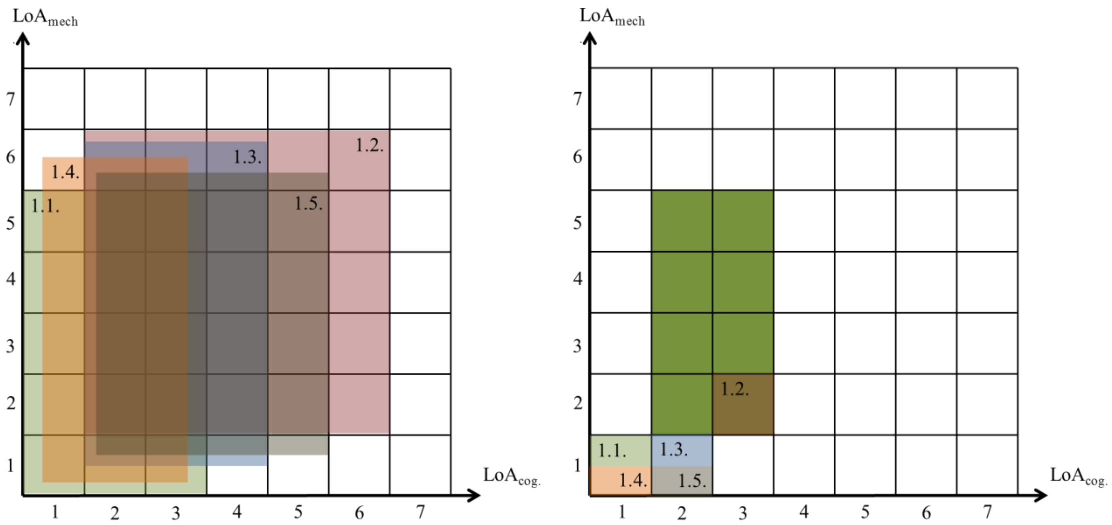

Figure 10-1: SoPI on task level (left) and operation level (right) of the cutting operation

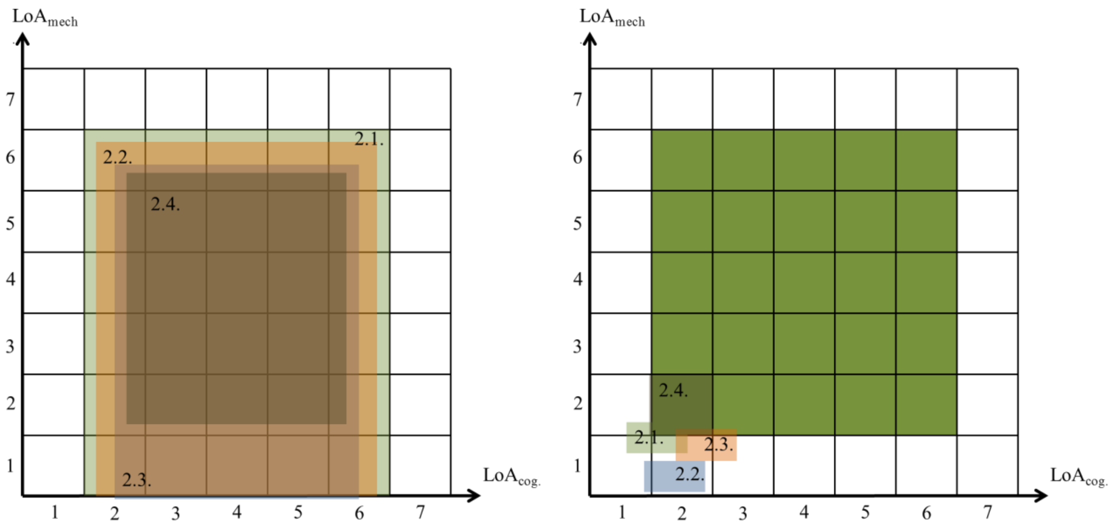

Figure 10-2: SoPI on task level (left) and operation level (right) of the stacking operation

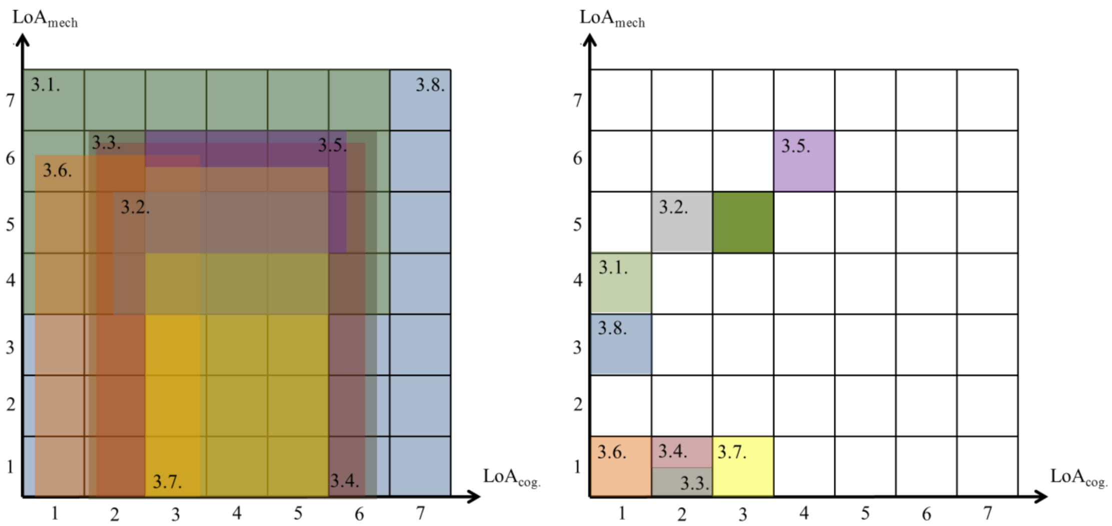

Figure 10-3: SoPI on task level (left) and operation level (right) of the press operation

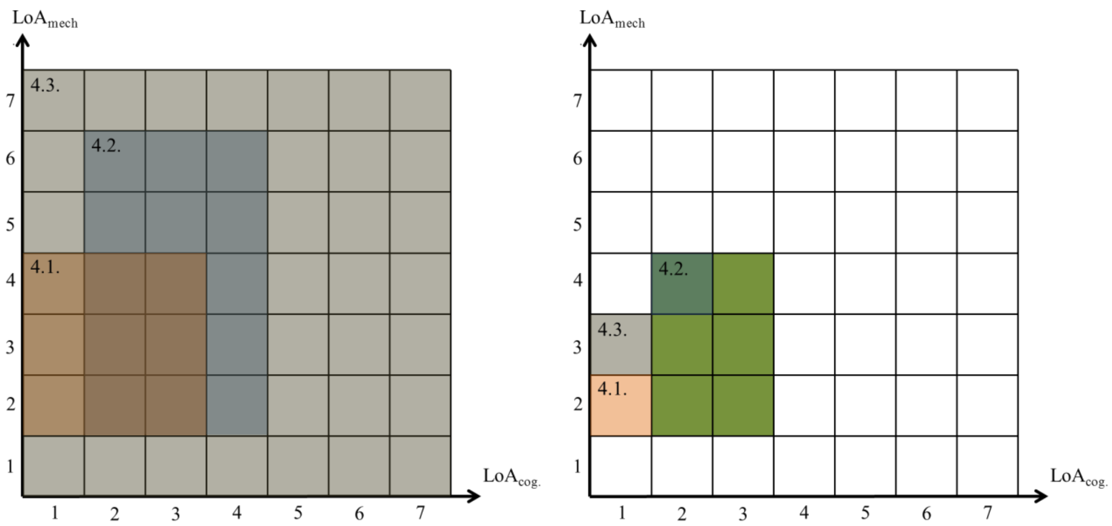

Figure 10-4: SoPI on task level (left) and operation level (right) of mechanical processing operation

