The Development of Material Removal Solutions within Wind Blade Manufacturing

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Utveckling av bearbetande verktyg inom turbinbladstillverkning

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Abstract

The market for wind energy systems has grown tremendously during the past 15 years and is expected to keep growing in the next decade. However, the industry faces some major challenges, mainly concerning costs, reliability and energy capture. As the wind blade is a critical component to the overall performance, cost and reliability of a wind turbine, this study has been focused on identifying the needs within wind blade manufacturing in order to enable manufacturing plants to deal with future challenges.

Empirical data indicate that cost reduction is the main priority among blade manufacturing plants within Europe. Historically, these plants have focused more on improving quality but reduced subsidies within the industry has forced manufacturers to decrease production costs in order to reach the competitive threshold and be able to compete with conventional energy forms. In order to reduce the production costs, manufacturers is looking for economically justified manufacturing solutions, which enable an increased productivity rate. The material removal process is considered as the most or one of the most time consuming parts of the blade manufacturing processes and all visited plants expressed a will to increase the efficiency within these steps in order to reduce the manufacturing time. Furthermore, the time consumption regarding material removal processes is a growing problem as the blades continuously increase in sizes. Thus, there is a need for more efficient material removal solutions. Furthermore, as the wind energy sector keeps growing along with the number of workers enrolled in the industry, safety and health aspects become a prime concern. Unsustainable ergonomic conditions do not only increase the risk for injuries but also affects the quality and time needed to perform certain tasks. Thus, there is a need for tools which can be operated in ergonomic positions as well as tools with a decreased weight, decreased vibration levels and a decreased exposure to dust.

The implementation of automated solutions could enable wind blade manufacturers to deal with future challenges as it contributes to cost reduction, increased productivity and improved quality as well as improved health conditions for operators. As wind blade manufacturing plants most likely will continue to produce at least two blade modules within the same plant, there is a need for flexibility within the process. Thus, a semi-automated solution is considered to be more applicable than a fully automated solution. Furthermore, as the blades become increasingly difficult to move due to their size, there is a need for mobile material removal solutions, which can be transported between different blades.

**Key-words:** Wind Blade Manufacturing, Material Removal Tools, Automated Solutions, Ergonomics.
Sammanfattning

Marknaden för vindkraftsystem har vuxit enormt under de senaste 15 åren och förväntas fortsätta växa under nästa årtionde. Industrin står dock inför påtagliga utmaningar, huvudsakligen gällande kostnader, tillförlitlighet och energi-omfång. Eftersom att turbin-bladet är en kritisk komponent som påverkar den totala prestationen, kostnaden och tillförlitligheten för ett vindkraftverk, har denna studie fokuserat på att identifiera behoven inom bladstillverkning i syfte att möjliggöra hantering av framtida utmaningar.


Implementering av automatiska lösningar kan möjliggöra blad-tillverkares hantering av framtidiga utmaningar eftersom att automatisering bidrar till reducerade kostnader, ökad produktivitet, ökad kvalitet och även förbättrade hälsoförhållanden för operatörerna. Eftersom att bladstillverkningsanläggningar mest sannolikt kommer att producera minst två olika modeller av blad inom samma anläggning finns ett behov av flexibilitet inom processen. En semi-automatiserad lösning anses således vara mer tillåmplig än en helt automatiserad lösning. Vidare, finns ett behov av mobila material-avverkande lösningar som går att transporterera mellan olika blad eftersom att bladen kontinuerligt ökar i storlek och blir allt svårare att flytta.

Nyckelord: Turbinbladstillverkning, bearbetande verktyg, automatiserade lösningar, ergonomi.
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Foreword

This master thesis has been written within the department of Industrial Management at KTH - the Royal Institute of Technology. The thesis has been written in collaboration with Atlas Copco, which has been referred to as the case company of this thesis.

We want to start off by thanking all interview respondents from Atlas Copco as well as external companies for taking the time to share their knowledge and contribute to our research. Furthermore we would like to thank the visited manufacturing plants for guiding us through each step of the blade manufacturing process and sharing their expertise of the different steps and experienced problems with us.

We would also like to thank our KTH supervisor, Marin Jovanovic. And last but not least we want to show our gratitude towards Magnus Brunn from Atlas Copco, who has supported our continuous work and guided us through all obstacles along the way.

Parmis Bonyadlou & Anna Larsson

Stockholm, June 2017
1. Introduction

For this thesis, a pre-study was conducted in order to identify which market would be more relevant to investigate and research in order to develop the Atlas Copco offering (see Appendix 1 - Pre-study; Foundry Vs. Wind Energy). Based on the pre-study the wind energy segment was chosen as the area of investigation for this thesis. In this chapter the background of the chosen area of study has been presented, followed by the problematization, research purpose, research questions and report outline.

1.1 Background

During recent years there has been a significant increase in the use of non-hydro renewable energy sources, which mainly include wind and solar power (Kulin and Enmalm, 2016). According to Statistiska Centralbyrån, the generation of electricity within wind power increased with 44.8 percent in Sweden during 2015 (Kulin and Enmalm, 2016). The consultancy firm McKinsey argues that the demand for electricity will grow rapidly as electricity will account for a quarter of all energy demand by 2050, compared to 18 percent as of today (Nyquist, 2016). 77 percent of this new capacity is expected to come from wind and solar power, whereas these power sources are expected to grow four to five times faster than every other source of power.

The market for wind energy systems has grown tremendously during the past 15 years and is expected to keep growing in the next decade (Goch, Knapp and Härtig, 2012). However, the industry faces some major challenges, mainly concerning costs, reliability and lifetime, especially related to the offshore segment. Firstly, wind energy must reach the competitive threshold and be able to compete with conventional energy supply without governmental subsidies. Secondly, the reliability throughout the objective lifetime of 20 years for a wind turbine has to be enhanced as only few wind turbines reach this target without two or more breakdowns of major components. Reliability is an even greater problem in the offshore segment (Shafiee, 2015). The marine environment, with its harsh and rapidly changing weather conditions, results in a decreased availability as well as a decreased reliability compared to onshore wind farms. Decreased availability results in longer lead-times and increased costs for operation and maintenance, while decreased reliability results in an increased need for operation and maintenance. As of today, the electricity generated by offshore wind turbines is estimated 2.6 times more expensive than electricity generated onshore. Thus, the reliability of offshore wind farms needs to be improved in order to be cost competitive compared to onshore wind turbines as well as other power sources.

The wind blade is a critical component to the overall performance, cost and reliability of a wind turbine (Sainz, 2015). The blades transform the wind energy into a rotary motion, which can be converted to electrical energy. Longer blades sweep a larger area and thus increases the energy yield. Power output is related to the square of the rotor radius which means that even small increases in rotor diameter can generate significantly more power (Goch, Knapp and Härtig, 2012). Furthermore, wind velocity is the most important factor in wind energy and increases steadily with height (Howard, 2012). Thus, manufacturers strive to build higher towers and
larger blades in order to maximize productivity in a cost efficient way (Howard, 2012; Engström et al., 2010).

In addition to trends towards cost reduction and increased reliability, ergonomics is a major concern within blade manufacturing (European Agency for Safety and Health at Work, 2013). With the increasing number of operators working in the wind sector, following the expanding market, safety and health at manufacturing plants is considered a prime concern. The manual handling of tools and machines, followed by high noise levels and exposure to dangerous chemicals such as GFRP and Epoxy resins, constitute a base for the increased concern regarding ergonomics to decrease health and safety hazards within the plants. It is during the grinding and sanding process of the blades where operators are mainly exposed to the mentioned chemicals. Furthermore, the heavy and demanding grinding operations affect the productivity rate at manufacturing plants and the quality level of the products (FlexArm, 2014). Injury rates for grinding operations are extremely high which affect the overall performance of the company.

The Atlas Copco group is a world-leading provider of solutions focused on productivity, energy efficiency, safety and ergonomics (Atlas Copco, 2016). They offer products in a variety of market segments, including the wind segment where a selection of material removal solutions are targeted towards blade manufacturing processes. Atlas Copco has a vision to become and remain the first choice of their customers and aims to achieve profitable growth through sustainable development. The Atlas Copco group underlines the importance of customer interaction in order to create close relationships and increased market presence and penetration. A part of their strategy is to look for opportunities to expand their product and service offerings in order to provide complete solutions which increase customers’ productivity.
1.2 Problematization

Wind power manufacturers are expected to experience tremendous growth in years to come, which creates a path of opportunity in their market (Nyquist, 2016). However, the industry faces some major challenges, mainly concerning costs, reliability and lifetime, especially related to the offshore segment (Goch, Knapp and Härtig, 2012). Thus, manufacturers are pressured to develop new and improved manufacturing processes in order to maintain their market share (Howard, 2012). As a world-leading provider of productivity solutions, Atlas Copco needs to support this development regarding manufacturing processes and respond to the transformation pressure in the wind power industry, in order to meet market demand. Furthermore, Atlas Copco needs to look for new opportunities to expand their product and service offerings in order to become and remain the first choice of their customers.

1.2.1 Research Purpose

The purpose with this thesis is to investigate the wind blade manufacturing process of wind turbines, in order to find strengths and weaknesses in Atlas Copco’s existing offerings in the area of material removal tools. By mapping the manufacturing process we aim to identify how the product range of material removal tools of Atlas Copco can be expanded or developed in order to support the changes and improvements of blade manufacturing processes within the wind industry.

1.2.2 Research Question

A research question, followed by three sub questions have been developed and will be answered in this thesis. The sub questions are mutually exclusive and collectively exhaustive, meaning that there is no overlap between them and that they cover all areas of the intended research.

*How should Atlas Copco support the development of blade manufacturing processes within the wind industry by expanding or developing their product range within material removal tools?*

Sub research questions:

- How will new market trends impact the manufacturing processes within the wind industry?
- What are the underlying customer needs within the manufacturing processes of wind turbine blades?
- What kind of material removal tools are needed to support the development of the blade manufacturing processes?
1.3 Report Outline

The outline of the report which has been used in order to investigate and present the results, analysis and conclusion of the previously presented research questions have been presented in this chapter.

Chapter 1 - Introduction

A background for the main study which focuses in the wind energy industry, and more specifically wind blade manufacturing has been presented, followed by the problematization of the thesis. The problematization mainly includes the purpose of the research and the main and sub research questions.

Chapter 2 - Literature Review and Theoretical Concepts

In this chapter, a literature review in the area of trends and challenges within the wind turbine industry, wind blade manufacturing, ergonomics and material removal solutions within wind blade manufacturing have been presented. Furthermore, the theoretical concepts of Value Stream Mapping as well as the application of a system perspective have been presented.

Chapter 3 - Method

The methodology which was used in regards to research design, data collection, delimitations, validity and reliability as well as ethical aspects has been presented in chapter 5. Furthermore, the handling and analysis of gathered data from conducted interviews and plant visits have been presented.

Chapter 4 - Results and Analysis

In this chapter, the gathered empirical data which has been gathered through interviews and plant visits has been presented. Furthermore, an analysis has been conducted and presented which is based on the presented empirical data as well as the literature review.

Chapter 5 - Conclusion

The conclusion of the thesis has been presented in this chapter, together with a suggested solution and discussion. Furthermore, the empirical as well as theoretical contribution of this thesis, its generalizability and its limitations and suggestions for further work have been stated.
2. Literature Review and Theoretical Concepts

Previous research and literature in areas relevant to the research question of this thesis have been investigated and presented in this chapter. The literature includes trends, challenges and customer needs within the wind turbine industry, a description of the wind blade manufacturing process as well as different forms of material removal solutions.

2.1 System Perspective Framework

Blomkvist and Hallin (2015) claim that a problem needs to be solved with a systematic approach, meaning that a problem should be investigated on different organizational levels. Blomkvist and Hallin define three different levels; the individual, the functional and the industrial level whereas these levels are connected and affect each other. The individual level represents the management and employees perspective. The functional level involves processes and production and the industrial level represents the overall industry. Looking at all of these three levels, it is possible to grasp the complexity of a problem and thus be able to reach a sustainable solution.

Applying a system perspective approach to this case study entails looking at industrial trends in order to understand functional requirements for manufacturing and thus be able to find an applicable solution on an individual level. Figure 1 illustrates the connection between the individual, the functional and the industrial level.

![Diagram](image)

**Figure 1.** Shows the connection between industry trends, their direct effect on blade manufacturing processes and how these create a base for future material removal solutions.
2.2 Trends and Challenges within the Wind Turbine Industry

The market for wind energy systems has grown tremendously during the past 15 years and is expected to keep growing in the next decade (Goch, Knapp and Härtig, 2012). However, the industry faces some major challenges, mainly concerning reliability, lifetime and costs, especially related to the offshore segment.

2.2.1 Growth within the Offshore Segment

There has been a significant growth in the offshore wind power segment during the past decade (Shafiee, 2015). The cumulative installed capacity in the European Union has grown 29 percent each year during the years 2003 to 2013 and the growing trend of offshore capacity is expected to continue in the coming years. The average wind velocity for offshore wind parks is significantly higher and the wind flows are more steady (Goch, Knapp and Härtig, 2012). Furthermore, this is a great option for European countries with limited space for the installation of new onshore wind farms. The offshore wind industry is forecasted to cover over 4 percent of the EU’s electricity demand in 2020 and 14 percent in 2030 (Arapogianni et al., 2012). Due to this growing market, many wind turbine manufacturers have chosen to manufacture wind turbines which are specifically adapted to the offshore environment (Arapogianni et al., 2012).

Technical trends within the offshore wind industry are wind turbines with a higher capacity and a larger rotor diameter (Arapogianni et al., 2012). Furthermore, instead of having a geared system within the wind turbine, focus is being put on having hybrid systems or direct drive. Also, offshore wind turbines will implement full conversion as opposed to partial. Overall the offshore wind industry is decoupling itself from the onshore wind industry and is aiming for achieving lower energy costs, increased reliability as well as an increased energy capture.

The marine environment with its harsh and rapidly changing weather conditions result in a decreased availability as well as reliability compared to onshore wind farms (Shafiee, 2015). Decreased availability result in longer lead-times and increased costs for operation and maintenance. As of today, the electricity generated by offshore wind turbines is estimated 2.6 times more expensive than electricity generated onshore. Thus, the availability, reliability and maintainability of offshore wind farms needs to be improved in order to be cost-competitive compared to onshore wind and other power sources. Due to these concerns, logistics and supply chain management of maintenance becomes increasingly important and is considered as a highly critical task in the offshore wind energy industry today. Furthermore, trends show that new offshore projects tend to move to deeper waters and further off the shore (Arapogianni et al., 2012). Thus, vertical integration is preferable for wind turbine manufacturers, meaning that partnerships or other forms of collaborations between manufacturers and other levels within the supply chain would be relevant. Therefore, new entrants should focus on establishing partnerships with component manufacturers.

2.2.2 Energy Capture

New onshore capacity will to a high extent consist of the repowering of older and smaller wind turbines which means that these systems will be replaced by new and bigger models (Goch, Knapp and Härtig, 2012). In a study investigating the manufacturing selection criteria of wind
turbines in Finland, production volume, i.e. the maximal volume of the selected wind turbine’s energy production was considered as the second most important selection criteria, after reliability (Sarja and Halonen, 2012). Blade length and tower height was often discussed in regards to this criteria as well as production unit price. Thus, a main objective for wind turbine manufacturers is to increase the rated power of each wind turbine (Sainz, 2015). Also, the wind turbines are designed and constantly developed to harness energy in less windy conditions, i.e. produce energy from less intense wind speeds (Sainz, 2015). This involves increasing the size of the wind turbine, minimize the weight and make design adjustments on all included components.

A post-doctoral researcher named Marcio Loos has designed a new blade made of polyurethane reinforced with carbon nanotubes (Kirkpatrick, 2011). The new design is lighter even though it is eight times tougher and more durable than blades currently in use. The new design was a result of the need to develop stronger and lighter materials which enable manufacturing of blades with a larger energy capture. As of today, wind turbines do not gather as much energy as they possibly could due to their size and the weight of the blades. A high weight leads to energy losses since more wind is needed in order to turn the blade around. Furthermore, a high flexibility within the blade increase the likelihood for the blade warp and lose efficiency.

The blade is a critical component to the overall performance, cost and reliability of a wind turbine since it transforms the wind energy into a rotary motion, which can be converted to electrical energy (Sainz, 2015). Longer blades sweep a larger area, thus the energy yield can be increased. Power output is related to the square of the rotor radius which means that even small increases in rotor diameter can generate significantly more power (Goch, Knapp and Härtig, 2012). From 1980 to 2008, the rotor diameter has increased 8.4 times and the hub high 4.5 times. In the same period, the annual yield (in MWh) generated by a wind turbine has increased more than 500 times. Today the maximum length of rotor blades is limited to 70 meter but by the end of this decade, the maximum length is foreseen to reach 110 meters.

### 2.2.3 Cost and Reliability

Goch, Knapp, & Härtig (2012) argue that three major technical and economic objectives must be achieved in order to enable wind energy and other renewable sources to contribute to more than 25 percent of the electrical energy supply in industrialized countries. Firstly, wind energy must reach the competitive threshold and be able to compete with conventional energy supply without subsidies. This objective could be reached as soon as in the end of this decade. Secondly, the reliability throughout the objective lifetime of 20 years has to be enhanced as only few wind turbines reach this target without two or more breakdowns of major components. Thirdly, to be able to increase the efficiency of the blade structures, it is necessary to not only focus on decreasing the costs but to also focus on increasing its lifetime (ETIP Wind, 2016). Sainz (2015) mentions reliability as one out of four drivers which affect the advancement of wind turbine efficiency. Furthermore, the Wind Energy Initiative (2017) at the Iowa State University are attempting to increase blade reliability as well as plant efficiency by developing new inspection methods for blades.
Wind power generation can currently be compared to coal power generation in China in regards to costs (Yuan et al., 2015). In 2009, China passed the U.S. and became the country with highest rate of wind power installations and also became the second largest in the world in regards to installed capacity. The main focus within the wind power industry in China had for several years been large scale and high speed production (Yuan et al., 2015). This kind of production resulted in emerging problems including overcapacity, quality issues and lack of competency in key components. To deal with these issues, there is now a larger focus on transitioning to efficiency, quality and final utilization within the manufacturing of wind turbines. Quality problems with domestically produced wind power equipment in China has been a significant problem. While techniques and design still rely on European and American companies, there is a lack of testing of manufactured products as well as certification systems within the wind turbine manufacturing in China. Issues such as blade damage, principal axis fracture, motor fire, gearbox damage and control system failure are some of the most typical problems which most domestic manufacturers have been experiencing. While quality issues usually emerge after five years on average globally, in China they appear after two to three years. Yuan et al. (2015) argues that “As turbines must work in harsh environment for 20–25 years, high quality is essential for wind power industry. Therefore, the competition in the wind turbine manufacturing is like a marathon race. To win the final victory, not only speed at the start of the race matters, but also the physique and character during the whole race does. Without acceptable reliability and performance, the rapid growth of China's wind power industry is destined to be unsustainable.”

In a study investigating the manufacturing selection criteria of wind turbines in Finland, reliability was found to be the most important criteria, followed by production volume and price (Sarja and Halonen, 2012). In this context reliability refers to the supplier’s reputation and reliability, and their ability to collaborate and solve upcoming problems rather than the reliability of the product itself. A good reputation based on past experiences or information from other companies, was a general demand and a necessary condition, before starting any negotiations related to a future purchase. Also, the supplier’s availability and warranty coverage was highly considered during the manufacturer selection. A factory or a representative nearby was considered to improve the reliability since a problem could be solved more rapidly during such circumstances. Furthermore, production statistics and track records together with suitability for weather conditions were also mentioned but not considered as important as supplier’s reputation and availability.

The failure frequency on electrical components are higher than those of mechanical components (Goch, Knapp and Härtig, 2012). However, electrical components can be repaired more easily whereas failures of mechanical components often require heavy cranes and acceptable weather conditions which lead to a downtime of several days or in worst case weeks. The failure frequency for rotor blades is approximately one every eighth year but the average downtime is more than three days. Thus, the costs related to mechanical components are significantly higher than assumed by looking at probability statistics. Failures on the rotor blades are not only expensive but also a safety issue. The blades are exposed to high centrifugal forces and broken parts can cause severe accidents. Thus, problems such as delamination of glass or carbon fiber
reinforced plastic material, blizzard damages, propagation cracks as well as out-of-balance errors have to be recognized in an early stage.

In order to increase the lifetime of wind turbines it is crucial to develop lighter blades which are stronger and stiffer (ETIP Wind, 2016). For instance, high performance composites together with advanced technology in the vacuum infusion process have created more reliable composite structures. Moreover, more advanced tooling systems have facilitated ultra-precise molding and assembly systems. Lastly, more advanced measurement, inspection and testing tools has been introduced which enable high accuracy and quality assurance. Aligned with this development, wind turbine manufacturers need to keep focus on combining new technology with new and improved materials such as new steel, concrete and composite structures. It is the use of new and improved materials together with improved methods of life prediction and defect identification which are key to optimizing the lifetime of a wind turbine and its components. Nolet (2011) argues in a similar way and declares that trends are moving towards larger but also lighter weight rotor blades. Nolet also mentions a growing trend of smart blades with integrated sensors which enable advanced turbine control applications and health monitoring systems for prevention of failures.
2.3 Wind Blade Manufacturing

The process of building wind turbines includes four main steps; building the blades, building the nacelle which include the hub, gearbox and generator, building the tower, and finally assemble all parts together (Gatu, 2016). According to the European Wind Energy Association, EWEA (2007) the manufacturing of the rotor blades of a wind turbine constitutes for 22.2 percent of the total costs of producing a wind turbine (see Figure 2).

![How a Wind Turbine Comes Together](image)

**Figure 2.** Shows the cost allocation within wind turbine manufacturing, where rotor blades constitutes 22.2 percent of the total costs of a wind turbine (EWEA, 2007).

This is the second largest percentage to which costs are allocated during the wind turbine production and is therefore a relevant area to investigate when analyzing opportunities for cost reduction. In order to do so, an understanding of the different steps of the wind blade manufacturing process is needed.

2.3.1 The Process

There are three main blade manufacturing methods; the boat building method, the vacuum infusion method and the IntegralBlade technology (Gatu, 2016). The most common blade material is glass fiber, which at times is combined with carbon and wood. The blades are built out of two shells which are attached to each other, where each shell is made in a mold. After the attachment of the two shells, a material removal and a finishing process follows.

2.3.1.1 Molding

There are several methods which can be used during the molding of the blade, where the vacuum infusion method is the most common and can be executed in some different ways. TPI
which is a company within the wind turbine industry has a patented one of these methods, which is a vacuum infusion technology named Seemann Composite Resin Infusion Molding Process, SCRRIMP, as can be seen in Figure 3 (Nolet, 2011).

![Diagram of the Seemann Composite Resin Infusion Molding Process](image)

**Figure 3.** Shows the Seemann Composite Resin Infusion Molding Process (Nolet, 2011).

Another method which is used during the molding process of the blades is Siemens's patented IntegralBlade technology, which is a process that molds the blade in a single piece (Siemens, 2017). While most methods such as the SCRRIMP method, molds each blade half separately and glues it together, the IntegralBlade method aims to eliminate weak areas of the blade by molding it in one piece. This is claimed to increase the quality, strength and reliability of the blades, according to Siemens (2017). LM Wind Power (2017) argues that the combination of optimized resin and vacuum infusion, results is a strong blade where air bubbles and rapid hardening can be avoided. Furthermore it is also claimed that this method reduces the production time of the molding of the blades.

Nolet (2011) explains that the materials which are used within the molding within wind blade manufacturing are the drivers in the performance of the system as well as the costs of the production. The materials which are used are structural composite materials and can be divided into two different categories; reinforcements and resins. LM Wind Power (2017) argues that it is the glass fiber which determines the blade strength, while the resin does not play a great part in this, whereas different combinations of glass fiber and resin can result in different strengths and other properties of the blade. The two most used reinforcement materials are glass fiber and carbon fiber, but there are also others such as aramids or basalt (ReinforcedPlastics, 2012; Nolet, 2011). While glass fiber has a low cost, it is a high strength material with modest stiffness, meaning it is somewhat flexible (Nolet, 2011). Carbon fiber however is a high cost material which has high strength but also high stiffness, which makes it less flexible than the glass fiber. There are also several different sorts of resin, such as epoxy, polyester,
thermoplastics and what Nolet (2011) calls “toughened” resins which include ETBN/CTBN reactive liquid polymers, core shell rubber and nano-technologies.

The reinforcement forms which are used for blade manufacturing can either be preimpregnated or dry (Nolet, 2011). The preimpregnated forms which are also called wet forms, consists of pre-combined fiber reinforcements with resin (CompositesWorld, 2014). The dry forms on the other hand are only fiber reinforcements and have not been combined with resin. Woven fabrics are mainly used in wet forms, which have an overall higher cost but are less applicable for the manufacturing of wind turbine blades (Nolet, 2011). It is the non-woven dry reinforcement forms which are mainly used for blade manufacturing in combination with different kinds of vacuum resin infusion processes. The non-woven reinforced materials are of lower cost and provide a better end result without any crimps and with superior performance. These reinforcements are usually manually placed in the blade mold (ReinforcedPlastics, 2012). Furthermore, different materials such as balsa, structural foam and 3D materials function as the core of the blade, which support the blade shells.

To ensure the quality of the blade mold, continuous polishing and maintenance is needed (Gatu, 2016). Surface finishing tools are mainly used for this purpose.

2.3.1.2 Material Removal

During the initial material removal process, excess glue is removed from where the two shells have been attached (Gatu, 2016). The currently known customer needs for this process are tools with dust extraction, oil free tools and tools which cut close against the blade.

The glue removal process continues after the first step of removal, where it prepares for a possible gel coating application (Gatu, 2016). The current customer need for this process are tools which are oil free, low vibration and which have dust extraction and a high level of productivity. During this process sanding is executed with a coarse grit fiber disc.

Some blade manufacturers use gel coating on the blades, while others do not (Gatu, 2016). The main reason for not applying gel coating is to keep the blades transparent, which simplifies the detection of possible defects. However, if no gel coat is applied, there is a need to paint the blades for UV-radiation protection. Regardless of whether the blades have been painted or coated with a layer of gel, there is a need to smoothen the surface through orbital sanding. This is a time consuming process, which requires tools which are lubrication free with low vibration and high capacity. Orbital sanders in the Atlas Copco series of LST and LSO can be used during this smoothing process.

2.3.1.3 Inspection and Reparation

The blades are lastly inspected for possible defects, which could both occur on the surface of the blade as well as under its surface (Gatu, 2016). If a defect is detected under the blade surface, a hole is drilled and filled with resin. For this process drills are of course needed, as well as a light to enhance the worker’s vision of their work. Also, sanders are needed to smoothen the surface of the repaired area. However, if the defect is on the surface of the blade in the form of a blister, it is repaired through a sanding process, whereas the area is then filled with resin and
then smoothed in accordance to the rest of the blade surface. The sanding process creates large amounts of dust, and therefore a tool is needed which has dust extraction as well as low vibration and sound levels. As the blisters can be of different sizes, there is also a need for sanders with different sizes to avoid reparation of a larger area than needed.