Appendix C

Table 10-3: Complete solution space matrix developed on the basis of the SoPIs

	(LoA_{mech};LoA_{cog})	(2;2)	(3;2)	(4;2)	(5;2)	(6;2)	(2;3)	(3;3)	(4;3)	(5;3)	(6;3)	(2;4)	(3;4)	(4;4)	(5;4)	(6;4)	(2;5)	(3;5)	(4;5)	(5;5)	(6;5)	(2;6)	(3;6)	(4;6)	(5;6)	(6;6)	Other
Cutting	Cut Plies	Possible but lower LoA_{cog} than current state	Current levels	-	-	-	No reasonable technical solution		-	-	-	Possible but lower LoA_{cog} than current state	LoA_{mech}: Electric/oscillating hand cutter and templates LoA_{cog}: Cutting templates	-	-	-		LoA_{mech}: Manually controlled NC-Cutter LoA_{cog}: Cutting Templates	-	-	-		LoA_{mech}: Automated NC-Cutter LoA_{cog}: Guidance to perform the task (choose right program etc.)	-	-	-	Plies delivered already cut from material supplier
Stacking	Rib SMC Plies	Possible but lower LoA_{cog} than current state	LoA_{mech}: Cover foil peel off aid and template LoA_{cog}: Templates (pins and holes in plies)	LoA_{mech}: Cover foil peel off aid and template LoA_{cog}: Laser projection system and hand device	LoA_{mech}: Cover foil peel off aid and template LoA_{cog}: Camera and signal system, image recognition assistance system		Possible but lower LoA_{cog} than current state	No reasonable technical solution	No reasonable technical solution	No reasonable technical solution		Possible but lower LoA_{cog} than current state	LoA_{mech}: Hand gripper with vacuum/needles LoA_{cog}: Templates (pins and holes in plies)	LoA_{mech}: Hand gripper with vacuum/needles LoA_{cog}: Laser projection system and hand device	LoA_{mech}: Hand gripper with vacuum/needles LoA_{cog}: Camera and signal system, image recognition assistance system			LoA_{mech}: Static pick and place machine LoA_{cog}: Marks that show stacking position	LoA_{mech}: Static pick and place machine LoA_{cog}: Laser projection system and hand device	LoA_{mech}: Static pick and place machine LoA_{cog}: Camera and signal system, image recognition assistance system	LoA_{mech}: Static pick and place machine LoA_{cog}: Camera and adjustment system		LoA_{mech}: Articulated, SCARA or parallel kinematic robot LoA_{cog}: Machine moves to programmed coordinates (no referencing)	LoA_{mech}: Articulated, SCARA, or parallel kinematic robot LoA_{cog}: Position confirmation	LoA_{mech}: Articulated, SCARA, or parallel kinematic robot LoA_{cog}: Camera and signal system, image recognition assistance system	LoA_{mech}: Articulated, SCARA, or parallel kinematic robot LoA_{cog}: Robot references itself	The same solution should be picked for Rib Plies and TFPs because of their similarity
	Punch Holes for Inserts	LoA_{mech}: Current solution (hammer and punch) LoA_{cog}: Work order (risk of bad positioning)	LoA_{mech}: Current solution with hammer and punch LoA_{cog}: Template (foil with hole positions)	LoA_{mech}: Current solution with hammer and punch LoA_{cog}: Laser projection system and hand device	LoA_{mech}: Current solution with hammer and punch LoA_{cog}: Camera and signal system		LoA_{mech}: Hand punch tool with adjustable diameter LoA_{cog}: Only work order, risk of bad positioning	LoA_{mech}: Hand punch tool with adjustable diameter LoA_{cog}: Template (foil with hole positions)	LoA_{mech}: Hand punch tool with adjustable diameter LoA_{cog}: Laser projection system and hand device	LoA_{mech}: Hand punch tool with adjustable diameter LoA_{cog}: Camera and signal system		LoA_{mech}: Pneumatic/Hydraulic/Electric punching tool LoA_{cog}: Only work order, risk of bad positioning	LoA_{mech}: Pneumatic/Hydraulic/Electric punching tool LoA_{cog}: Template (foil with hole positions) or drawing and mark position	LoA_{mech}: Pneumatic/Hydraulic/Electric punching tool LoA_{cog}: Laser projection system and hand device	LoA_{mech}: Pneumatic/Hydraulic/Electric punching tool LoA_{cog}: Camera and signal system			LoA_{mech}: Static punching machine LoA_{cog}: Template (foil with hole positions)	LoA_{mech}: Static punching machine LoA_{cog}: Laser projection system and hand device	No reasonable technical solution			LoA_{mech}: SCARA robot or same as for place ribs LoA_{cog}:Machine moves to programmed coordinates (no referencing)	LoA_{mech}: SCARA robot or same as for place ribs LoA_{cog}: Position and tool confirmation	LoA_{mech}:SCARA robot or same as for place ribs LoA_{cog}: Camera, tool recognition and signal system	LoA_{mech}: SCARA robot or same as for place ribs LoA_{cog}: Robot references itself and changes tool automatically	Eliminated if holes are integrated in Cutting and perfect stacking is achieved
	Position TFPs	Possible but lower LoA_{cog} than current state	LoA_{mech}: Static Tool to preload TFPs while placing LoA_{cog}: Templates (pins and holes in plies)	LoA_{mech}: Static Tool to preload TFPs while placing LoA_{cog}: Laser projection system and hand device	LoA_{mech}: Static Tool to preload TFPs while placing LoA_{cog}: Camera and signal system, image recognition assistance system		Possible but lower LoA_{cog} than current state	LoA_{mech}: Adjustable tool to preload the TFPs LoA_{cog}: Templates (pins and holes in plies)	LoA_{mech}: Adjustable tool to preload the TFPs LoA_{cog}: Laser projection system and hand device	LoA_{mech}: Adjustable tool to preload the TFPs LoA_{cog}: Camera and signal system		Possible but lower LoA_{cog} than current state	LoA_{mech}: Hand gripper with vacuum/needles that can preload TFPs LoA_{cog}: Templates (pins and holes in plies)	LoA_{mech}: Hand gripper with vacuum/needles that can preload TFPs LoA_{cog}: Laser projection system and hand device	LoA_{mech}: Hand gripper with vacuum/needles that can preload TFPs LoA_{cog}: Camera and signal system, image recognition assistance system			LoA_{mech}: Static pick and place machine LoA_{cog}: Marks that show stacking position	LoA_{mech}: Static pick and place machine LoA_{cog}: Laser projection system and hand device	LoA_{mech}: Static pick and place machine LoA_{cog}: Camera and signal system, image recognition assistance system	LoA_{mech}: Static pick and place machine LoA_{cog}: Camera and adjustment system		LoA_{mech}: Articulated, SCARA, or parallel kinematic robot LoA_{cog}: Machine moves to programmed coordinates (no referencing)	LoA_{mech}: Articulated, SCARA, or parallel kinematic robot LoA_{cog}: Position confirmation	LoA_{mech}: Articulated, SCARA, or parallel kinematic robot LoA_{cog}: Camera and signal system, image recognition assistance system	LoA_{mech}: Articulated, SCARA, or parallel kinematic robot LoA_{cog}: Robot references itself	The same solution should be picked for Rib Plies and TFPs because of their similarity
Press	Place Inserts in Press	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	LoA_{mech}: Static place machine, inserts are feeded automically LoA_{cog}:Marks to position the mould	LoA_{mech}: Static place machine, inserts are feeded automically LoA_{cog}: Verfication of several preconditions (clean mould, right postion of the mould etc.)	LoA_{mech}: Static place machine, inserts are feeded automically LoA_{cog}: Precondition detection and signal system	LoA_{mech}: Static place machine, inserts are feeded automically LoA_{cog}: Precondition detection and adjustment system	-	LoA_{mech}: Articulated, SCARA, low-cost or parallel kinematic robot LoA_{cog}: Machine moves to programmed coordinates (no referencing)	LoA_{mech}: Articulated, SCARA, low-cost or parallel kinematic robot LoA_{cog}: Position confirmation	LoA_{mech}: Articulated, SCARA, low-cost or parallel kinematic robot LoA_{cog}: Camera and signal system	LoA_{mech}: Articulated, SCARA, low-cost or parallel kinematic robot LoA_{cog}: the system detects a displaced insert and corrects the issue	
	Press Cycle	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	LoA_{mech}: Manually controlled press LoA_{cog}: Guidance to machine and process (press programme, temperature and other process parameters)	LoA_{mech}: Manually controlled press LoA_{cog}: Verfication of several preconditions by operator (exact position of preform, placed inserts, right pressure and temperature)	LoA_{mech}: Manually controlled press LoA_{cog}: System that detects preconditions and gives signal	LoA_{mech}: Manually controlled press LoA_{cog}: System controls and acts automatically (hold right temperature and pressure)	-	LoA_{mech}: Programmable press with different programmes LoA_{cog}: Guidance to machine and process (press programme, temperature and other process parameters)	LoA_{mech}: Programmable press with different programmes LoA_{cog}: Verfication of several preconditions (exact position of preform, placed inserts, right pressure and temperature)	LoA_{mech}: Programmable press with different programmes LoA_{cog}: System that detects preconditions and gives signal	LoA_{mech}: Programmable press with different programmes LoA_{cog}: System controls and acts automatically (hold right temperature and pressure)	
	Place Preform in Press	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	LoA_{mech}: Handling tool/machine that executes placing or removing preform if prompted, optional tool slide LoA_{cog}: Guidance to use machine and change tool, laser projection system (only placing)	LoA_{mech}: Handling tool/machine that executes placing or removing preform if prompted, optional tool slide LoA_{cog}: Verfication of several preconditions by operator (preform placed in picking position, right tool attached, mold open etc.)	LoA_{mech}: Handling tool/machine that executes placing or removing preform if prompted, optional tool slide LoA_{cog}: System that detects preconditions and gives signal	An intervention of the technical system to deviations would require a programmable machine which is LoAmech=6	-	LoA_{mech}: Articulated robot, combination with other tasks (SCARA robot or cartesian machine if tool slide is used) LoA_{cog}: Guidance to operate robot, no position referencing	LoA_{mech}:Articulated robot, combination with other tasks (SCARA robot or cartesian machine if tool slide is used) LoA_{cog}: Verfication of several preconditions by operator (preform placed in picking position, right tool attached, mold open etc.)	LoA_{mech}:Articulated robot, combination with other tasks (SCARA robot or cartesian machine if tool slide is used) LoA_{cog}: System that detects preconditions and gives signal	LoA_{mech}: Articulated robot, combination with other tasks (SCARA robot or cartesian machine if tool slide is used) LoA_{cog}: System controls and acts automatically (choose right end effector, calls for preform) and communicates with peripheral machines (press)	Place and remove the preform is such a similar task that a solution should be applicable to both
	Remove Preform from Press	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-					-					
Mechanical Processing	Surface Treatement for Bonding and Finishing	LoA_{mech}: Simple handtool such as abrasive paper and cloth and cleaning agent LoA_{cog}: Simple work order and knowledge by operator	LoA_{mech}: Simple handtool such as abrasive paper and cloth and cleaning agent LoA_{cog}: Detailed work instructions (grain size etc.) and description of desired outcome (boundary parts etc.)	-	-	-	LoA_{mech}: Tool to hold different grain sized abrasive paper LoA_{cog}: Simple work order and knowledge by operator	LoA_{mech}: Tool to hold different grain sized abrasive paper LoA_{cog}: Detailed work instructions (grain size etc.) and description of desired outcome (boundary parts etc.)	-	-	-	LoA_{mech}: Electric/pneumatic grinding hand tool LoA_{cog}: Simple work order and knowledge by operator	LoA_{mech}: Electric/pneumatic grinding hand tool LoA_{cog}: Detailed work instructions (grain size etc.) and description of desired outcome (boundary parts etc.)	-	-	-	-	-	-	-	-	-	-	-	-	-	Sandblast machine would give a uniform surface preparation for bonding but is out of the mech LoA is out of range (LoAmech=5) because it is not suitable for filling and deburring

Appendix D

Table 10-4: Production step time estimation

Work Station	Process Step	Baseline Process (Manual)		Technocentric Approach		Human-Centred Approach		Lean Manufacturing Approach		Human Machine Collaboration		Human-Machine Task Allocation	
		Time [h]	Remarks / Assumption / Calculation	Time [h]	Remarks / Assumption / Calculation	Time [h]	Remarks / Assumption / Calculation	Time [h]	Remarks / Assumption / Calculation	Time [h]	Remarks / Assumption / Calculation	Time [h]	Remarks / Assumption / Calculation
Cutting	Unroll prepreg material	0,01 h	Time to change roll neglected	0,01 h	No time savings by NC-cutter	0,01 h	No changes in the process	0,01 h	No changes in the process	0,01 h	No changes in the process	0,01 h	No time savings by NC-cutter
	Cut Plies	0,27 h	Place and remove template: 0.5 min/ply	0,03 h	No templates used, factor to compensate for speed reduction in corners and move from ply to ply: 0.7	0,18 h	Cutting speed doubled by electric cutter	0,05 h	No templates used, factor to compensate for speed reduction in corners and move from ply to ply: 0.7, 1 min added for hole cutting and cutter set-up	0,05 h	No templates used, factor to compensate for speed reduction in corners and move from ply to ply: 0.7, 1 min added for hole cutting and cutter set-up	0,03 h	No templates used, factor to compensate for speed reduction in corners and move from ply to ply: 0.7
	Mark Plies	0,04 h	Estimation: 0.25 min/ply	0,02 h	Time cut in half by automated marking	0,04 h	No changes in the process	0,02 h	Time cut in half by automated marking	0,02 h	Time cut in half by automated marking	0,02 h	Time cut in half by automated marking
	Remove Cut-offs and Kitting	0,04 h	Estimation: 0,25 min/ply	0,00 h	Not necessary due to direct placement	0,01 h	Image Recognition System reduces time by 75% due to	0,04 h	No changes in the process	0,04 h	No changes in the process	0,04 h	No changes in the process
Stacking and Press	Lower SMC Ply	0,02 h	Includes removal of cover foil	0,004 h	0.25 min/ply	0,01 h	Time cut in half due to less mental strain and easier placement	0,01 h	Time cut in half due to easier guided placement	0,02 h	No changes in the process	0,01 h	Time cut in half due to easier guided placement
	Position TFP Patches	0,09 h		0,03 h	0.25 min/ply due to high speed of the SCARA robot	0,04 h	Time cut in half due to less mental strain and easier placement	0,02 h	Time cut by 75% due to guided placement of TFPs with tight tolerances	0,03 h	0.25 min/ply due to high speed of the SCARA robot + 10 sec to move preform to SCARA and back	0,02 h	Time cut by 75% due to guided placement of TFPs with tight tolerances
	SMC Fabric	0,02 h	Includes removal of cover foil	0,004 h	0.25 min/ply due to high speed of the SCARA robot	0,01 h	Time cut in half due to less mental strain and easier placement	0,01 h	Time cut in half due to easier guided placement	0,02 h	No changes in the process	0,01 h	Time cut in half due to easier guided placement
	Upper SMC Ply	0,02 h	Includes removal of cover foil	0,004 h	0.25 min/plydue to high speed of the SCARA robot	0,01 h	Time cut in half due to less mental strain and easier placement	0,01 h	Time cut in half due to easier guided placement	0,02 h	No changes in the process	0,01 h	Time cut in half due to easier guided placement
	Rib SMC Plies	0,06 h	Includes removal of cover foil	0,03 h	0.2 min/ply+10 sec to move preform to punching station	0,03 h	Time cut in half due to less mental strain and easier placement	0,03 h	Time cut by 75% due to guided placement of rib plies with tight tolerances	0,03 h	0.25 min/ply due to high speed of the SCARA robot + 10 sec to move preform to SCARA and back	0,03 h	Time cut by 75% due to guided placement of rib plies with tight tolerances
	Punch Holes for Inserts	0,13 h		0,03 h	10 sec/insert, punching in batches of 10 parts due to big working area of machine	0,09 h	Time reduced one quarter due to reduce ental workload, time is mainly determined by process of punching	0,00 h	Hole intergration during cutting makes step redundant	0,00 h	Hole intergration during cutting makes step redundant	0,03 h	10 sec/insert, punching in batches of 10 parts due to big working area of machine
	Preparation of Press	0,03 h	Cleaning, application of release agent and intensive at start of production day (20 min)	0,02 h	Cleaning time cut in half, only cleaning of mould at production start (5 min time saving)	0,02 h	use tool slide to move mould for better accessibility, time is compensated by easier cleaning	0,03 h	No changes in the process	0,03 h	No changes in the process	0,03 h	No changes in the process
	Exchange/Adapt mould	0,04 h	Estimation: 60 min, at the end of every production day, heating during night	0,02 h	No changes in the process	0,03 h	No changes in the process	0,02 h	Time is cut in half by SMED principle	0,03 h	No changes in the process	0,03 h	No changes in the process
	Position Inserts	0,13 h		0,06 h	20 sec/insert	0,06 h	Time cut in half due to better access and easier placement	0,13 h	No changes in the process	0,07 h	20 sec/insert, insert placed by robot, preparation done by human during time SCARA places ribs and TFPs	0,13 h	No changes in the process
	Place Preform in Press	0,02 h	Estimation: 1 min	0,01 h	Time cut in half by robotic manipulator	0,01 h	Time cut in half due to better access and easier placement	0,01 h	Time cut in half due to better access and easier placement	0,01 h	Time cut in half due to better access and easier placement	0,01 h	Time cut in half due to better access and easier placement
	Press Cycle	0,07 h	Estimation: 4 min, includes close press, curing part and open press	0,07 h	No time savings possible due to curing time	0,08 h	0.5 min to move mould back in press	0,07 h	No time savings possible due to curing time	0,07 h	No time savings possible due to curing time	0,07 h	No time savings possible due to curing time
	Remove Part from Press	0,02 h	Estimation: 1 min	0,01 h	Time cut in half by robotic manipulator	0,01 h	Time cut in half by robotic manipulator	0,01 h	Time cut in half by robotic manipulator	0,01 h	Time cut in half by robotic manipulator	0,01 h	Time cut in half by robotic manipulator
	Visual Quality Check	0,01 h	Estimation: 0.5 min	0,00 h	Performed during cooling, no extra time needed	0,01 h	No changes in the process	0,01 h	No changes in the process	0,01 h	No changes in the process	0,01 h	No changes in the process
	Part Cooling	0,00 h	Estimation: 15 min process time, no operator required	0,00 h	Estimation: 15 min process time, no operator required	0,00 h	Estimation: 15 min process time, no operator required	0,00 h	Estimation: 15 min process time, no operator required	0,00 h	Estimation: 15 min process time, no operator required	0,00 h	Estimation: 15 min process time, no operator required
	Transport to Mechanical Processing	0,01 h	Transport in batches	0,00 h	Transport by cooling tunnel with conveyor	0,01 h	Transport in batches	0,01 h	Transport in batches	0,01 h	Transport in batches	0,01 h	Transport in batches
Mechanical Processing	Deburring of Part Edges	0,04 h		0,02 h	Time cut in half due to electric grinding tool	0,02 h	Time cut in half due to electric grinding tool	0,02 h	Time cut in half due to electric grinding tool	0,02 h	Time cut in half due to electric grinding tool	0,02 h	Time cut in half due to electric grinding tool
	Surface Treatment for Bonding and Finishing	0,20 h	Preparation for bonding: 5 min + 8 h Drying Time Filler	0,20 h	Preparation for bonding: 5 min + 8 h Drying Time Filler	0,18 h	Preparation for bonding: 4 min + 8 h Drying Time Filler, reduced cycle time due to use of boundary parts	0,18 h	Preparation for bonding: 4 min + 8 h Drying Time Filler, reduced cycle time due to use of boundary parts	0,20 h	Preparation for bonding: 5 min + 8 h Drying Time Filler	0,20 h	Preparation for bonding: 5 min + 8 h Drying Time Filler
	Transport to Assembly	0,01 h	Transport in batches	0,01 h	Transport in batches	0,01 h	Transport in batches	0,01 h	Transport in batches	0,01 h	Transport in batches	0,01 h	Transport in batches
Total Cycle Time		1,24 h	The cycle time refers to one sidewall left or right	0,57 h		0,86		0,68		0,68		0,72	
Assembly	Assembly	0,25 h	4-6 h curing time (process time), 0.5 h/OHSC, 0.25 h/sidewall	0,25 h	4-6 h curing time (process time), 0.5 h/OHSC, 0.25 h/sidewall	0,25	4-6 h curing time (process time), 0.5 h/OHSC, 0.25 h/sidewall	0,25	4-6 h curing time (process time), 0.5 h/OHSC, 0.25 h/sidewall	0,25	4-6 h curing time (process time), 0.5 h/OHSC, 0.25 h/sidewall	0,25	4-6 h curing time (process time), 0.5 h/OHSC, 0.25 h/sidewall
	Transport to Quality Assurance	0,00 h	Transport in batches	0,00 h	Transport in batches	0,00	Transport in batches	0,00	Transport in batches	0,00	Transport in batches	0,00	Transport in batches
Quality Assurance	Quality Assurance	0,04 h	Estimation: 5 min/OHSC, 2.5 min/sidewall	0,00 h	QA continuously done by automated system, 5 sec/part	0,02	Estimation: 4 min/OHSC, 2 min/sidewall, the weight was already check before compression moulding	0,02	Estimation: 4 min/OHSC, 2 min/sidewall, principle of poka yoke ensure use of right plies and check is rendundant	0,04	Estimation: 5 min/OHSC, 2.5 min/sidewall	0,04	Estimation: 5 min/OHSC, 2.5 min/sidewall
Surface Finishing	Surface Finishing	0,50 h	Estimation: 1 h/OHSC, 0.5 h/sidewall	0,50 h		0,50	Estimation: 1 h/OHSC, 0.5 h/sidewall	0,50	Estimation: 1 h/OHSC, 0.5 h/sidewall	0,50	Estimation: 1 h/OHSC, 0.5 h/sidewall	0,50	Estimation: 1 h/OHSC, 0.5 h/sidewall
Total Cycle Time		0,80 h		0,76 h		0,78		0,78		0,80		0,80	