2.3.1.4 Root Joint

A root joint is attached to the blade which in turn connects the blade to its hub (Gatu, 2016). Previous to the attachment of the root joint, the root end of the blade often requires sanding and grinding (Corbyn and Little, 2008). The joint is built of glass fiber and metal, and is attached to the blade with threads in which bolts are tightened for cleaning purposes and then removed (Gatu, 2016).

2.3.1.5 Protection from Lightning and Finishing

There are different ways with which the blades can be protected from lightning, where one method is to place receptors along the sides of the blades (Gatu, 2016). The receptors protect the wind turbine and all of its components from lightning by transporting it through a safe path down to the electrical grounding (Siemens, 2017). It is further important to keep the surface of the receptors resin-free (Gatu, 2016). Lastly, to optimize the efficiency of the blade installations, the surface needs to be smooth with a low level of gloss. To achieve this there is a need for a high torque sander.

2.3.2 Plant Layout

With the rapidly growing segment of wind energy, companies are continuously striving to optimize their manufacturing and increase productivity. Actors such as Enercon are working to optimize their wind blade production, where Jost Backhouse the managing director of the company’s blade production states that their aim is to improve the efficiency of their blade manufacturing by systematically streamline the manufacturing processes (Gardinger, 2016). The company also had the first blade manufacturing plant in which a continuous flow production was implemented, which increased their production volume from between four and five blade sets each week to between seven and eight. Continuous flow production means that the blades are moved between the different process steps within the manufacturing plant of Enercon; “Blades are moved along the production line in mobile molds, with the following steps completed at set stations: lay glass fabrics, infuse with resin, install pre-made webs and spar boom, apply bonding agent, fold blade halves together and demold semi-finished bonded blade.” Similarly, Vestas uses specific production lines within their blade manufacturing, which has been recently changed due to the production of new blade designs (Vestas, 2015).
2.4 Ergonomics

Ergonomics is an important aspect since heavy and demanding grinding operations affect the productivity rate at manufacturing plants and the quality level of the products (FlexArm, 2014). Injury rates for grinding operations are extremely high which affect the overall performance of the company. Furthermore, in 2005 regulations regarding hand-arm vibration was introduced based on a European Union Directive requiring employers to introduce technical and organizational measures to reduce exposure (HSE, 2017).

2.4.1 The Importance of Ergonomics

The wind segment is growing along with the number of workers enrolled in the wind energy sector (European Agency for Safety and Health at Work, 2013). Thus, safety and health aspects become a prime concern. Wind blade operators are exposed to a number of hazards whereas injuries due to manual handling, injuries due to machinery usages, electrical hazards, noise and exposure to hazardous chemicals are the most discussed.

The importance of ergonomics in regards to improved quality and productivity has been well documented, although generally not well recognized (Grossmith and Chambers, 1998). Historically, companies have tended to work reactively instead of proactively i.e. they have initiated ergonomic interventions after an injury has occurred instead of before, which have led to financial losses. Thus, Grossmith and Chambers (1998) underline the importance of proactive ergonomic interventions in order to support organizational goals such as productivity and profitability. Kevin Reiland, product manager for the Panasonic Assembly Tool Division, highlights the importance of ergonomics regarding assembly tools in manufacturing plants (Samarxhiu, 2014). Ergonomics is key when reducing work-related musculoskeletal disorders (WRMD) which are the most common work related injuries. WRMD originate from repetitive and forceful exertions and causes injuries such as carpel tunnel, arthritis, back pain and hernias. Reiland argues that both the employer and the operator benefit from having more ergonomic tools. An injured worker results in both direct and indirect costs for the company. Atlas Copco agrees on the correlation between ergonomics and economic gain, “Good Ergonomics is great Economics” (Atlas Copco, 2017). Atlas Copco argues that ergonomics can have a significant impact on productivity, quality and work environment. Furthermore, Atlas Copco states that ergonomics can improve the quality of a product with as much as 30 percent.

In a study investigating attention and priorities among managers within manufacturing companies in Sweden, profitability was considered as the main objective of their companies (Nordlöf, Wijk and Lindberg, 2011). However, almost all respondents answered that there had been more prioritization of work environment issues compared to the previous year.

2.4.2 Tool Weight

Referring to grinding operations in the foundry industry, FlexArm argues that most grinding processes require the power and surface of a large grinder (FlexArm, 2014). As of today grinders can weigh as much as 15 pounds (6.8 kg) and even more with belonging attachments. A number that possibly can increase even more as the usage of diamond abrasives is a growing trend which demand a higher surface speed on the tools, thus a higher tool weight. The handling
of this weight is very demanding and often lead to back issues and high injury rates among
grinding operators. Injury rates for grinding operations are extremely high. Workers often need
to take breaks in order to manage their heavy duties which affects the productivity rate.
Furthermore, losing trained employees due to injuries also affect the overall performance of the
company.

2.4.2.1 Handling Tool Weight

The Company FlexArm is since 1984 a recognized leader within tapping and ergonomics
(FlexArm, 2017). The company is specialized in assembly arms and provides tapping, die-
grinding, torque and helicoil arms as well as solutions to support heavy grinding operations.
FlexArm provides a solution called the Flexarm Gimbal which is a support arm developed to
work effectively with heavy hand grinders in order to enable smooth and almost effortless
grinding (FlexArm, 2014). The Gimbal attachment provides four additional rotation points
compared to an existing assembly arm which gives the operator an unrestricted freedom of
movement while counterbalancing tool weight, see Figure 4. FlexArm argues that the gimbal
attachment gives companies an opportunity to improve ergonomics as well as increase
productivity and quality by maintaining consistency and accuracy within operations.

![Figure 4. Shows the usage of the FlexArm Gimbal (FlexArm, 2014).](image)

2.4.3 Vibrations

In 2005, regulations regarding hand-arm vibration was introduced based on a European Union
Directive requiring similar basic laws throughout the Union regarding health and safety risks
caused by vibrations (HSE, 2017). The regulations introduced an exposure action value of 2.5
indicating when employers need to introduce technical and organizational measures to reduce exposure. Furthermore, the regulation also introduced an Exposure limit value of 5.0 m/s² which should not be exceeded. A limit value of 5.0 m/s² means that a tool with a vibration level of 5.0 m/s² can be used during a full workday of 8 hours (Ljunggren and Karlsson, 2016).

The regulations require employers to make a risk assessment and decide what an operator’s exposure level is likely to be (HSE, 2011). During this process, monitoring may be necessary in order to understand how long operators use particular tools in a typical day or week. However, continuous monitoring is not required nor recommended, unless for rather specific circumstances. Even though the exposure level is below the limit, the employer is required to minimize the exposure in order to achieve a level “as low as reasonably practicable”. Exposure levels just below the Exposure Limit Value will still result in many workers developing hand-arm vibration syndrome (HAVS). Furthermore, if the Exposure Limit Value is reached on a regular basis, the employer needs to take action and change the conditions for the operators.

2.4.3.1 Measuring Vibrations

Vibration level is measured in m/s², which is a combined measurement of amplitude and frequency (Ljunggren and Karlsson, 2016). A vibration is rarely one-dimensional and is therefore measured in three dimensions, transformed into a vector, which describes the total acceleration. The vector size is used when calculating the daily exposure level to determine whether individuals has reached the Exposure Action Value or Exposure Limit Value.

The vibration level can be measured with the use of an accelerometer, which may be attached directly on the machine or on the hands of the operator (Ljunggren and Karlsson, 2016). It is increasingly common to attach the accelerometer in the glove, either on the back of the hand or in the palm. In this way it is possible to measure the vibration level transmitted into the hands of the operator. The accelerometer is then connected to a vibration monitor which in most cases can show the vibration level in real time and also collect data over a longer time period. However, some devices marketed as vibration meters do not measure the vibration exposure of operators, only the amount of time that a tool is being used, similar to a stopwatch (HSE, 2011). These values may not be accurate since the vibration levels may vary over time depending on the condition of the tool (Ljunggren and Karlsson, 2016). The wear and imbalance within the tool can make a difference as well as how the machine is handled, the amount of applied pressure or variations on the angle or material of the ground. Furthermore, the type of abrasive used may also be of great importance. Such factors may lead to significant deviations between the values stated in the data sheet for a specific product and actual values.

2.4.3.2 Handling Vibrations

It is possible to reduce the vibration level by implementing different technical solutions (Ljunggren and Karlsson, 2016). A cheap and simple alternative is to use a balance ring which eliminates imbalance in machines with rotating parts, such as grinders. Regarding pneumatic impact machine tools, it is possible to use a damper in order to reduce the levels significantly. A third option is to isolate the engine from the handle. This technique has been available in lawn mowers since 2005 but is rarely used as the demand for such solutions has been too low.
In a study conducted by Lund University, measurements were made on one of Atlas Copco’s rammers which is used to compress bricks or concrete. By rebuilding the machine and attaching an outer handle on a vibration damped bracket, the vibration levels could be reduced from 42 m/s² to 7 m/s².

The companies Makita and Hitachi have both developed brands to be able to indicate a lower level of vibration (Ljunggren and Karlsson, 2016). Products which include technologies that contribute to a lower vibration level are marked ATV (Anti Vibration Technology) respectively UVP (User Vibration Protection). However, this marking does not necessarily indicate a low vibration level.

Cleco, a brand included in the Apex Tool group has developed an electronic counter called Cleco TULMan which is the first universal monitoring device for small pneumatic tools such as sanders and grinders (Apex Tool Group, 2016). The device can be connected to any pneumatic tool with an air flow between 5 cfm and 20 cfm, regardless of manufacturer, and allows users to monitor tool usage, and implement preventative maintenance. The TULMan enables maintenance intervals or calibration checks to be set based on cycles or run time. A yellow or red LED light indicates when the limits are near or reached. Furthermore, the device enables users to track tool usage and compare product usage among different operators in order to improve workforce productivity.

2.4.4 Dust and Chemicals

Wind turbine blades are produced from glass fiber-reinforced plastic (GFRP) with epoxy based resins (European Agency for Safety and Health at Work, 2013). Epoxy resins are synthetic chemicals, which can cause allergy and dermatitis. Furthermore, solvent (styrene) vapor is released during the blade manufacturing process and the exposure is notoriously difficult to control. The exposure rate among operators can increase along with the size of the final product. This makes wind turbine blade manufacturing critical as the blades can reach a length of 90 meters.

A study showed that skin problems were mainly associated with finishing work involving filling the gaps in the blade edges, adding a thin layer of fiberglass to the leading edge and sanding down imperfections (European Agency for Safety and Health at Work, 2013). Additionally, skin problems were reported within other steps in the manufacturing process such as the cutting of carbon fiber material, in association with mold production and during the application of composite materials in the mold.

A study solely investigating health concerns related to finishing work such as repairing defects by drilling and injecting resins, sanding and painting identified correlated health issues (European Agency for Safety and Health at Work, 2013). Problems such as the stopping of menstrual cycles, severe headaches, nosebleeds and dizziness, as well as throat and eye irritation were reported. These problems proved to be a result of the use of endocrine disruptors and highly toxic carcinogens, which were used in these tasks. These symptoms occurred even though all workers wore gloves, overalls and safety glasses. The chemicals penetrated through the protective equipment and were not sufficient to prevent these symptoms.
Increased automation of manufacturing processes, where operators are designed out of the manufacturing process as much as possible through the use of robotics is a suggested possibility for manufacturers to increase the safety and health conditions among operators (European Agency for Safety and Health at Work, 2013). This is increasingly important, as the wind turbine systems get larger. However, not all companies have the economical prerequisites to make such alterations. Furthermore clear instructions, information and training are given as other suggestions.

2.5 Material Removal Solutions within Wind Blade Manufacturing

The manual as well as automated tools in regards to material removal which are used in the wind blade manufacturing process have been presented in this chapter. Furthermore, the application of automation within the process has been presented.

2.5.1 Manual Tools

The product segments mainly used in wind turbine manufacturing are tools within bolting and material removal (Atlas Copco, 2015). The tools which are mainly included in the material removal product offering that Atlas Copco has towards the wind blade manufacturing are LSV grinders, GTG sanders, circular cutters such as the LCS series, die grinders and the LST/LSO orbital and random orbital sanders.

The LSV38 can be used as a grinder for general purpose grinding or cutting-off applications (Atlas Copco, 2015). It is an ergonomically designed tool with high power-to-weight ratios and low vibrations and noise levels which means that it can be used all day without strain. The LSV38 can also be used as a sander and is then suitable for medium rough to rough sanding applications.

The GTG25 is explained as “More efficient than a conventional vane grinder motor, the 2 stage turbine motor in the GTG25 provides an extremely high efficiency leading to great rate of material removal. When it comes to power, performance and operator comfort, the GTG25 is in a class of its own.” (Atlas Copco, 2015).

The LCS38 is a circular cutter and can be used during the cutting of excess glue from the blade during its manufacturing process (Atlas Copco, 2015). The tool cuts to a depth of 26 mm and can cut through steel, aluminum, wood and glass fiber.

The orbital and random orbital sanders in the LST and LSO tool series are designed to give the operator the best surface result in the shortest possible time before painting and coating (Atlas Copco, 2015). All models are lubrication and silicone free to avoid contamination of the workpiece. They are also suitable for polishing with wax and surface conditioner.