Table 10-5: Production lead time calculation and determination via discrete event simulation

<table>
<tr><th>Cycle and Process Steps</th><th>Baseline Process</th><th>Techncocentric Approach</th><th>Human-Centred Approach</th><th>Lean Manufacturing Approach</th><th>Human-Machine Collaboration</th><th>Human-Machine Task Allocation</th></tr>
<tr><td>Cutting</td><td>0,36 h</td><td>0,06 h</td><td>0,24 h</td><td>0,12 h</td><td>0,12 h</td><td>0,11 h</td></tr>
<tr><td>Stacking</td><td>0,32 h</td><td rowspan="2">0,07 h</td><td rowspan="3">0,31 h</td><td rowspan="3">0,24 h</td><td>0,10 h</td><td rowspan="2">0,07 h</td></tr>
<tr><td>Stack Rib Plies/TFPs</td><td rowspan="4">0,31 h</td><td>0,06 h</td></tr>
<tr><td>Punch Holes for Inserts</td><td>0,03 h</td><td rowspan="3">0,17 h</td><td>0,03 h</td></tr>
<tr><td>Prepare Press</td><td rowspan="2">0,18 h</td><td rowspan="2">0,10 h</td><td rowspan="2">0,10 h</td><td>0,19 h</td></tr>
<tr><td>Press</td><td>0,10 h</td></tr>
<tr><td>Cooling Time</td><td>0,25 h</td><td>0,25 h</td><td>0,25 h</td><td>0,25 h</td><td>0,25 h</td><td>0,25 h</td></tr>
<tr><td>Mechanical Processing</td><td>0,25 h</td><td>0,23 h</td><td>0,21 h</td><td>0,21 h</td><td>0,23 h</td><td>0,23 h</td></tr>
<tr><td>Drying Time Filler</td><td>8,00 h</td><td>8,00 h</td><td>8,00 h</td><td>8,00 h</td><td>8,00 h</td><td>8,00 h</td></tr>
<tr><td>Assembly</td><td>0,25 h</td><td>0,25 h</td><td>0,25 h</td><td>0,25 h</td><td>0,25 h</td><td>0,25 h</td></tr>
<tr><td>Curing Time Adhesive</td><td>6,00 h</td><td>6,00 h</td><td>6,00 h</td><td>6,00 h</td><td>6,00 h</td><td>6,00 h</td></tr>
<tr><td>Quality Assurance</td><td>0,04 h</td><td>0,00 h</td><td>0,02 h</td><td>0,02 h</td><td>0,04 h</td><td>0,04 h</td></tr>
<tr><td>Surface Finishing</td><td>0,50 h</td><td>0,50 h</td><td>0,50 h</td><td>0,50 h</td><td>0,50 h</td><td>0,50 h</td></tr>
<tr><td>Throughput Time</td><td>16,28 h</td><td>15,57 h</td><td>15,88 h</td><td>15,70 h</td><td>15,73 h</td><td>15,77 h</td></tr>
<tr><td rowspan="2">Savings</td><td>0,00 h</td><td>0,71 h</td><td>0,40 h</td><td>0,58 h</td><td>0,56 h</td><td>0,52 h</td></tr>
<tr><td>0%</td><td>4%</td><td>2%</td><td>4%</td><td>3%</td><td>3%</td></tr>
<tr><td>Lead Time by DES</td><td>17,02</td><td>15,89</td><td>16,36</td><td>16,09</td><td>16,26</td><td>16,18</td></tr>
<tr><td rowspan="2">Savings</td><td>0,00 h</td><td>1,13 h</td><td>0,66 h</td><td>0,93 h</td><td>0,76 h</td><td>0,83 h</td></tr>
<tr><td>0%</td><td>7%</td><td>4%</td><td>5%</td><td>4%</td><td>5%</td></tr>
</table>

Appendix E

Table 10-6: Calculation of press needed for the different scenarios

Process Steps Press in Use		Baseline Process	Techncocentric Approach	Human-Centred Approach	Lean Manufacturing Approach	Human-Machine Collaboration	Human-Machine Task Allocation
Preparation of Press		0,13 h	0,03 h	0,09 h	0,00 h	0,00 h	0,03 h
Exchange/Adapt mould		0,03 h	0,02 h	0,02 h	0,03 h	0,03 h	0,03 h
Position Inserts		0,04 h	0,04 h	0,04 h	0,02 h	0,04 h	0,04 h
Place Preform in Press		0,13 h	0,06 h	0,06 h	0,13 h	0,06 h	0,13 h
Press Cycle		0,02 h	0,01 h	0,01 h	0,01 h	0,01 h	0,01 h
Remove Part from Press		0,07 h	0,07 h	0,08 h	0,07 h	0,07 h	0,07 h
Total Cycle Time		0,40 h	0,21 h	0,29 h	0,25 h	0,19 h	0,29 h
Number of Presses	A350	5	3	4	3	3	4
	SA	10	5	7	6	5	7
	SA+A350	15	8	11	9	7	11

Appendix F

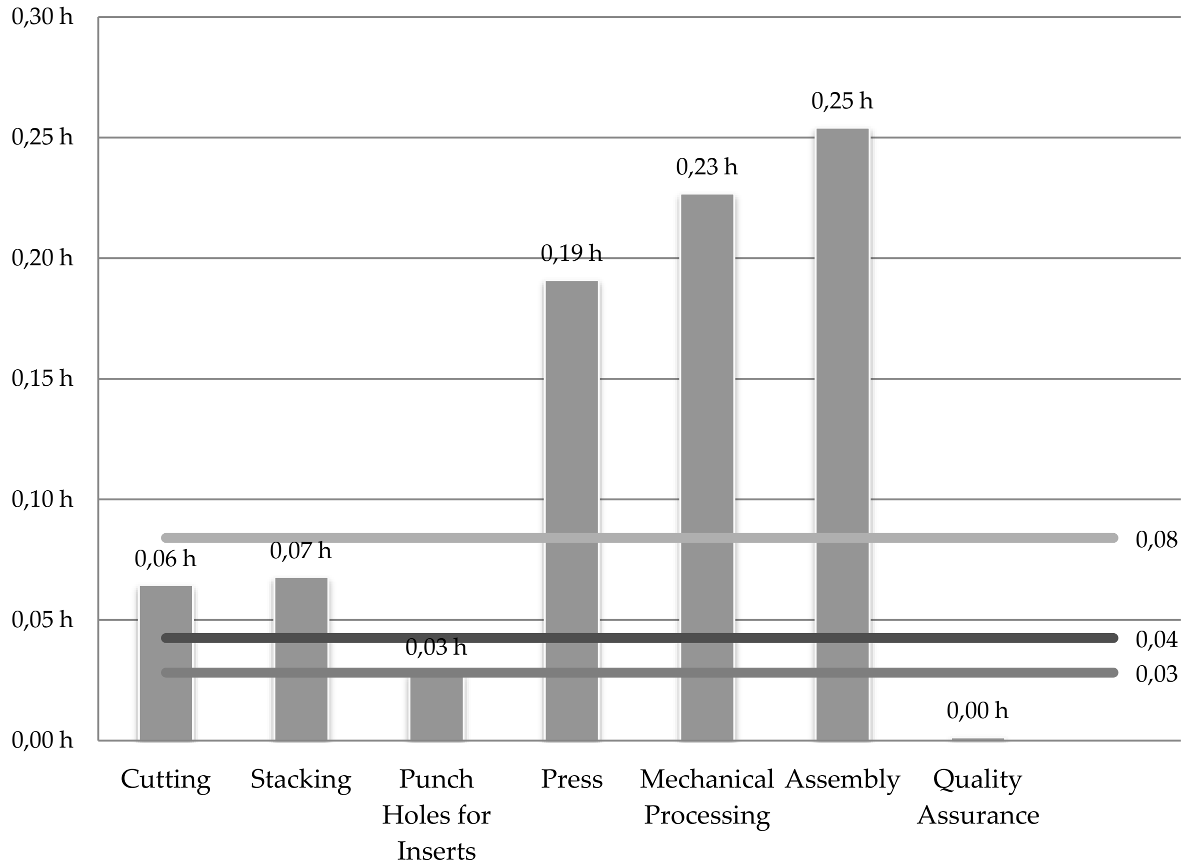

Figure 10-5: Cycle time chart of technocentric approach

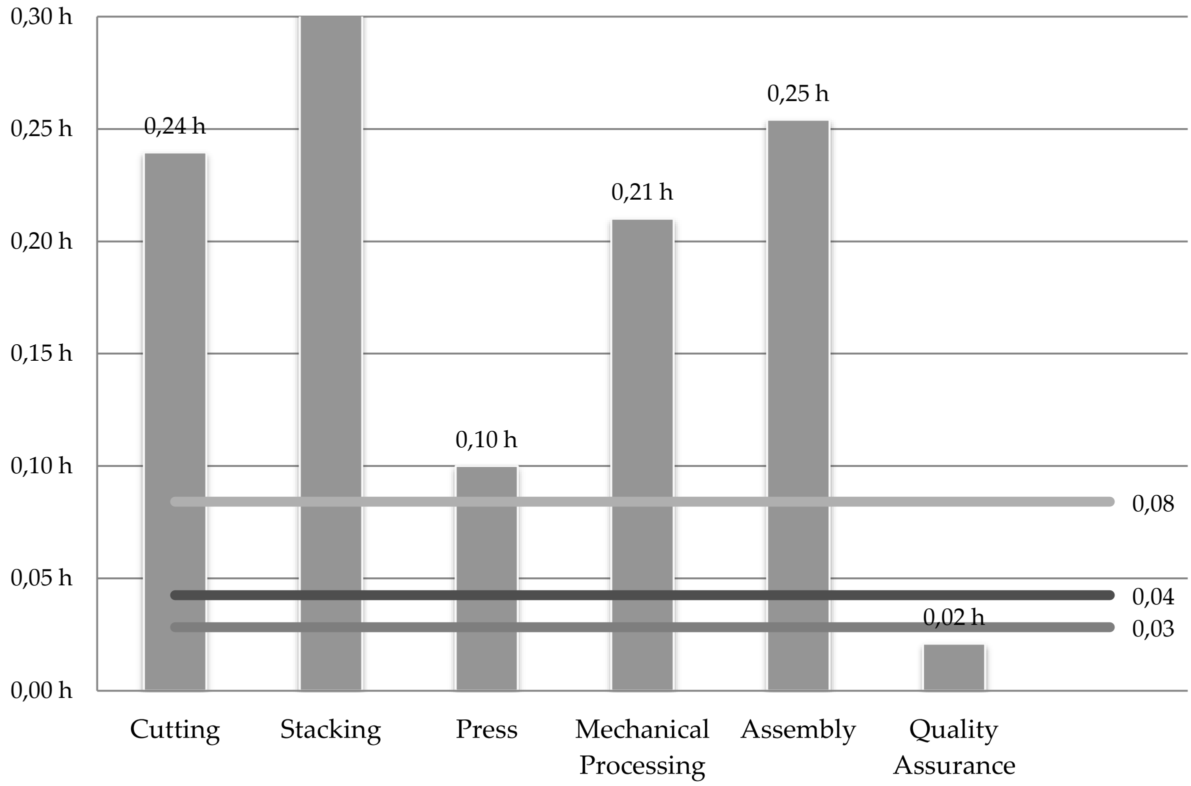

Figure 10-6: Cycle time chart of human-centred approach

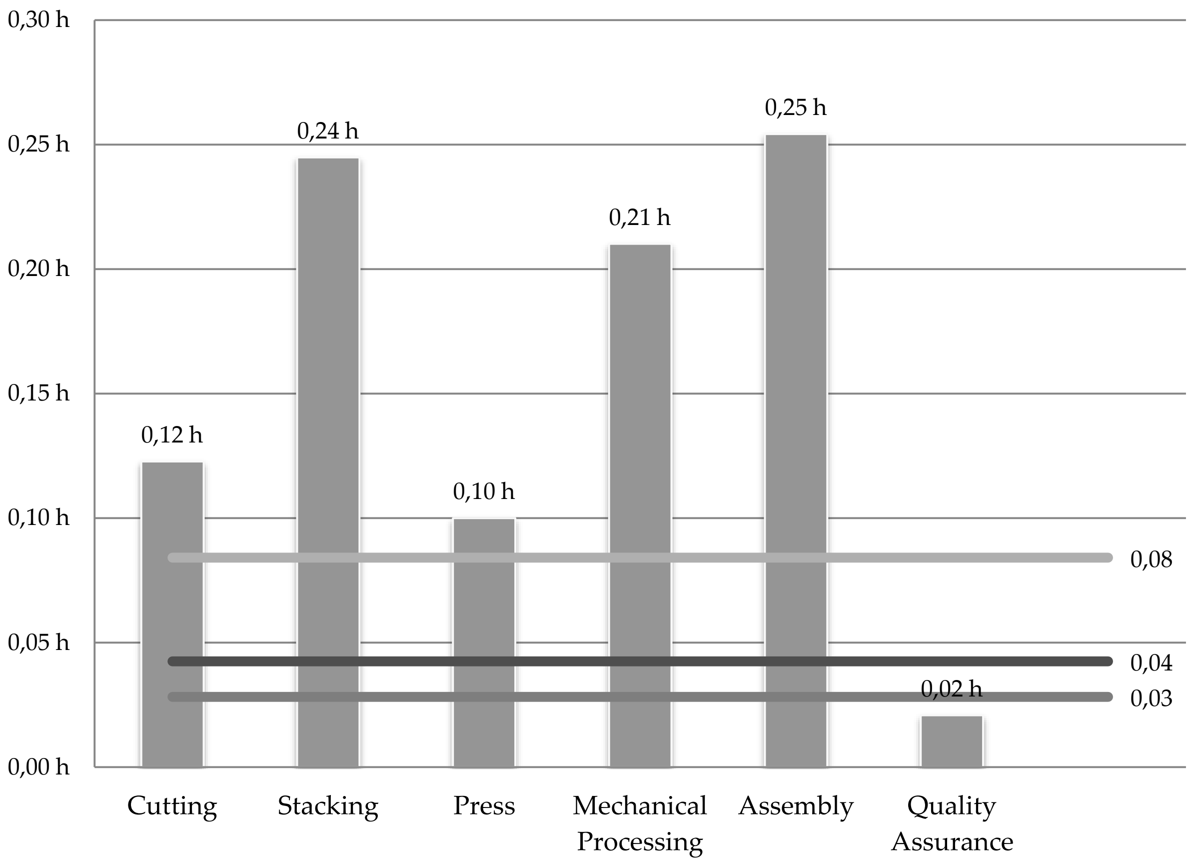

Figure 10-7: Cycle time chart of lean manufacturing approach