In addition to the classic material removal tools in the area of cutting, grinding and sanding, tools are being developed to better apply to the material removal process within wind blade manufacturing. The company Flex Trim has grown to be a market leader in brush sanding solutions (Flex Trim, 2017). Flex Trim has designed a machine called the Blade Sander which is specifically developed for the sanding of wind turbine blades. The Blade Sander has a sanding width of 300 mm consisting of strips of flexible brushes and sanding material. This combination
of strips ensure that the material is pressed evenly towards the surface. The machine has a weight of 34 kg and is used similarly like a lawnmower; with the use of a handle it can be moved back and forth on the blade (see Figure 5). In this way it is possible to sand 90 percent of the surface.

![Flex Trim Blade Sander](image)

**Figure 5.** Shows the Blade Sander developed by Flex Trim for sanding operations of wind turbine blades (Flex Trim, 2017).

Flex Trim argues for the many advantages generated with the use of the Blade Sander (Flex Trim, 2017). The sanding process with the Flex Trim machine has proven to be many times faster than a regular sander, which reduces the number of manual working hours and thus the cost and the total production time for the blade. Furthermore, the Blade Sander gives a better and more uniform quality compared to hand sanding and avoids cutting too deep into the material. Furthermore, Flex Trim argues that the Blade Sander improves the working environment as it is equipped with a dust control system which removes the dust before being whirled into the air.

### 2.5.2 Automation and Automated Solutions

Blade manufacturing has previously been and is often still characterized by labor intensive processes (Wind Energy Initiative, 2017). In order for blade manufacturers to be able to increase their production volumes as well as keep it financially feasible by decreasing costs, automation and quality control need to be developed and implemented within the processes. According to Hagelberg (2015) the degree of automation within a system affects its degree of efficiency. If the degree of automation is too low or too high within a system, it becomes less efficient, as can be seen in Figure 6. The low automation requires increased manual labor which decreases the efficiency level of a system, while high automation levels could restrict the flexibility of the system and in turn decrease its efficiency.
GE Energy argues that while the implementation of automation within blade manufacturing is beneficial mainly in terms of improved quality but also reduced costs, it does decrease the level of flexibility within the processes in comparison to manual labor (Composites Manufacturing, 2012). The need for flexibility within a system depends on several factors (Hagelberg, 2015). If there is high variety in products there is a need for flexibility in the area of conversions within a system or if the variety lies in the production volume of the same product, flexibility within the capacity is crucial. Further there is also a need for process flexibility within systems to be able to handle variations in the processes such as changes in workpiece material or wear of used tools.

2.5.2.1 Standardization Paving the Way for Automated Solutions

As the wind turbine industry has grown rapidly during recent years, the automation level and optimization of production infrastructure and processes have lagged behind (Goch, Knapp and Härtig, 2012). Blade manufacturing, among other components of a wind turbine, are in a high extent produced manually. Many steps within the blade manufacturing process, for instance the finishing of the outer blade surface, require approximately 80% of individual manual work. Manufacturers should be able to increase the automation level within blade manufacturing significantly. However Goch, Knapp and Härtig (2012) argue that this process is hampered by high quality requirements and the increasingly growing sizes and weights. In 2012 the maximum length of rotor blades were limited to 70 meter but by the end of this decade, the maximum length is foreseen to reach 110 meters. Handelsman and Zald’s (2010) argumentation is somewhat conflicting with the ones of previous authors even though they agree on a future potential for automated solutions and robotics. Handelsman and Zald (2010) argue that increasingly growing sizes for wind turbine blades are a driving force towards automation. As the size of wind turbines increase, it is no longer financially feasible for manufacturers to keep labor intensive processes, thus automation becomes rather essential in the long term (Guillermin and Shankar, 2012). In the past, blade manufacturing has been a craftmanship; a manual process, but newer models are no longer possible to produce in this way due to their size (Sainz,}

![Figure 6. Shows the level of efficiency in regards to the level of automation within a manufacturing system (Hagelberg, 2015).](image-url)
As the blades are continuously increased in size there is a need to make the production processes more automated (Sainz, 2015).

“The increase in size of onshore and offshore wind energy systems in combination with new design and production methods for rotor blades causes a high number of rotor blade variants, which are produced during a limited time frame” (Kaczmarek et al., 2016). The high number of variants affect the blade manufacturing processes and prevents the application of approaches of serial production. Most blade manufacturers in China have to develop and produce several models and blade designs in order to meet the requirements from the different wind turbine manufacturers (Yuan et al., 2015). Siemens Wind Power (2017) believes that standardization and modular systems are key factors to achieving financially sustainable wind turbines at a fast pace. To reach this state, Morten Pilgaard Rasmussen, head of Research & Development at Siemens Wind Power states that the goal is to reduce the amount of components as well as the complexity of the designs.

In order to reduce costs and increase capacity within the wind power industry, industrialization is considered to be a key factor (ETIP Wind, 2016). This includes an increased standardization of processes as well as the development of value chains within the wind industry. Projects which have been conducted in the wind industry have often been treated as customized cases, whereas knowledge have not been transferred between different projects. There is however many similarities between wind power projects. ETIP Wind (2016) believes that these similarities should be taken advantage of in order to build a common base of standardized components, methods and equipment which in turn will reduce costs and save time.

Some areas of priority for standardization within manufacturing of wind turbines are quality requirements, surface treatment and optimized safety factors, as can be seen in Figure 7 (ETIP Wind, 2016). Standards within these areas can improve factory interactions where a common knowledge base can be developed. By doing this factories could avoid component over-engineering and decrease their costs.

Figure 7. Shows the topics which should be priority during standardization (ETIP Wind, 2016).
While standardization is one part of increasing efficiency and reducing costs within the wind power industry, the development of the full value chain of a wind turbine is also beneficial as it would provide further optimization, interoperability between the different systems and increase the speed to market (ETIP Wind, 2016).

### 2.5.2.2 Automated Solutions within Wind Blade Manufacturing

Automation generates a number of benefits such as significant cost reduction, increased productivity through shorter life cycle times and dramatically improved quality of the final product as a result of improved accuracy and repeatability (Sainz, 2015). The automation of different finishing processes allows a perfect protection against weather conditions such as wind, water and ultraviolet radiation, as a robot can traverse the full length of the blade in a single step. Moreover, health problems for workers could be minimized as direct contact to fine dust and chemicals can be avoided.

Nolet (2011) predicts the automation within blade manufacturing to increase within the coming years. Nolet (2011) further believes that automated material removal and finishing solutions such as grinding, sanding and coating will increase; “The advance in vision systems and on the floor computational power coupled with the availability of low cost multi-axis robots makes automation of many tedious processes possible.”

Within blade manufacturing, automation can currently be found within different processes such as molding, surface treatment, finishing and the processing of the root end of a blade (Handelsman and Zald, 2010). An example of this is DRS (Dynamic Robotic Solutions) which have developed the patented AccuFind technology which can identify and locate the root and center of a blade for the processing of the root end of the blade (DRS Robotics, 2013). Another example of automation of the processes within blade manufacturing is the Liebherr Automation Systems for blades up to 60 meters, where processes such as the trimming of blade components, polishing of blade surfaces and the layout of glass- and carbon fiber sheets have been automated (Liebherr, 2017).

Surface treatment such as grinding and sanding of a blade is considered to be one of the most challenging processes for automation (Handelsman and Zald, 2010). This process is also the most labor intense part of the blade manufacturing process and is also rather time consuming. The challenge mainly lies in the high variation of blade designs and sizes, where an automated solution must be able to identify and locate the size of the blade as well as the features on its surface and edges. In order for an automated solution to be able to conduct such actions, it needs to be programmed based on the specifications of the particular blade which is being treated. EINA is a company which offers an automated sanding solution with a robotic sanding head which conducts the process after being programmed with the start- and end point of the workpiece (EINA, 2017; Handelsman and Zald, 2010). The solution claims to create a consistent result with higher quality and less rework in comparison to manual labor (Handelsman and Zald, 2010). DRS has a similar automated grinding and sanding solution which has a tracking device to identify and trim excess material from the molding process.
Most of these automated grinding and sanding solutions such as the robotic arms from EINA, DRS or even Liebherr are stationary, meaning that they cannot move freely and have a restricted work space area (EINA, 2017; Liebherr, 2017; DRS Robotics, 2013). However, as the wind turbines are becoming larger, the blades are also increasing in size. This makes the application of stationary automated solutions less feasible in terms of accessibility, which means that a stationary robotic arm may not be able to reach the whole surface of a blade. Furthermore, with the increasing size of a blade, its mobility decreases. This makes it harder to for example move a blade from one area of the factory to another. Eltronic and Blade Treatment are two Danish companies which have developed mobile semi-automatic sanders focusing on blade manufacturing (Blade Treatment, 2017; Eltronic, 2017). The semi-automatic sander from Eltronic is adaptable to all shapes and sizes of blades, where it is able to detect the blade and its features in order to sand the surface (Eltronic, 2017). While the sanding process is fully automated, an operator is required to control the unit. The mobile semi-automatic sander 800, also called MMS 800, from Blade Treatment has similar features and functions as the device from Eltronic (Blade Treatment, 2017). In comparison to manual sanding on blades, these semi-automated sanders are believed to be faster and more efficient, while providing a result with consistent quality (Blade Treatment, 2017; Eltronic, 2017). Even when comparing to stationary automatic sanding solutions, Eltronic’s device is adaptable to the workpiece and does not require preprogramming to identify the shape of a blade. It is also claimed that these solutions will reduce the operation costs for the material removal process.

2.6 Value Stream Mapping

As defined by Weiss (2013); “Value stream mapping consists of establishing the flow of any process with the goal of incorporating only those activities that deliver value”. VSM is thus a method within the area of business process management which is used to detect non-value adding activities within a process and thereby used to reduce waste and to optimize the flow within a development lifecycle (Tyagi et al., 2014; Weiss, 2013). In order to identify the non-value adding activities, a mapping of the current state of a specific process needs to be done. The current state should be analyzed, whereas all activities which add value to the end product or service need to be identified, as well as those activities which are non-value adding. A future state map of the process with a reduced amount of waste then needs to be developed, for future implementation. The method of VSM can therefore be divided into three parts; current state mapping, future state mapping and action plan.

2.6.1 Current State Map

A current state map specifies all activities and steps within a certain process (Tyagi et al., 2014). By mapping the different steps and the activities which are conducted during each step, an overview of the process can be given, whereas the activities can be analyzed. In order to develop a current state map the first step is to define the boundaries and the value of the process (Weiss, 2013). This is followed by an identification of tasks and flows within the different steps of the process. To gather this information, a Gemba approach can be conducted (Tyagi et al., 2014). The Gemba walk is a Lean Manufacturing approach which involves being present at the location where the process is taking place and where value is created. Using this approach to
gather information regarding the different steps of the process is considered to increase the level of knowledge and understanding of the steps, which in turn will simplify the analysis of the developed map. Once an understanding of the process has been achieved and the tasks and material flows have been identified, a current state map can be developed (Weiss, 2013). The current state map will then function as base for further analysis of the current conditions of a process.

2.6.2 Future State Map

The future state map has the purpose of reducing activities which are considered as waste within the process in the current state map (Tyagi et al., 2014). According to lean manufacturing, there are three categories of actions within a process; value adding, non-value adding but necessary and non-value adding and not necessary, also called waste (Womack and Jones, 2003). In order to reduce waste, the waste first needs to be identified in the current state map through an analysis (Tyagi et al., 2014). Once the waste has been identified, a future state map is developed where the waste has been removed from the manufacturing process (Tyagi et al., 2014).

2.6.3 Action Plan

An action plan can be defined as “A sequence of steps that must be taken, or activities that must be performed well, for a strategy to succeed.” (BusinessDictionary, 2017). It is a plan which includes the sequence of steps and actions needed in order to reach a potential future state. An action plan should also include the specific tasks which need to be conducted, a time horizon of each task and also an allocation of resources needed for the conduction of each task.

According to Atlas Copco:D (2017) there are three main strategies for reaching a future state regarding the expansion or development in the Atlas Copco product range; internal development, partnership or acquisition. This means that if a gap or an improvement is detected in the product offerings, one of these approaches are used to gain the expertise and knowledge within the new area. Thus, when applying the action plan theory to the approach of Atlas Copco regarding the expansion or development of their product offerings, there is a need to build an action plan which includes either internal development, partnership or acquisition in order to reduce the gap and reach the future state.

2.6.4 The Application of Value Stream Mapping in this Thesis

In this thesis, a VSM approach has been used in order to map each step of the wind blade manufacturing process, with the aim to identify all operations within the process which include material removal operations. However the current state map has not been analyzed with the aim to identify direct waste, but to identify non-efficient activities in regards to material removal processes. It has further been used to identify what material removal tools are used during these processes. Based on this analysis, a future state map has been developed which includes tools and solutions which can reduce the waste in the form of time consumption within the material removal processes. The action plan has been presented in the form of suggested material removal solutions which could be applied in order to reach the future state map. The action plan does however not include strategic suggestions regarding the steps which need to be taken in
order for Atlas Copco to develop or expand their product offering in regards to internal development, partnership or acquisition.

2.7 Summary – Applying a System Perspective

By applying a system perspective approach, this case study has involved looking at industrial trends in order to understand functional requirements for manufacturing and thus be able to find an applicable solution on an individual level. Figure 8 illustrates identified industry trends, their direct effect on blade manufacturing processes and how these create a base for future material removal solutions.

**Figure 8.** Shows the developed framework for current industry trends, their direct effect on blade manufacturing processes and how these create a base for future material removal solutions.

Based on the literature review, the industrial trends have been identified as an increased energy capture from wind turbines, decreased costs in the manufacturing, an increased consideration of operator ergonomics and health, increased reliability and a growing offshore market. These identified trends from the industrial level constitute a base for the requirements which are needed on a functional level within blade manufacturing plants, in order to meet the industry trends. They have therefore been transferred to a functional level of the wind blade manufacturing process and include the need for ergonomic tools, standardization, automation, changes regarding blade design as well as affected plant layout.