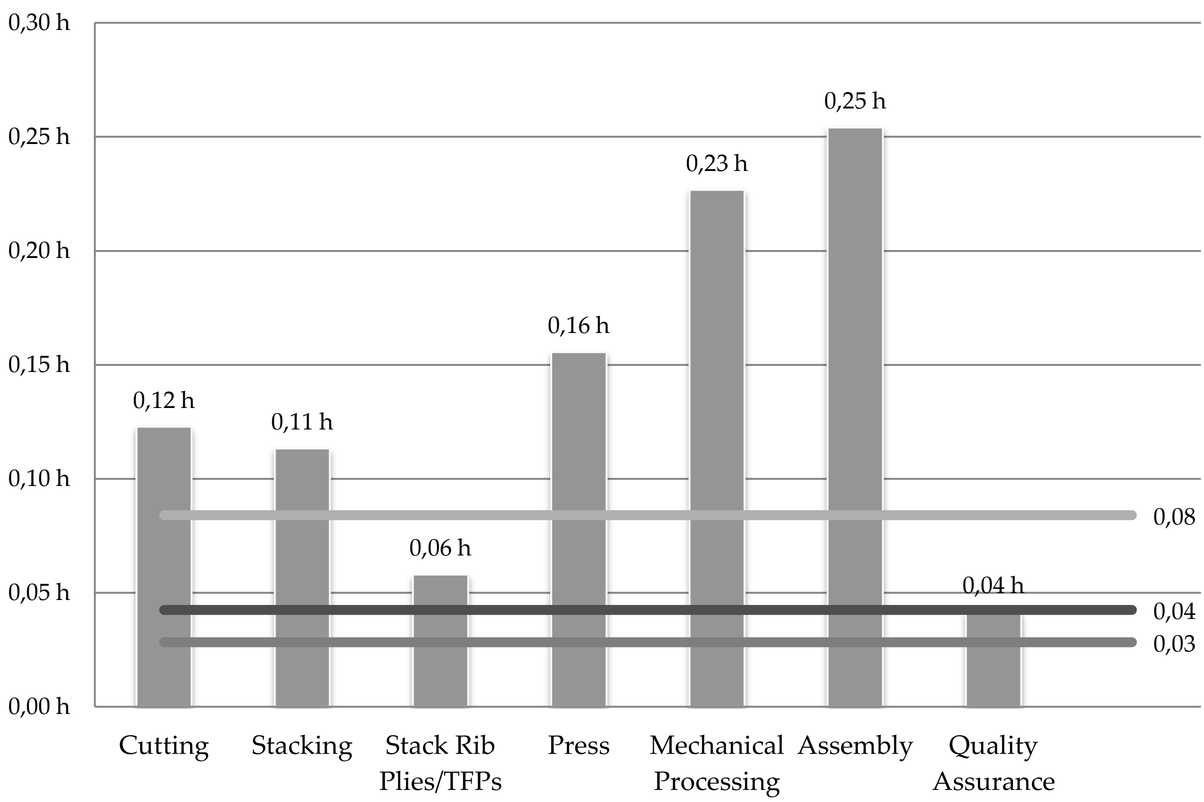

Figure 10-8: Cycle time chart of human-machine collaboration approach

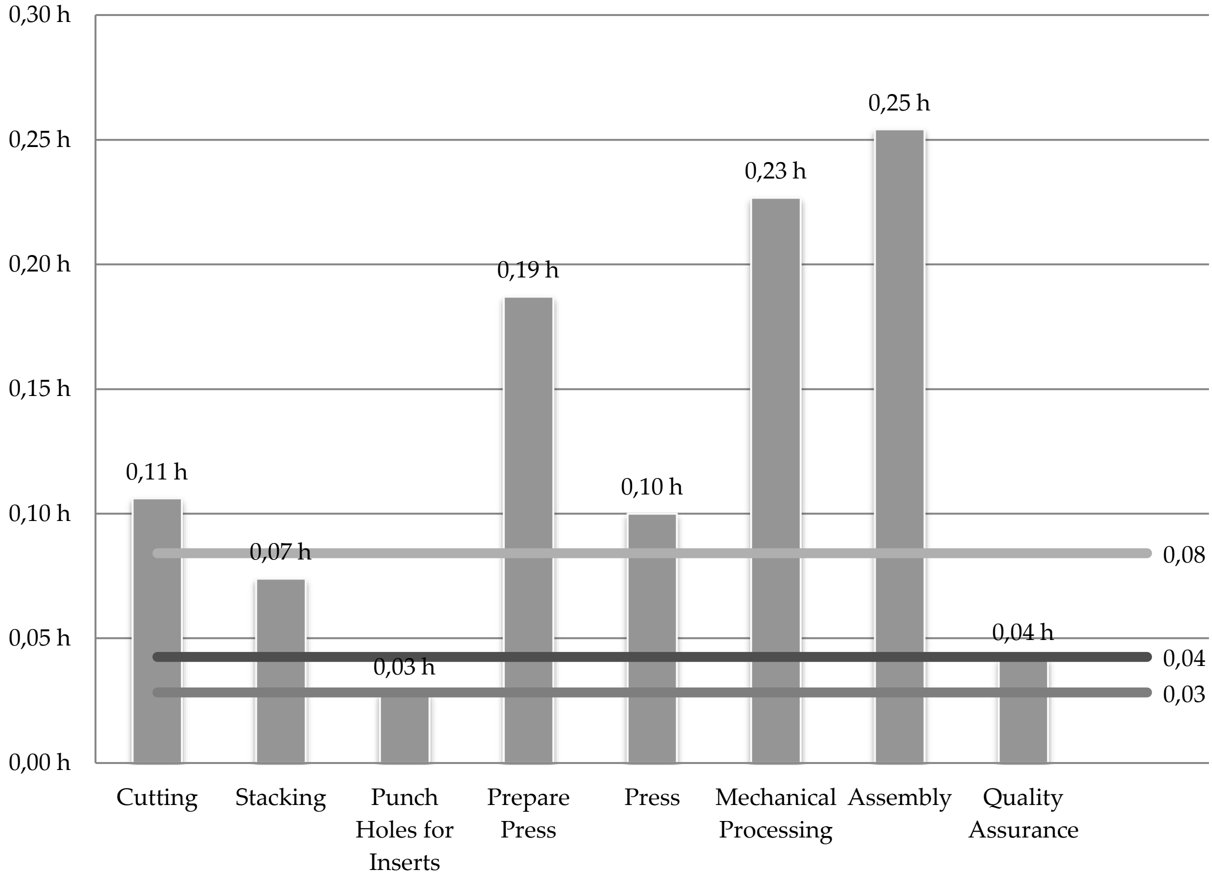

Figure 10-9: Cycle time chart of human-machine allocation approach

Appendix G

Table 10-7: RC and NRC calculation of manual baseline process and technocentric approach

			Manual Processing						Technocentric Approach					
			A350		SA		SA+A350		A350		SA		SA+A350	
RC			Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks
	Operator Costs	Cutting	36,33 €		36,33 €		36,33 €							
		Stacking												
		Stack Rib Plies/TFPs												
		Punch Holes for Inserts	62,71 €		62,71 €		62,71 €		13,45 €	1 full time operator per NC-cutter, operator operates other machines as well, little assistance necessary due to high level of mechanical	13,60 €	1 full time operator per NC-cutter, operator operates other machines as well, little assistance necessary due to high level of mechanical	13,55 €	1 full time operator per NC-cutter, operator operates other machines as well, little assistance necessary due to high level of mechanical
		Prepare Press												
		Press												
		Mechanical Processing	24,76 €		24,76 €		24,76 €		22,68 €		22,68 €		22,68 €	
		Assembly	25,42 €		25,42 €		25,42 €		25,42 €		25,42 €		25,42 €	
		Quality Assurance	4,17 €		4,17 €		4,17 €		0,14 €		0,14 €		0,14 €	
	Total Operator Costs per Part		153,39 €		153,39 €		153,39 €		61,69 €		61,84 €		61,79 €	
	Maintenance Costs per Part		9,52 €		8,67 €		8,93 €		9,99 €		8,13 €		7,45 €	
	Material Costs per Part		144,10 €		144,10 €		144,10 €		142,70 €		142,70 €		142,70 €	
	Total RC per Part		307,01 €		306,16 €		306,41 €		214,38 €		212,67 €		211,93 €	
NRC (payback period 2 years)			No. of Stations	Remarks	No. of Stations	Remarks	No. of Stations	Remarks	No. of Stations	Remarks	No. of Stations	Remarks	No. of Stations	Remarks
	Stations	Cutting	5		9		13		1		2		3	
		Stacking	8		15		23		1		2		3	
		Stack Rib Plies/TFPs	0		0		0		0		0		0	
		Punch Holes for Inserts	0		0		0		1		1		1	
		Press	4		7		11		3		5		7	
		Mechanical Processing	3		6		9		3		6		9	
		Assembly	4		6		10		4		6		10	
			Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks
	Investment Costs	Press	4.000.000,00 €		7.000.000,00 €		11.000.000,00 €		3.000.000,00 €		5.000.000,00 €		7.000.000,00 €	
		Curing Mould	1.200.000,00 €	One curing for each press	2.400.000,00 €	One curing tool for each press plus one to get an even number	3.600.000,00 €	One curing tool for each press plus one to get an even number	1.200.000,00 €	One curing tool for each press plus one to get an even number	1.800.000,00 €	One curing tool for each press plus one to get an even number	2.400.000,00 €	One curing tool for each press plus one to get an even number
		Cutting/Stacking Table	13.000,00 €		24.000,00 €		36.000,00 €		1.000,00 €		2.000,00 €		3.000,00 €	
		NC-Cutter	- €		- €		- €		100.000,00 €		200.000,00 €		300.000,00 €	
		Electric Cutter	- €		- €		- €		- €		- €		- €	
		Laser Projection System	- €		- €		- €		- €		- €		- €	
		Stacking Template	- €		- €		- €		- €		- €		- €	
		Image Recognition Assistance System	- €		- €		- €		- €		- €		- €	
		Articulated Robot System	- €		- €		- €		450.000,00 €	2 robots per press for place and de-mould, 1 pair of robots operates 2 presses, factor 1.5 for robot price due to expensive multifunctional end effector	750.000,00 €	2 robots per for place and de-mould, 1 pair of robots operates 2 presses, factor 1.5 for robot price due to expensive multifunctional end effector	1.050.000,00 €	2 robots per for place and de-mould, 1 pair of robots operates 2 presses, factor 1.5 for robot price due to expensive multifunctional end effector
		Collaborative Robot System (incl. Endeffector)	- €		- €		- €		- €		- €		- €	
		SCARA Robot System	- €		- €		- €		50.000,00 €		100.000,00 €		150.000,00 €	
		Peripheral and Safety Equipment	- €		- €		- €		150.000,00 €		250.000,00 €		350.000,00 €	
		Tool Slide	- €		- €		- €		- €		- €		- €	
		Punching Machine	- €		- €		- €		100.000,00 €		100.000,00 €		100.000,00 €	
		Cooling Tunnel	- €		- €		- €		75.000,00 €	1 cooling tunnel is feeded by two press	125.000,00 €	1 cooling tunnel is feeded by two press	175.000,00 €	1 cooling tunnel is feeded by two press
		Automated Visual Inspection	- €		- €		- €		250.000,00 €	1 at cooling and 1 at QA	350.000,00 €	1 at cooling and 1 at QA	450.000,00 €	1 at cooling and 1 at QA
		Assembly and comissioning	100.000,00 €		150.000,00 €		200.000,00 €		200.000,00 €		300.000,00 €		400.000,00 €	
		Total Investment Costs (NRC)	5.313.000,00 €		9.574.000,00 €		14.836.000,00 €		5.576.000,00 €		8.977.000,00 €		12.378.000,00 €	
	Parts during Payback Period		33488		66240		99728		33488		66240		99728	
	Total NRC per part		158,65 €		144,54 €		148,76 €		166,51 €		135,52 €		124,12 €	
	Total cost per part		465,66 €		450,69 €		455,18 €		380,89 €		348,19 €		336,05 €	

Table 10-8: RC and NRC calculation of human-centred approach and lean manufacturing approach

			Human-Centred Approach						Lean Manufacturing Approach					
			A350		SA		SA+A350		A350		SA		SA+A350	
RC			Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks
	Operator Costs	Cutting	23,96 €		23,96 €		23,96 €		12,28 €		12,28 €		12,28 €	
		Stacking												
		Stack Rib Plies/TFPs	30,58 €		30,58 €		30,58 €		24,29 €		24,29 €		24,29 €	
		Punch Holes for Inserts												
		Prepare Press												
		Press	- €	No operator required	- €	No operator required	- €	No operator required	- €	No operator required	- €	No operator required	- €	No operator required
		Mechanical Processing	21,01 €		21,01 €		21,01 €		21,01 €		21,01 €		21,01 €	
		Assembly	25,42 €		25,42 €		25,42 €		25,42 €		25,42 €		25,42 €	
		Quality Assurance	2,08 €		2,08 €		2,08 €		2,08 €		2,08 €		2,08 €	
	Total Operator Costs per Part		103,05 €		103,05 €		103,05 €		85,08 €		85,08 €		85,08 €	
	Maintenance Costs per Part		9,58 €		8,03 €		7,41 €		10,54 €		8,01 €		8,17 €	
	Material Costs per Part		142,70 €		142,70 €		142,70 €		142,70 €		142,70 €		142,70 €	
	Total RC per Part		255,34 €		253,79 €		253,16 €		238,32 €		235,79 €		235,95 €	
NRC (payback period 2 years)			No. of Stations	Remarks	No. of Stations	Remarks	No. of Stations	Remarks	No. of Stations	Remarks	No. of Stations	Remarks	No. of Stations	Remarks
	Stations	Cutting	3		6		9		2		3		5	
		Stacking	4		8		11		3		6		9	
		Stack Rib Plies/TFPs	0		0		0		0		0		0	
		Punch Holes for Inserts	0		0		0		0		0		0	
		Press	3		5		7		4		6		9	
		Mechanical Processing	3		5		8		3		5		8	
		Assembly	4		6		10		4		6		10	
			Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks
	Investment Costs	Press	3.000.000,00 €		5.000.000,00 €		7.000.000,00 €		4.000.000,00 €		6.000.000,00 €		9.000.000,00 €	
		Curing Mould	1.200.000,00 €	One curing tool for each press plus one to get an even number	1.800.000,00 €	One curing tool for each press plus one to get an even number	2.400.000,00 €	One curing tool for each press plus one to get an even number	1.200.000,00 €		1.800.000,00 €		3.000.000,00 €	One curing tool for each press plus one to get an even number
		Cutting/Stacking Table	7.000,00 €		14.000,00 €		20.000,00 €		3.000,00 €		6.000,00 €		9.000,00 €	
		NC-Cutter	- €		- €		- €		200.000,00 €		300.000,00 €		500.000,00 €	
		Electric Cutter	1.500,00 €		3.000,00 €		4.500,00 €		- €		- €		- €	
		Laser Projection System	90.000,00 €		150.000,00 €		210.000,00 €		- €		- €		- €	
		Stacking Template	- €		- €		- €		30.000,00 €		60.000,00 €		90.000,00 €	
		Image Recognition Assistance System	525.000,00 €		1.050.000,00 €		1.500.000,00 €		- €		- €		- €	
		Articulated Robot System	150.000,00 €	robot for de-mould, 1 robots operates 2 presses	250.000,00 €	robot for de-mould, 1 robots operates 2 presses	350.000,00 €	robot for de-mould, 1 robots operates 2 presses	200.000,00 €	robot for de-mould, 1 robots operates 2 presses	300.000,00 €	robot for de-mould, 1 robots operates 2 presses	450.000,00 €	robot for de-mould, 1 robots operates 2 presses
		Collaborative Robot System (incl. Endef	- €		- €		- €		- €		- €		- €	
		SCARA Robot System	- €		- €		- €		- €		- €		- €	
		Peripheral and Safety Equipment	75.000,00 €		125.000,00 €		175.000,00 €		100.000,00 €		150.000,00 €		225.000,00 €	
		Tool Slide	150.000,00 €		250.000,00 €		350.000,00 €		- €		- €		- €	
		Punching Machine	- €		- €		- €		- €		- €		- €	
		Cooling Tunnel	- €		- €		- €		- €		- €		- €	
		Automated Visual Inspection	- €		- €		- €		- €		- €		- €	
		Assembly and comissioning	150.000,00 €		225.000,00 €		300.000,00 €		150.000,00 €		225.000,00 €		300.000,00 €	
		Total Investment Costs (NRC)	5.348.500,00 €		8.867.000,00 €		12.309.500,00 €		5.883.000,00 €		8.841.000,00 €		13.574.000,00 €	
	Parts during Payback Period		33488		66240		99728		33488		66240		99728	
	Total NRC per part		159,71 €		133,86 €		123,43 €		175,67 €		133,47 €		136,11 €	
	Total cost per part		415,05 €		387,65 €		376,59 €		414,00 €		369,26 €		372,06 €	