The requirements needed on a functional level create a base for the investigation which needs to be conducted in order to apply solutions on the individual level. In this thesis, VSM has been used as a theoretical concept and applied to the processes of wind blade manufacturing plants in order to identify the individual needs of each plant but also to verify the requirements set on the functional level. By doing so, a material removal solution on an individual level has been presented.
3. Method

A qualitative research method was chosen for this research, with the aim to investigate “how” Atlas Copco can increase value for their customers by expanding or developing their product range within material removal tools by looking at “why” current process activities are included in the wind blade manufacturing process and their potential value. A qualitative approach was identified as the appropriate research method for this research since this approach is suitable when analyzing a phenomenon in depth (Ghauri and Gronhaug, 2010). A quantitative approach would not be an appropriate approach since the answer to the main research question does not depend upon the gathering of quantitative data. A qualitative research method is associated with an inductive research approach (Blomkvist and Hallin, 2015). The inductive approach is based on an empirical case study of an identified problem area, whereas theories are continuously used in order to deepen the understanding of the researched phenomenon.

3.1 Research Design

To answer the presented research questions, an exploratory case study was chosen as the research design. A case study generates in-depth empirical data and makes it possible to explore new dimensions of a phenomenon (Blomkvist and Hallin, 2015). Atlas Copco, together with a selection of their customers within wind blade manufacturing were chosen as case companies and were used as a tool to explore the phenomenon of material removal tools within the wind blade manufacturing industry. According to Blomkvist and Hallin (2015), criticism has been directed towards case studies, where they are believed to be subjective and primitive. This form of criticism is however based on the execution of such studies, where a systematic approach was followed in this case to avoid a primitive and subjective study.

3.2 Data Collection

Both primary and secondary sources were used for the gathering of data in this thesis. The primary sources included employees of the case company Atlas Copco as well as of the customer companies of Atlas Copco. The primary data was gathered both through interviews and through observations during study visits. Secondary sources have mainly been used for the gathering of data for the literature review and theoretical concepts used for this thesis. The secondary sources include scientific articles, company written reports, and literature which is relevant to the area of study. As an inductive approach was used, the gathering of secondary sources for this purpose was proceeded throughout the writing of the thesis.

3.2.1 Interviews

Interviews were conducted to gather data from primary sources in the pre-study as well as in the main study of this thesis. The aim with all conducted interviews was to understand the underlying needs of a certain market, the customer as well as the needs of Atlas Copco. In order to increase value for Atlas Copco as well as their customers, it is crucial to review and analyze their needs and further weigh these against existing resources. During interviews it can however be difficult to grasp the underlying need to the problems that are communicated. To overcome this difficulty the customer need interview framework was used, as seen in Figure 9.
Figure 9. Shows the customer need interview framework which can be used to obtain the customer need during meeting with the customer (Atlas Copco:E, 2017).

The customer need interview process is a concept which aims to reach the core customer need behind a problem within a process, a solution or a function of a product or service (Atlas Copco:E, 2017). This is executed by asking why the problem is perceived as a problem within the different levels. Once the need has been reached, it is time to go back to how the customer need affects the areas of function, solution and process. This framework was applied to all interview guides that were used during the conducted interviews, which will be further explained in this chapter.

3.2.1.1 Pre-study

In the pre-study qualitative data was gathered through semi-structured interviews, which were held with key-individuals within Atlas Copco. The interviews were based on the pre-study interview guide, were questions were adapted to the role of each respondent (see Appendix 2 - Pre-study Interview Guide). Semi-structured interviews were chosen as it allows the respondent to reflect and answer the questions based on their own interpretation and experiences. This approach was preferable as it allowed the respondents to further explore a question and gave the interviewer the freedom of adjusting the questions based on the answer of the respondent (Ghauri and Gronhaug, 2010). This approach can however also be problematic if the respondent is less prone to deliver a detailed or developed answer. However such a problem was not experienced during the conducted interviews. As can be seen in Table 1, five respondents were interviewed for the pre-study of this thesis, with the aim to achieve a deeper understanding of the two markets of Foundries and Wind Energy. The respondents were chosen based on their assumed knowledge within the foundry and wind energy markets, within material removal tools, within customer relations and within the strategic guidelines of Atlas Copco in regards to developing their business.
Table 1. Shows the interviewed respondents during the pre-study.

<table>
<thead>
<tr>
<th>PRE-STUDY</th>
<th>Area of Business</th>
<th>Role of Respondent</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlas Copco: Respondent A</td>
<td>Case Company</td>
<td>RnD - Tightening</td>
<td>Face-to-face Interview</td>
</tr>
<tr>
<td>Atlas Copco: Respondent B</td>
<td>Case Company</td>
<td>Product Manager – Material Removal</td>
<td>Face-to-face Interview</td>
</tr>
<tr>
<td>Atlas Copco: Respondent C</td>
<td>Case Company</td>
<td>RnD – Metal Fabrication</td>
<td>Face-to-face Interview</td>
</tr>
<tr>
<td>Atlas Copco: Respondent D</td>
<td>Case Company</td>
<td>Business Development</td>
<td>Face-to-face Interview</td>
</tr>
<tr>
<td>Atlas Copco: Respondent E</td>
<td>Case Company</td>
<td>Voice of Customer</td>
<td>Face-to-face Interview</td>
</tr>
</tbody>
</table>

All interviews were conducted face-to-face with the respondents. Furthermore, all interviews conducted for the pre-study were recorded and transcribed.

3.2.1.2 Main Study

Qualitative as well as quantitative data was gathered for the main study of this thesis from the primary sources through semi-structured interviews. The interviews were mainly held with key individuals within Atlas Copco but also with external respondents, in order to achieve a deeper understanding of the material removal products, their function and their use within wind blade manufacturing. The qualitative and quantitative data which was gathered have been presented in the empirical results. The quantitative data which has been gathered have not been presented in the form of tables or graphs as it was rather used for achieving a deeper understanding of the qualitative questions which were asked during the interviews. For the main study of this thesis seven individuals were interviewed, as can be seen in Table 2. Five of these interviews were conducted internally with respondents working with different roles within Atlas Copco, while two of them, Company B and Company C, were conducted externally with respondents working within two different abrasives companies.

Table 2. Shows the interviewed respondents during the main study.

<table>
<thead>
<tr>
<th>MAIN STUDY</th>
<th>Area of Business</th>
<th>Role of Respondent</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlas Copco: Respondent F</td>
<td>Case Company</td>
<td>Product Manager/Sales – Metal Fabrication</td>
<td>Face-to-face Interview</td>
</tr>
<tr>
<td>Atlas Copco: Respondent G</td>
<td>Case Company</td>
<td>Regional Sales Manager – Wind segment</td>
<td>Face-to-face Interview</td>
</tr>
<tr>
<td>Atlas Copco: Respondent H</td>
<td>Case Company</td>
<td>Product Manager – Metal fabrication, Aerospace and Wind Segment</td>
<td>Face-to-face Interview</td>
</tr>
<tr>
<td>Atlas Copco: Respondent I</td>
<td>Case Company</td>
<td>Market Manager</td>
<td>Digital Interview</td>
</tr>
<tr>
<td>Atlas Copco: Respondent J</td>
<td>Case Company</td>
<td>Regional Sales Manager – Wind segment</td>
<td>Digital Interview</td>
</tr>
<tr>
<td>Company B</td>
<td>Abrasives</td>
<td>Product Manager</td>
<td>Face-to-face Interview</td>
</tr>
<tr>
<td>Company C</td>
<td>Abrasives</td>
<td>Owner of Company</td>
<td>Face-to-face Interview</td>
</tr>
</tbody>
</table>
The internal semi-structured interviews were based on an interview guide containing open-ended questions within the area of wind blade manufacturing, including its processes, the tools which are used, the wind blade itself, potential areas of development, trends and ergonomic aspects (see Appendix 3 - Internal Interview Guide). The external interviews were based on a separate interview guide focusing on abrasives in regards to the wind blade manufacturing process, the used tools and the trends and challenges within the wind energy segment (see Appendix 4 - External Interview Guide). The interviews were executed as face-to-face interviews as well as digitally through video and audio due to geographical restrictions. Conducting digital interviews through audio could pose a risk as it might change the perception of the answers and restrict the depth of the replies. Therefore this was taken into consideration during these interviews by continuously confirming the answers of the respondents directly after their response throughout the interview.

3.2.2 Plant Visits

Four plant visits were conducted for the main study of this thesis, as can be seen in Table 3. During the plant visits, data was gathered through observations of the plant as well as through interviews with the plant guide. Observation was chosen as a method of data gathering during the plant visits with the aim to achieve a greater understanding for the processes within the plants, the tools which are used in each step as well as the work conditions for the operators and thereby be able to identify the needs and requirements of the plants. A gemba walk approach was used to gather information about the different steps of the processes. This is a Lean Manufacturing approach and refers to being present at the location where the process is taking place and where value is created (Tyagi et al., 2014). Furthermore, an observation guide (see Appendix 5 - Plant Visit Observation Guide) was used, which included topics such as the steps of the process, the used tools and their level of automation, plant layout, ergonomic aspects of the plant and data collection. In addition to observing different aspects of the plant, an interview was also conducted at the end of each guided tour of the different plants. The interviews were conducted with individuals working at each plant, which in the case of Plant A was a quality manager, in the case of Plant B and Plant C were maintenance managers and in the case of Plant D was a process engineer. All of the respondents had knowledge of all steps in the process, while also having a main focus within a certain area of the blade manufacturing. An interview guide (see Appendix 6 - Plant Visit Interview Guide) was used during these interviews which included open-ended questions but also structured quantitative questions. The mix of open-ended question together with quantitative and structured questions allowed for a deeper understanding within the researched areas but also for achieving an understanding of the researched areas in a quantitative manner which allows for a more structured comparison between the answers of the respondents. The quantitative questions have however not been presented in the form of tables or graphs, but rather in text. All interviews at the visited plants were executed as face-to-face interviews.
Table 3. Shows the visits to customer plants.

<table>
<thead>
<tr>
<th>PLANT VISITS</th>
<th>Type</th>
<th>Guide</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant A</td>
<td>Nacelle assembly</td>
<td>Quality Manager</td>
<td>Works with quality assurance, but has general knowledge of all processes.</td>
</tr>
<tr>
<td>Plant B</td>
<td>Blade manufacturing</td>
<td>Maintenance Manager</td>
<td>Works with tool maintenance and has knowledge of all parts of the process.</td>
</tr>
<tr>
<td>Plant C</td>
<td>Blade manufacturing</td>
<td>Maintenance Manager</td>
<td>Works with tool maintenance and has knowledge of all parts of the process.</td>
</tr>
<tr>
<td>Plant D</td>
<td>Blade manufacturing</td>
<td>Process Engineer</td>
<td>Mainly works with the material removal and finishing process but has knowledge of all parts of the process.</td>
</tr>
</tbody>
</table>

While the aim with the plant visits was to visit blade manufacturing plants, only three of the four visited plants were blade manufacturing plants. Plant A was a nacelle assembly plant, which was situated next to the company’s blade manufacturing plant. However access was denied to enter their blade manufacturing plant due to what Plant A explained as security and safety reasons. Therefore, no visual data collection through observation could be gathered regarding the blade manufacturing processes during this visit and the focus was rather put on data gathering through a conducted interview.

3.2.3 Documentation and Analysis of Data

The documentation of gathered data from conducted interviews and study visits is of great importance as this is believed to benefit the analysis of data (Blomkvist and Hallin, 2015). Therefore, audio recordings of the conducted interviews were performed, with the consent of the respondents. In addition to the recorded audio, notes were taken during the interviews, which allowed us to go back and look at previously asked questions if needed. Furthermore, all audio recorded interviews were also transcribed, whereas the transcriptions of the interviews were later used during the analysis. The main form of documentation during the plant visits was in the form of taking notes, as audio recordings were not allowed and therefore not possible. The gathered notes were then transcribed as soon as possible after the conducted plant visit with the aim to not forget or lose any information that was gathered during the visit.

The primary and secondary sources have been analyzed in a critical manner. This was done in order to increase the reliability of the data presented from these sources. During the analysis of the data gathered from the primary sources, ethical aspects, confidential restrictions, corporate motives and other surrounding factors was taken into consideration and looked into, as such factors could affect the respondents’ answers. Any reflection on the answers of the respondents and possible underlying factors have been discussed in chapter 7.2 Discussion. Furthermore, an information and data triangulation method was used for the analysis of data originating from secondary sources. Descombe (2011) suggests that a triangulation method increases the validity and reliability of the gathered data. Information triangulation is made by using multiple sources.
of information and has been implemented by always comparing data between at least two secondary sources. Data triangulation is made through gathering data from different formats of secondary sources, which has been done throughout the thesis.

3.2.4 Ethical Aspects

The writing of this thesis was based on the Swedish Research Council’s principles of ethical research for the humanities and social science. This includes four principles focusing mainly on the ethical aspects of research; (1) the information requirement - individuals included in the research have to be informed of the purpose of the research; (2) the consent requirement - individuals included in the research have to give their consent to this matter; (3) the confidentiality requirement - gathered information should be treated with confidentiality; (4) the good use requirement - gathered data should be used for purposes stated at the time the data was being gathered (Blomkvist and Hallin, 2015).

In order to follow these principles some measures have been taken into action:

(1) All respondents were informed of the purpose of the research prior to the interview, as well as conducted plant visits.

(2) Audio recording the conducted interviews was identified as beneficial for the following analysis of the gathered data, and was therefore done with the consent of the respondents. As consent was not given during the plant visits, no audio recording were conducted during these visits. Notes were instead taken with pen and paper, which was also done with the consent of the plant guide.

(3) The data gathered from the conducted interviews and study visits has been treated with confidentiality, whereas the anonymity of the respondents has been reserved in all cases. This has been done to respect the integrity of the respondents and protect their interests. To do so, no visited plants have been mentioned by name or a specific location. Furthermore, any gathered information which has been identified as sensitive or confidential has been either removed or anonymized.

(4) Previous to any conducted interview, the respondents were given access to the interview guide and the purpose of the interview.

3.3 Delimitations

This research has been delimited to focus on the manufacturing processes of the rotor blades of wind turbines. Furthermore, the research focuses on the material removal solutions which are used or can be used within the wind blade manufacturing process. Therefore, the analysis of possible development or expansion of Atlas Copco’s product offerings has been delimited to tools within the area of material removal. Tools within the area of material removal include tools used for operations such as cutting, grinding and sanding. In order to achieve an understanding of how and where material removal tools can be used within the process, the entire wind blade manufacturing process has been investigated, where the steps which include material removal activities have been identified.

As this research has been conducted as a case study with Atlas Copco as the case company, the gathering of data from primary sources was limited to Atlas Copco, as well as their customers.
within the wind energy segment. Furthermore a geographical limitation was set to investigate the European market, where all conducted plant visits were within this geographical limitation. Some comparison has been done to the American and Asian markets within literature and empirical data, however this has not affected the main focus which is the European market.

The investigation was conducted on a functional level, even though a systems perspective approach was taken where all levels had to be considered in order to grasp the overall picture. This means that while trends were identified in the industrial level, and solutions were investigated on an individual level within each visited plant, this was later applied to the functional level. A systems perspective framework was developed to explain this connection further.

3.4 Validity and Reliability

Validity and reliability are two important factors when writing a thesis whereas validity refers to researching the correct object while reliability refers to whether the research of the object is being done correctly (Blomkvist and Hallin, 2015). High validity depends on the connection between the problematization, research purpose and research question to the theory which is presented. The research question focuses on the manufacturing processes of wind blades within the wind turbine industry and how Atlas Copco can expand and develop their material removal product range within the area. Furthermore, the sub research questions focus on customer needs and market trends within the wind blade manufacturing processes. This corresponds well with the theory which is presented in the areas of VSM, wind turbine manufacturing and trends within wind blade manufacturing. The reliability of the research mainly includes dialogic reliability whereas the analysis of the gathered empirical data was done in an impartial matter with mutual respect among those who analyzed it.
4. Results and Analysis

The empirical data which was gathered through interviews and observations has been thematically divided and presented in this chapter. Furthermore, an analysis has been conducted including the empirical data, the literature and theoretical concepts within each theme. The themes include the blade manufacturing process, material removal solutions, offshore, cost and reliability and ergonomic aspects.

4.1 Trends and Challenges

The empirical data regarding trends and challenges together with its analysis in regards to literature are presented in this chapter.

4.1.1 Offshore

*The gathered empirical data in the area of the offshore segment of wind turbines has been presented in this chapter, following an analysis of the area.*

4.1.1.1 Empirical Data

Plant A (2017) claims that offshore is a growing trend right now. However, Plant A has chosen not to work towards the offshore segment due to a number of factors. Firstly, maintenance is hard and expensive since the wind turbines are positioned out seas with a decreased availability. Secondly, there are laws and regulations limiting the number of new offshore wind mills. Thirdly, it is hard to transport the electricity back to the mainland and store it. This is partly a grid problem and partly a storage problem. Atlas Copco agrees on the issues regarding transportation and storage of electricity and claims that these problems are hampering the growth within the offshore segment (Atlas Copco: H, 2017). Long distances between the offshore wind farms and the mainland lead to waste during the transportation. Furthermore, offshore wind turbines have a decreased lifetime due to corrosion.

4.1.1.2 Analysis

Literature supports empirical data regarding a continuous growth within the offshore wind power segment. However, offshore manufacturers stand towards a number of challenges and far from all wind blade manufacturers are willing to invest in this part of the industry. As of today, the electricity generated by offshore wind turbines is considerably more expensive than electricity generated onshore, whereas offshore manufacturers are aiming for achieving lower energy costs, increased reliability as well as an increased energy capture in order to become cost competitive. A part in this development is to increase the rotor diameter through the creation of larger blades. Furthermore, manufacturing towards the offshore segment sets high standards of reliability. Decreased availability generates high maintenance costs and therefore reliability is even more important in the offshore segment compared to the onshore segment. Additionally, as of today, offshore wind turbines have a decreased lifetime due to corrosion.

The willingness to focus on the offshore segment also depends on the location of the plant/company and the conditions prevailing in this area. Laws and regulation restricting the
possibility to build new onshore as well as offshore wind farms along with grid capacity in the area affects the possibility for companies to invest in this segment. Furthermore, there is currently a lack of storage solutions needed to stabilize the grid. The development of storage solutions could possibly enable the production of additional offshore wind farms.

4.1.2 Energy Capture

The gathered empirical data in the area of energy capture, followed by an analysis of the empirical data and previously gathered literature have been presented in this chapter.

4.1.2.1 Empirical Data

Wind turbine manufacturers aim to create wind turbines that produce an increased amount of energy. This development results in higher towers and larger blades (Atlas Copco: H, 2017). The customers are asking for larger parts which makes it necessary to expand the plants and install equipment which enable heavy lifting (Plant A, 2017). Plant C (2017) believes that the blades will continue to increase in size whereas the design will not change that much. However, Plant D (2017) has recently developed the blade design for a new model. Furthermore, wind turbine manufacturers aim to use lighter material. As of today, GFRP is commonly used within blade manufacturing (Atlas Copco: H, 2017) but Plant B is currently looking into the possibility of using carbon fiber in order to reduce the number of layers and thus the weight of the blade (Plant B, 2017). However, Plant C (2017) is not planning to use carbon fiber at the moment as it is rather expensive. Plant D (2017) has planned to make changes regarding material but cannot share specific information as it is confidential.

4.1.2.2 Analysis

A main objective for wind turbine manufacturers is to increase the rated power of each wind turbine which results in continuously increased blade sizes. This is a fact not only for the offshore segment but also for the onshore segment as new onshore capacity will, to a high extent, consist of the repowering of older and smaller wind turbines. In 2012 the maximum length of rotor blades was limited to 70 meters but by the end of this decade, the maximum length is foreseen to reach 110 meters (Goch, Knapp and Härtig, 2012). Plant C believes that the design of the blade will more or less remain the same in the future whereas literature points towards a continuous development regarding the design of the blade. Sainz (2015) argues that wind turbines are designed and constantly developed to harness energy in less windy conditions, i.e. to produce energy from less intense wind speeds.

Both literature and empirical data support a trend towards the use of lighter materials within wind blade production. The increased use of carbon fiber is a discussed subject among the plants even though some plants do not see this as a possibility due to the high price of this material. However, changes regarding materials could be necessary in order to enable manufacturing of blades with an increased size and a larger energy capture (Kirkpatrick, 2011). As of today, wind turbines do not gather as much energy as they potentially could due to their size and the weight of the blades. A high weight leads to energy losses since more wind is needed in order to rotate
the blade. Furthermore, a high material flexibility within the blade increases the likelihood for the blade to warp and lose efficiency.

4.1.3 Cost and Reliability

The gathered empirical data in the area of the cost and reliability have been presented in this chapter, followed by an analysis of the area.

4.1.3.1 Empirical Data

At the moment cost reduction is more important than improving quality (Plant A, 2017; Plant C, 2017; Plant D, 2017). Plant A (2017) has historically focused on improving quality but has recently changed their focus to cost reduction since they perceive that their customers value cost more than quality. Plant C (2017) argues that the quality of the blades has reached a level which is good enough and is therefore focusing more on costs. Trends in regards to whether the customers focus more on quality or cost is highly dependent on the government and regulations and subsidies which wind companies can get for installing windmills (Company A:H, 2017). If the subsidies are reduced, the focus will most likely be on cost reduction. Due to the current reductions of subsidies in central Europe, the trends lean more towards a cost focus within companies in this region.

4.1.3.2 Analysis

Empirical data indicate that wind blade manufacturing plants within Europe have changed focus from quality improvement to cost reduction. This could be a result of reduced subsidies in the industry. Without government money, wind energy must reach the competitive threshold to be able to compete with conventional energy forms. Furthermore, Plant C (2017) argues that the quality of the blades has reached a level which is good enough and is though this argument explaining this change. However, studies investigating future challenges within the wind power industry highlights the need to increase the reliability and lifetime. To be able to increase the efficiency of the blade structures, it is necessary to not only focus on decreasing the costs but also focus on increasing its lifetime. Furthermore, the costs of failures related to mechanical components such as rotor blades are often underestimated. The failure frequency for rotor blades is approximately one every eighth year which may sound low but the average downtime is more than three days which results high reparation costs. Also, failures on the rotor blades are not only expensive but also a safety issue. In order to increase the lifetime of wind turbines it is crucial to develop lighter blades which are stronger and stiffer. It is the use of new and improved materials together with improved methods of life prediction and defect identification which are key to optimizing the lifetime of a wind turbine and its components.

In China the set focus has been reversed. The main focus within the wind power industry in China has for several years been large scale and high speed production (Yuan et al., 2015). This kind of production resulted in emerging problems including overcapacity, quality issues and lack of competency in key components. To deal with these issues, there is now a larger focus on transitioning to efficiency, quality and final utilization within the manufacturing of wind turbines. Both European and Chinese wind turbine manufacturing plants have recently changed
focus whereas European plants will focus more on cost reductions and Chinese plants on quality improvements. This focus may affect companies’ choices regarding tool purchases.

4.2 Wind Blade Manufacturing Process

The empirical data and analysis presented in this chapter include the different steps of the blade manufacturing process as well as the plant layout within blade manufacturing plants.

4.2.1 The Process

The gathered empirical data in the area of the blade manufacturing processes, has been presented in this chapter. Furthermore, an analysis of the different steps in the process has been conducted.

4.2.1.1 Empirical Data

During the visits to the four blade manufacturing plants, data regarding each step of the manufacturing process of wind blades was gathered. While there were some differences between the different plants, mainly based on the size of the plant and the model of blade which they produced, a clear series of similar steps could be identified within all plants. As can be seen in Figure 10, the blade manufacturing process can be divided into five steps; Step 1 - Molding, Step 2 - Gluing, Step 3 - Material removal, Step 4 - Finishing and Step 5 - Attachments.
The mapping of the different steps of the blade manufacturing process is a generalization of the processes that were identified within each manufacturing plant. Deviations within the presented steps in Figure 10 occurred within the different plants which will be further presented and explained. Furthermore, input given from the interview respondents in regards to the blade manufacturing processes is presented.

**Step 1 – Molding**

Different blade manufacturers use different manufacturing techniques for the molding of the blades (Atlas Copco:I, 2017). According to Atlas Copco:G (2017), some companies use a specific vacuum technique which uses vacuum pressure to remove most of the excess glue and material in order to produce a lighter blade. In this method, step two explained below is not performed as the injection process involve both blade halves which results in a unified blade. This technique also requires less material removal after the molding process. However, it is a more expensive process and it is also more time consuming. The molding process of Plant B and Plant D includes the application of dry glass fiber sheets, the application of wood layers and the injection of resin in the mold of the blade as well as the beam (Plant B, 2017; Plant D, 2017).
The glass fiber sheets at Plant D are currently spread out manually by operators (Plant D, 2017). The plant is not planning on implementing automation within this process as they believe it would be problematic due to high investment costs. The glass fiber sheets which are applied to the blade mold are cut by their supplier in accordance with the right measurements of the mold and ready for application. This means that the operators do not need to cut the pieces themselves, but use a pair of scissors to do so if any trimming is needed. The glass fiber sheets which are used are dry, however the plant also has wet glass fiber sheets which are used for older blade models where an older manufacturing method is used.

The molding process of Plant C is a bit different from the other visited plants as they claim to use an older molding method (Plant C, 2017). Due to this, their molding process does not include the application of a wood layer, just glass fiber and PVC. Furthermore, the beam of the blade is not built similarly to the other plants. The plant instead builds a long cone-formed beam that functions as the skeleton of the blade. This is molded by applying glass fiber sheets around a hydraulic cylinder form. They then glue the two blade halves onto this cone formed beam. The glass fiber sheets are cut automatically for the dimensions of the mold by a cutting machine which has been preprogrammed with the right dimensions. The application of glass fiber is a manual process at Plant C, wet glass fiber sheets are used which are spread out by operators. The glass fiber rolls are heavy and weigh around 20 kg. The removal of the plastic from the wet glass fiber sheets is also done manually, which is difficult. Plant C is interested in automated solutions for this process to improve the health of their operators as the manual process has resulted in back pain and back problems for the operators.

Plant B identifies the molding and injection process as the most critical process within the blade manufacturing due to its complexity and the large number of parameters (Plant B, 2017). The process takes them around 22-24 hours to conduct and it is the level of success of the process which determines the amount of work that needs to be done during the material removal process. The spreading of glass fiber sheets in Plant B is done automatically by a machine that rolls the sheets out in the mold. This has increased the ergonomic benefits for the operators of the plant as they do not have to carry the heavy rolls and do not have to work in a bent down position.

After the molding process of a couple of blades have been conducted, there is a need for maintenance of the blade molds. This requires operations such as great amounts of sanding of the blade mold. Plant C and Plant D maintain their blade molds every one to two weeks to keep them in good condition (Plant C, 2017; Plant D, 2017).