Table 10-9: RC and NRC calculation of human-machine collaboration approach and human-machine allocation approach

			Human-Machine Collaboration						Human-Machine Task Allocation					
			A350		SA		SA+A350		A350		SA		SA+A350	
RC			Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks
	Operator Costs	Cutting	12,28 €		12,28 €		12,28 €		10,61 €		10,61 €		10,61 €	
		Stacking	10,33 €		10,33 €		10,33 €		7,40 €		7,40 €		7,40 €	
		Stack Rib Plies/TFPs												
		Punch Holes for Inserts	5,81 €		5,81 €		5,81 €		- €	No operator required	- €	No operator required	- €	No operator required
		Prepare Press							18,71 €		18,71 €		18,71 €	
		Press	- €	No operator required	- €	No operator required	- €	No operator required	- €	No operator required	- €	No operator required	- €	No operator required
		Mechanical Processing	22,68 €		22,68 €		22,68 €		22,68 €		22,68 €		22,68 €	
		Assembly	25,42 €		25,42 €		25,42 €		25,42 €		25,42 €		25,42 €	
		Quality Assurance	4,17 €		4,17 €		4,17 €		4,17 €		4,17 €		4,17 €	
	Total Operator Costs per Part		80,68 €		80,68 €		80,68 €		88,98 €		88,98 €		88,98 €	
	Maintenance Costs per Part		9,05 €		7,41 €		7,55 €		10,66 €		9,56 €		8,76 €	
	Material Costs per Part		142,70 €		142,70 €		142,70 €		142,70 €		142,70 €		142,70 €	
	Total RC per Part		232,43 €		230,79 €		230,93 €		242,34 €		241,24 €		240,43 €	
NRC (payback period 2 years)			No. of Stations	Remarks	No. of Stations	Remarks	No. of Stations	Remarks	No. of Stations	Remarks	No. of Stations	Remarks	No. of Stations	Remarks
	Stations	Cutting	2		3		5		2		3		4	
		Stacking	2		3		4		1		2		3	
		Stack Rib Plies/TFPs	1		2		3		0		0		0	
		Punch Holes for Inserts	0		0		0		1		1		1	
		Press	3		5		8		4		7		10	
		Mechanical Processing	3		6		9		3		6		9	
		Assembly	4		6		10		4		6		10	
			Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks	Costs [EUR]	Remarks
	Investment Costs	Press	3.000.000,00 €		5.000.000,00 €		8.000.000,00 €		4.000.000,00 €		7.000.000,00 €		10.000.000,00 €	
		Curing Mould	1.200.000,00 €	One curing tool for each press plus one to get an even number	1.800.000,00 €	One curing tool for each press plus one to get an even number	2.400.000,00 €		1.200.000,00 €		2.400.000,00 €	One curing tool for each press plus one to get an even number	3.000.000,00 €	
		Cutting/Stacking Table	2.000,00 €		3.000,00 €		4.000,00 €		1.000,00 €		2.000,00 €		3.000,00 €	
		NC-Cutter	200.000,00 €		300.000,00 €		500.000,00 €		200.000,00 €		300.000,00 €		400.000,00 €	
		Electric Cutter	- €		- €		- €		- €		- €		- €	
		Laser Projection System	- €		- €		- €		- €		- €		- €	
		Stacking Template	- €		- €		- €		- €		- €		- €	
		Image Recognition Assistance System	- €		- €		- €		- €		- €		- €	
		Articulated Robot System	- €		- €		- €		200.000,00 €	robot for de-mould, 1 robots operates 2 presses	350.000,00 €	robot for de-mould, 1 robots operates 2 presses	500.000,00 €	robot for de-mould, 1 robots operates 2 presses
		Collaborative Robot System (incl. Endef	300.000,00 €		500.000,00 €		800.000,00 €		- €		- €		- €	
		SCARA Robot System	50.000,00 €		100.000,00 €		150.000,00 €		- €		- €		- €	
		Peripheral and Safety Equipment	150.000,00 €		250.000,00 €		400.000,00 €		100.000,00 €		175.000,00 €		250.000,00 €	
		Tool Slide	- €		- €		- €		- €		- €		- €	
		Punching Machine	- €		- €		- €		100.000,00 €		100.000,00 €		100.000,00 €	
		Cooling Tunnel	- €		- €		- €		- €		- €		- €	
		Automated Visual Inspection	- €		- €		- €		- €		- €		- €	
		Assembly and comissioning	150.000,00 €		225.000,00 €		300.000,00 €		150.000,00 €		225.000,00 €		300.000,00 €	
		Total Investment Costs (NRC)	5.052.000,00 €		8.178.000,00 €		12.554.000,00 €		5.951.000,00 €		10.552.000,00 €		14.553.000,00 €	
	Parts during Payback Period		33488		66240		99728		33488		66240		99728	
	Total NRC per part		150,86 €		123,46 €		125,88 €		177,71 €		159,30 €		145,93 €	
	Total cost per part		383,29 €		354,25 €		356,82 €		420,05 €		400,54 €		386,36 €	

Appendix H

Table 10-10: Explanation of evaluation of chosen criteria for the different concepts

	Manual Process (reference)	Technocentric Approach	Human-Centred Approach	Lean Manufacturing Approach	Human-Machine Collaboration	Human-Machine Task Allocation
Production Lead Time	Calculated	Calculated	Calculated	Calculated	Calculated	Calculated
Non-Recurring Costs (NRC)	Calculated	Calculated	Calculated	Calculated	Calculated	Calculated
Recurring Costs (RC)	Calculated	Calculated	Calculated	Calculated	Calculated	Calculated
Quality	Manual quality checks No technical aid for QA Stacking and Placement of preform without cognitive aids	Two 100% quality checks by different camera system No supervision during stacking but automated system assures correct placement If systematic failure occur while stacking no detection possible	On-line quality control during stacking and kitting by image recognition and weighing after stacking No errors possible up to compression moulding Visual check after compression moulding Placement of preform manual but laser projection system to assure right position	Poka yoke principle during stacking avoids any errors Preform placement by robot to assure correct placement	Crucial part stacking ribs and TFPs done by robot but no check by operator possible, deviations can occur undetected Placement done by robot No QA during cutting and kitting	Template during stacking assures quality Holes punched by machine No additional aid after compression moulding
Safety	Baseline Risk of burnings while work in hot press Little machine use that can cause unsafe situation	No contact with hot press or part Number of different machines that act autonomously	Most crucial steps of insert and preform placement still manual Less safety risks while cutting and de-moulding (hot and sharp edges) Working with robot in proximity	Only place insert as interaction with hot press NC-cutter that reduces risks of injuries Load and unload machine by robot Operator works in proximity to robot	No contact with hot press at all Collaborative robot designed for working in close proximity to humans (sensors etc.) and therefore very safe	Most crucial steps of insert placement still manual Loading and unloading robotic Punching machine some safety risk
Ergonomics	Ergonomic issues are force while cutting plies, punching with hammer, place inserts and preform and demoulding	All ergonomic issues are resolved by the technology	Cutting force and demoulding released but still punching holes and place inserts	Cutting and punching holes resolved but working close to hot press	All ergonomically critical tasks are taken over by machines	Cutting and punching holes resolved but working close to hot press
Technical Complexity	Least amount of machines leads to the lowest possible technical complexity, press is inevitable	Highest number of machines but the system is very integrated thus the operator should have little contact with the technology	Little amount of machines and systems like image recognition system and laser projection system are more intuitive	No technical aids during stacking but NC-cutter and robot increase the complexity	Great number of different machines (SCARA, NC-cutter and collaborative robot) adds to complexity	Great number of different machines (NC-cutter, robot, punching machine) adds to complexity
Required Operator Skill Level	Baseline	Even if operator needs to intervene very many skills are required to operate the machine in case of failures	Aids are simple to operate, no programmable NC-cutter, little skill required	NC-cutter requires advanced skills, stacking no technical skills as simple template, some skill for operating the robot	NC-cutter requires advanced skills, stacking is combined with SCARA robot and collaborative robot is very intuitive while operating but a set of basic skills is still necessary, different machines need to be handled	NC-cutter and punching machine require advanced skills and the robot ads to the required set of skills
Flexibility	Variants can be shifted and volume is easy to alter using more or less operator combined with inexpensive equipment (cutting and stacking tables)	Expensive because everything is interconnected Coping with variants possible if they are programmed already	Loose connection between stations, easy to scale up with inexpensive equipment	Inexpensive template can be multiplied easily Most effort in new NC-cutter and robot	Tasks can be shifted between collaborative robot and human, no time-based hand-over but spatial relationship, increases flexibility SCARA robot inexpensive to duplicate compared to articulated robot	Great number of machines that need to be scaled up individually which can be expensive Not interconnected in the same way as technocentric approach - so easier