**Step 2 – Gluing**

The gluing process of Plant B and Plant D includes the application of the glue to the molded blade halves and the beam, and also the pressure applied onto the two blade halves (Plant B, 2017; Plant D, 2017). The application of glue is a manual process and is conducted by operators. At Plant C, the glue is automatically blended within a machine, before it is manually applied by operators (Plant C, 2017). The assembly of the two blade halves is done automatically, where the two blade halves which have been placed in a machine are pressured together for a period of time (Plant B, 2017; Plant C, 2017; Plant D, 2017). Plant C (2017) stated that this process
takes around 24 hours. Atlas Copco:G (2017) states that the gluing process and the heat treatment takes around 10-15 hours and claims that this is one of the most time consuming steps of the process, together with the material removal process.

In addition to the application of glue and pressure on the blades, the gluing process for Plant C also includes the injection of resin within the mold (Plant C, 2017). While the other visited plants inject resin during the molding process, here the injection of the resin is done at the same time as the gluing of the blade halves, which the plant mentions is an older method which they use. After the application of pressure, the gluing of the blade is inspected (Plant B, 2017; Plant C, 2017; Plant D, 2017). The inspection has to be made within approximately two hours, while the glue is still hot, since it is performed using an infrared light with heat sensor indicating where glue has been applied (Plant B, 2017; Plant C, 2017). If any defects are found, they are repaired. According to Plant B (2017), the reparation and material removal process of the blade can take between one day and up to a week depending on the number of defects on the blade.

**Step 3 – Material Removal**

The material removal process of all visited plants included the process of cutting excess glue, and grinding and sanding the blade smooth (Plant A, 2017; Plant B, 2017; Plant C, 2017; Plant D, 2017). The processes of Plant B and Plant D also included the application of glass fiber to the glued sides of the blade after the excess glue had been cut off and the sides had been ground (Plant B, 2017; Plant D, 2017). This was done in order to unify the blade into one consistent form. Atlas Copco:G (2017) states that it is mainly the different molding techniques among different companies which affect the trend of how material removal tools are used and how much time this process takes. Atlas Copco:G (2017) and Atlas Copco:I (2017) state that the material removal process is among the most time consuming steps of the blade manufacturing process. Furthermore, it is added that solutions such as semi-automated sanding robots will most likely reduce the time in this step (Atlas Copco:G, 2017). However, Atlas Copco:I (2017) states that the current sanding and grinding process of wind blade manufacturing is mostly manual.

The material removal process of Plant D is entirely manual (Plant D, 2017). The cutting of the excess glue from the sides of the blades is done by the operators and takes around 1 to 2 hours. The grinding and sanding of the blades is their most time consuming process and takes around 100 hours. The blades are placed in a vertical position during this process due to increased accessibility and ergonomic advantages for the operators during the sanding.

Plant C have designed their own semi-automatic solution for the sanding of the blades and are currently using a prototype of this design to sand the blades (Plant C, 2017). They have been using this solution for 1 year. The machine sands around 80 percent of the blade, where the rest needs to be sanded manually and has reduced the sanding time with 22 hours. Furthermore, the cutting process of Plant C is currently a manual process which they see as an area of development. The manual process is not good in regards to ergonomic and health aspects for the operators. This is a process that Plant C would like to automate.
**Step 4 – Finishing**

The process of applying a gelcoat and painting the blade is done manually at Plant B, Plant C and Plant D (Plant B, 2017; Plant C, 2017; Plant D, 2017). Plant D uses brushes for the application of gelcoat, while painting guns are used for application of paint (Plant D, 2017). Plant C (2017) states that they are in no need of automated solutions within this area. No information regarding this step could be retrieved from Plant A, due to restriction within the visit.

**Step 5 – Attachments**

The last step in the blade manufacturing process includes the grinding of the root end of the blade as well as the attachment of internal and external components to the blade (Plant B, 2017; Plant C, 2017; Plant D, 2017). Plant B uses an automated grinding device for sanding the root end of the blade, which had a grinder attached to a steel arm which moved in a circular pattern around the root end of the blade (Plant B, 2017). The grinding process of the root end of the blade at Plant C and Plant D are however manual (Plant C, 2017; Plant D, 2017). The attachment of components on the internal as well as the external surfaces of the blades varies between the different plants and is also dependent on the blade model and other factors.

**4.2.1.2 Analysis**

The identified pattern of steps within the blade manufacturing process during the plant visits was rather consistent to the presented data within current literature, as both included operations such as molding, gluing, material removal and finishing. Step 5 which was identified in the empirical data gathering has not been mentioned to its full extent in the literature. While the grinding of the root end of the blade is consistent to data found within literature, other external and internal attachments are not consistently mentioned. This can either indicate that this is not a common step among blade manufacturing, or that the step is executed differently within different plants. The variety of Step 5 within the visited plants was also noted and can thereby substantiate the indication of high variety of this step among different blade manufacturing plants.

As stated in the literature, the molding of the blade (Step 1) includes the application of materials such as dry glass fiber sheets, wood and in some cases carbon fiber to the mold, with the injection of resin to follow. Only Plant C deviated from this pattern by not including wood within the mold and by using wet glass fiber sheets in their molding process. The plant explained this deviation to be due to their outdated manufacturing method which was used on the smaller blades which they manufactured. It can therefore be concluded that this deviation is not a commonality while most molding processes include the application of dry glass fiber sheets, wood and in some cases carbon fiber to the mold, with the injection of resin to follow.

Plant C also deviates from the other visited plants as well as from the literature in regards to the gluing process (Step 2) of the blades, where the injection of resin in the mold is done simultaneously to the gluing. However the gluing process at all visited plants includes application of glue to the molded blade halves and to the beam, and also pressure applied onto the two blade halves.
The empirical data gathered in regards to the material removal process (Step 3) within blade manufacturing was highly consistent with the literature in the same area, where it can be concluded that operations such as cutting of excess material, grinding and sanding are all included here. The cutting and grinding operations were manually executed at all visited plants. Sanding was done manually in all plants except Plant C which used a semi-automatic solution. This step is considered as the most or one of the most time consuming parts of the blade manufacturing process and could take from 22 hours to 100 hours depending on the size of the blade, used tools and the type of molding technique used. All plants expressed a will to increase the efficiency within Step 3 and an interest to do so with automated solutions. This indicates that while all plants have not currently implemented automated solutions in this area, they are looking for such solutions to achieve an increased level of efficiency within Step 3.

The application of a gelcoat as well as paint on the blades after their sanding was executed at all plants from which this information could be retrieved, which is in accordance with what is found in the literature in regards to this area. This indicates that operations within Step 4 of the blade manufacturing process is consistent in theory as well as in practice.

The use of material removal tools within the blade manufacturing process has been identified in Step 1 for mold maintenance, Step 3 for material removal and Step 5 for grinding of the root end of the blade. However, both literature and gathered empirical data indicate that material removal tools are used within Step 3 to the highest extent in comparison to Step 1 and Step 5. Furthermore, all visited plants have indicated a will to develop their material removal solutions in Step 3 to become more efficient as well as productive. Therefore, it can be concluded that the development of material removal tools within Step 3 are considered as most crucial.

4.2.2 Plant Layout

The gathered empirical data regarding the layout of the plants has been presented in this chapter. Furthermore, an analysis of the empirical data together with the literature has been conducted.

4.2.2.1 Empirical Data

During the visits it was noted that the wind energy industry is quite new and has been expanding at a fast pace during recent years (Atlas Copco: H, 2017). The characterization of this young industry can for instance be seen within wind blade manufacturing where the processes are still at an early stage in their development and greatly characterized by manual labor (Plant A, 2017; Plant B, 2017; Plant C, 2017; Plant D, 2017). Due to this, Atlas Copco: H (2017) states that there is no specific flow line solution to be found within the manufacturing plants or any implementation of lean within its processes, as is often seen within other industries. However, even though there is currently no best practice for the implementation of lean within blade manufacturing, this is continuously improving and several actors are starting to implement flow lines and lean within their processes. An example of this is Plant A, which have implemented a line production where there previously was an island production system (Plant A, 2017). Plant C also has a flow line setup where the blades are moved from one area of the plant to another for different steps in the process (Plant C, 2017). They move the blades with cranes which are
attached to steel beams in the ceiling, where they move approximately one blade per day. The blades are moved twice between three of the manufacturing steps; between Step 1 and Step 2, and also between Step 2 and Step 3. The company states that they want to continue using a flow line layout in the plant. Similarly, Plant D has implemented a flow line where the blades are moved between Step 2 and Step 3 of the manufacturing process (Plant D, 2017). Here the blades are lifted with cranes onto a truck and transported to another part of the plant. Plant B had a similar setup where the blades were moved between Step 2 and Step 3 (Plant B, 2017).

In all of the visited plants, the blades are moved to a separated area of the plant for the material removal process (Plant A, 2017; Plant B, 2017; Plant C, 2017; Plant D, 2017). This is done in order to isolate the spreading of dust within the entire plant. Within Plant B, Plant C and Plant D it was observed that between three to four blades were placed in this isolated material removal area at the same time. The blades which are placed in the material removal area are not further moved around within this area, but placed at a certain position throughout the entire step. This means that all material removal operations on a certain blade are done at the position which the blade was originally placed. The operators and tools needed to adapt to the position of the blade within Step 3 of the material removal process, not the other way around.

Furthermore, blade manufacturing plants have an order to production setup, meaning that a product is only produced when an order has been made by a customer (Atlas Copco:G, 2017). The blades are never produced in advance and placed in stock.

4.2.2.2 Analysis

Literature states that actors within wind blade manufacturing have implemented or are in the process of implementing streamlines and production lines in their manufacturing process, where the blades are moved between different steps of the process (Gardinger, 2016; Vestas, 2015). Similarly, empirical data from the visited plants show that the blades were moved one to two times during the process, whereas this was mainly done between the gluing and the material removal steps. This can be compared to the literature where the transportation between the different steps was explained as more frequent. However, even though flow lines were identified at all visited plants, Atlas Copco:H (2017) argues that no best practice can be found within this area due to the early stage of development of the blade manufacturing processes. This can indicate that while many blade manufacturers have implemented or are in the process of implementing a flow line production within their blade manufacturing, this is not yet an optimized solution, where continuous development is being done.

Furthermore it can be concluded that there are several different ways of transporting the blades within the manufacturing plant. According to literature, mobile molds are used for this operation (Gardinger, 2016). However, empirical data shows that in some cases the blades are lifted with cranes onto a truck and transported to another part of the plant, where in other they are moved with cranes which are attached to steel beams in the ceiling of the plant (Plant B, 2017; Plant C, 2017; Plant D, 2017).

Empirical data further states that the blades are placed in a stationed position within an isolated part of the plant when moved to Step 3 the material removal step. This means that while there
are around three to four blades placed in this area at the same time, the operators and tools need to adapt to the position of the blades within the material removal process, not the other way around.

4.3 Ergonomics

The gathered empirical data in the area of ergonomics, which includes the importance of ergonomics, vibrations as well as dust and static electricity, has been presented in this chapter. Furthermore, an analysis of these areas has been conducted.

4.3.1 The Importance of Ergonomics

An analysis of presented empirical data as well as literature within the importance of ergonomics have been presented in this chapter.

4.3.1.1 Empirics

All visited plants in this study did underline the importance of ergonomic aspects (Plant A, 2017; Plant B, 2017; Plant C, 2017; Plant D, 2017). The importance of ergonomics can be seen as a growing trend (Company B, 2017). Plant C argues that ergonomics is rather important in order enable good health conditions for the operators during the employment and also in the future (Plant C, 2017). Thus, Plant C tries to find new solutions such as automated solutions in order to increase ergonomic and health conditions for their workers. For instance, they are currently testing a prototype; a semi-automated sanding machine which was initially built to improve the health-aspects for the operators. Furthermore, Plant C is interested in automating other processes such as the application of glass fiber sheets and the cutting of excess glue in order to improve the health of their operators. Among the four visited plants, Plant C valued ergonomics the highest. This is reflected by the quantitative questions that were asked during the plant visits but also the observations made regarding operating positions among the operators of the plants. The operators working at Plant B (2017) had an operator range of below knee height to above head height which could be considered as uncomfortable and demanding positions. Plant D (2017) operators had a working position from knee height to shoulder height whereas Plant C (2017) operators worked from waist height to shoulder height. Furthermore, one observation made on Plant B (2017) was that it is common to remove the handles of the grinders. Plant B removes the handles of the grinders since it is easier to press against the grinding head than to press against the handle. Further, if the operator presses too hard, the tool breaks as the plate gets heated and melts against the explosion protection shield.

Company C (2017) argues that ergonomic aspects are relevant and considered as important within factories in Europe, especially in the wind industry since it is partly funded with government money. Ergonomic aspect limits operators to work with material removal tools for more than four hours a day which makes it necessary to rotate between different stations (Plant D, 2017). However, Asia or other parts of the world do not share this focus. In many cultures employers do not value the health and safety of their employees to the same extent as in the Nordic countries (Atlas Copco:A, 2017; Company B, 2017; Company C, 2017). The employers in for example Asia know that their operators could easily be replaced and therefore do not
consider the health of the operators. Furthermore, Company C (2017) argues that the working conditions can differ from one plant to another based on its geographical location and the culture. Even though the plants are a part of the same company, and are theoretically built to function similarly, great differences can occur in practice. When production starts it is hard to control that set rules are followed which in theory makes the work procedures the same but in practice, most likely, different.

One source from Atlas Copco argues that there has been a big change in demand for ergonomic tools during recent years which has led Atlas Copco to focus more on ergonomics. (Atlas Copco:G, 2017). However, another source claims that it is hard to know to what extent Atlas Copco’s customers really care about ergonomics (Atlas Copco:H, 2017). It is hard to determine whether customers buy certain tools due to ergonomic aspects or due to other attributes such as productivity. For instance, Plant D (2017) is interested in ergonomically better solutions but mainly in manual tools which are bigger and more efficient.

4.3.1.2 Analysis

The wind segment is growing along with the number of workers enrolled in the wind energy sector whereas safety and health aspects become a prime concern. Wind blade operators are exposed to a number of hazards whereas injuries due to manual handling such as heavy lifting, injuries due to machinery usage, electrical hazards, noise, vibrations and exposure to hazardous chemicals are the most discussed.

All four visited manufacturing plants in Europe agree on the importance of ergonomic aspects. Empiric data supports that ergonomics is important in order to enable good health conditions for the operators during the employment and also in the future. However, it is hard to clarify to what extent companies really care about ergonomics in regards to health aspects for their workers. It is hard to distinguish if a company buys a certain tool due to ergonomic aspects or due to other reasons such as increased productivity. Furthermore, the importance of sustaining good health conditions among workers can differ from one plant to another and become less important in regions where workers can easily be replaced.

Literature supports the fact that ergonomics is important in order to keep the workers healthy and reduce work related injuries. Injury rates for grinding operations are extremely high and losing trained employees due to injuries affect the overall performance of the company. An injured worker results in both direct and indirect costs for the company. Thus, proactive ergonomic interventions are sometimes necessary in order to support organizational goals such as profitability. Furthermore, literature supports other ergonomic benefits such as improved quality and productivity. The importance of ergonomics in regards to improved quality and productivity has been well documented, although generally not well recognized. For instance, grinding tools are often very heavy and workers often need to take breaks in order to manage their heavy duties which affects the productivity rate. Furthermore, tiredness among workers can lead to an insufficient work performance which affects the quality rate. Atlas Copco (2017) argues that ergonomics can improve the quality of a product with as much as 30 percent.
Even though all visited plants have pointed out the importance of ergonomic aspects, we perceive that the mindset regarding this subject differed significantly among the factories, despite the fact that they are all located in Europe. For instance, Plant D (2017) are interested in ergonomically better solutions but mainly in manual tools which are bigger and more efficient while Plant C (2017) actively tries to find new solutions such as automated solutions in order to increase ergonomic and health conditions for their workers.

4.3.2 Vibrations

An analysis of presented empirical data as well as literature within vibrations has been presented in this chapter.

4.3.2.1 Empirical Data

During the grinding and sanding process the operator is exposed to a lot of vibration which can cause “white fingers”, a disease reducing the blood supply and the sensitivity in the fingers (Atlas Copco:H, 2017). Due to these risks, there are regulations in European countries that restricts the amount of time and the level of vibrations that each worker should receive during a day. The white finger illness is now a known phenomenon, where most employers consider vibration levels to a higher extent when buying tools (Company B, 2017). Furthermore, companies try to find solutions to reduce the level of vibrations in different ways (Atlas Copco:F, 2017). For instance, a Swedish company within the foundry industry has implemented a system, which prevents operators from working with certain machinery for more than a set number of hours. It is important for employers to prevent the white finger illness since it shortens the lifetime of the operator (Atlas Copco:H, 2017). Also, the operators need to be able to work at the same productivity rate during the entire shift in order to keep up a high quality level. This could be hard for operators with a reduced working capacity due to lack of sensitivity in their fingers and tiredness. However, in central Europe where the trend is to use short-term operators, ergonomics becomes less important. Ergonomics is not a focus area when operators can easily be replaced. Moreover, high-tech industries such as the aerospace industry focus more on reducing the vibration level than other industries such as the foundry industry.

The amount of vibrations can vary based on the brand of the grinder and the abrasives used on the grinder (Atlas Copco:H, 2017; Company B, 2017). It is important to look at the total system (Company B, 2017). The machine itself can give a low vibration and noise level but while combined with a support plate and an unsuitable choice of abrasives, these levels can be significantly increased. Thus, it is important to measure the vibration level on the total system in a real use environment in order to get realistic results. All visited plants in this study have highlighted the importance of keeping vibration levels down. Both Plant C and Plant D use an external medical company to measure actual vibration exposure rates among workers once a year (Plant C, 2017; Plant D, 2017).

Both tool and abrasive manufacturers are working on reducing the vibration level on their products (Company B, 2017). For instance, Atlas Copco uses special features such as an auto balancer to reduce the amount of vibrations on their tools (Atlas Copco:H, 2017). Abrasives
that generate a low vibration level are often more expensive and marked with a symbol indicating a low vibration level (Company B, 2017).

4.3.2.2 Analysis

The white finger illness caused by vibrations is now a known phenomenon and most employers care more about vibration levels when buying tools. It is important for employers to prevent the white finger illness since it shortens the working lifetime of the operators and may prevent operators from maintaining a high and consistent productivity rate. Furthermore, in 2005 regulations regarding hand-arm vibration was introduced in the European Union, introducing an exposure action value of 2.5 m/s² indicating when employers need to take technical and organizational measures to reduce exposure (HSE, 2017). The regulation also introduced an exposure limit value of 5.0 m/s² which should not be exceeded. The regulations require employers to make a risk assessment and decide what an operator’s exposure level is likely to be. During this process, monitoring may be necessary in order to understand how long workers use particular tools in a typical day or week. However, continuous monitoring is not required nor recommended, unless there are specific circumstances.

Literature and empirical data indicate that it is important to measure the vibration level in a real use environment and to look at the total system in order to get realistic results. The machine itself can give a low vibration and noise level but these levels can increase significantly when combined with other parts of the system such as support plates and abrasives. Furthermore, the vibration levels may vary over time depending on the condition of the tool. The wear and imbalance within the tool can make a difference as well as how the machine is handled and what amount of pressure that is applied. Also, variations can occur related to operating angle or used materials. Such factors may lead to significant deviations between the values stated in the data sheet for a specific product and actual values. Therefore, vibration levels should not be measured with a device only measuring time combined with the vibration level given in the data sheet for a specific product.

All visited plants in this study have highlighted the importance of keeping vibration levels down. Plant C and Plant D both use an external medical company, once a year, in order to measure actual vibration exposure rates among workers (Plant C, 2017; Plant D, 2017). However, it is hard to determine whether the companies measure vibration levels due to regulatory requirements or because they care about the health of their employees. As for ergonomics in general, the extent of which companies care about vibration levels varies between different plants and regions.
4.3.3 Dust and Static Electricity

An analysis of presented empirical data as well as literature within dust and static electricity has been presented in this chapter.

4.3.3.1 Empirical Data

Dust generated from grinding and sanding operations of Glass Fiber Reinforced Polymer (GFRP) is a problem when appearing in direct contact with the lungs or with the skin of the operator (Plant A, 2017; Atlas Copco:H, 2017). At the moment there is no clear knowledge of the damage that the dust can have on people’s health and therefore there is a need for solutions where direct contact could be avoided, for example covered solutions (Atlas Copco:H, 2017).

There is a split perception of whether or not the current dust extraction solutions on the machines need to be further developed. Some argue that the production environment of the material removal process requires a central exhaust system. This means that the extraction of the machine itself is less important and sufficient as it is today (Atlas Copco:G, 2017). However, others believe that there is potential for development in this area and a need for better machine-level extraction solutions. Plant C uses a central vacuum suction system and they do not consider dust to be a current problem within the plant.

Dust from GFRP material is considered as aggressive, and is not only harmful for the human body but also for the tools (Plant B, 2017). Plant B modifies their tools locally in order to create solutions with a longer lifetime. For example, the spot suction kit for fiber disc, used with the Atlas Copco Angle Grinder LSV38, is modified in order to receive a longer life time. Atlas Copco has designed a bend on the suction kit to make it more ergonomic as it leaves the hose in a more convenient position for the operator. However, the friction becomes too high and the part is destroyed after approximately one week of use. Plant B orders this part locally, with a straight design, and replaces it onto the tools. This design has a lifetime which is approximately ten times longer. Furthermore, grinding and sanding operators working with GFRP need to use tools where the dust extraction module is located externally, on the outside of the tool (Plant B, 2017; Plant C, 2017). The dust extraction module cannot be in contact with the machinery of the tool since the dust will destroy the tool from the inside. To extend the life time it is important to keep the dust extraction module separated from critical parts. The dust extraction module is cheaper to replace.

One source argues that static electricity created during grinding and polishing operations is problematic and that there is demand for grounded tools (Atlas Copco:F, 2017). However, none of the visited sites considered static electricity as a current problem as a cable is attached to the blades which grounds them (Plant A, 2017; Plant B, 2017; Plant C, 2017; Plant D, 2017; Atlas Copco:G, 2017). Previously the blades were not grounded and static electricity was therefore considered a problem. However, in some countries this might still be a problem.
4.3.3.2 Analysis

Dust generated from material removal operations of GFRP is a problem when appearing in direct contact with the lungs or with the skin of the operator. Empirical data indicate that there is no clear knowledge of the damage that the dust can have on people’s health and therefore there is a need for solutions where direct contact could be avoided, for example covered solutions. However, studies investigating finishing processes involving repairing defects and sanding down imperfections have revealed skin related issues among other health concerns. Problems such as the stopping of menstrual cycles, severe headaches, nosebleeds and dizziness, as well as throat and eye irritation have been reported. These symptoms occurred even though all workers wore gloves, overalls and safety glasses. The chemicals penetrated through the protective equipment and were not sufficient to prevent these symptoms.

The European Agency for Safety and Health at Work (2013) suggest an increased automation of manufacturing processes; workers being designed out of the manufacturing process as much as possible through the use of robotics in order to increase the safety and health conditions among workers within wind turbine manufacturing. This is increasingly important, as the wind turbine systems get larger. However, not all companies have the economical prerequisites to make such alterations.

There is a split perception of whether or not the extraction solutions on the machines today need to be further developed or not. Wind blade manufacturing plants which use a well-functioning central vacuum suction system may not consider dust to be a problem while other plants not using these kinds of solutions depend on the dust extraction kit supplied with the tool. Dust from GFRP is aggressive and is not only harmful for the human body but also for the tool (Plant B, 2017). In order to extend the lifetime of the tool it is important to keep the dust extraction module separated from critical parts within the tool. The dust extraction module must be located externally, otherwise the dust will destroy the tool from the inside and the entire machinery will break.

Static electricity is no longer considered as a problem within blade manufacturing plants in Europe since the blades are grounded (Plant A, 2017; Plant B, 2017; Plant C, 2017; Plant D, 2017).
4.4 Material Removal Solutions

Material removal solutions were mainly used within Step 3 of the blade manufacturing process for the cutting, grinding and sanding of the blade but were also used within Step 1 for mold maintenance and Step 5 for grinding and sanding the root end of the blade. However, Step 3 has been identified as having the most time consuming material removal process. Furthermore, three out of the four visited plants, namely Plant B, Plant C and Plant D, have a main focus on finding solutions to reduce the time and cost of the material removal process within Step 3 (Plant B, 2017; Plant C, 2017; Plant D, 2017). The main focus was therefore the material removal solutions which were used by the visited plants within Step 3. As can be seen in the current state map of Step 3 in Figure 11, both manual and semi-automated solutions were found during the plant visits.

Step 3 – Material Removal; Current state

![Diagram showing steps of material removal solutions](image)

Figure 11. Shows the current state of the tools used in Step 3 of the blade manufacturing process, and their level of automation.

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4.4.1 Manual Solutions

The gathered empirical data regarding manual material removal solutions within wind blade manufacturing has been presented in this chapter. Furthermore, an analysis of this areas has been conducted.

4.4.1.1 Empirical Data

As previously mentioned the material removal process includes cutting, grinding and sanding operations. The cutting of excess glue from the blades was manually done within all plants, using hand held tools. All cutting tools used within the visited plants are presented in Table 4. Plant C uses the Atlas Copco LCS10 for cutting the excess glue (Plant C, 2017). Plant D currently uses cutters from the brand Dynabrade, but have previously been using the Atlas Copco GTG21 with a diamond blade (Plant D, 2017). Plant D (2017) states that there are two main reasons for the switch to Dynabrade. Firstly, the Dynabrade tool has a lower price. Secondly, the plant and its employees are more familiar with the Dynabrade tools, meaning that they have more knowledge of the structure and functionality of the tool and are therefore able to repair and maintain the tools themselves. The tools from Atlas Copco which are most commonly used for the cutting of excess glue are the LCS cutters (Atlas Copco:G, 2017; Atlas Copco:J, 2017).

Table 4. Shows tools used by the visited plants within their cutting process.

<table>
<thead>
<tr>
<th>CUTTERS</th>
<th>Plant A</th>
<th>Plant B</th>
<th>Plant C</th>
<th>Plant D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brand</td>
<td>-</td>
<td>-</td>
<td>Atlas Copco</td>
<td>Dynabrade</td>
</tr>
<tr>
<td>Type</td>
<td>-</td>
<td>Pneumatic</td>
<td>Pneumatic</td>
<td>Pneumatic</td>
</tr>
<tr>
<td>Notes</td>
<td>-</td>
<td>-</td>
<td>Model: LCS10</td>
<td>Lower price and knowledge of tool structure and functionality</td>
</tr>
</tbody>
</table>

The polishing of the blades includes grinding and sanding operations. As can be seen in Table 5, three out of four visited plants use pneumatic tools for this process, while Plant A uses electric tools (Plant A, 2017; Plant B, 2017; Plant C, 2017; Plant D, 2017). Similarly, all visited plants except for Plant A use Atlas Copco’s LSV38 during their polishing process. According to Atlas Copco:G (2017) and Atlas Copco:H (2017), it is the LSV38 which is the most common Atlas Copco tool to be used for grinding the sides of the blade after the excess glue has been cut off, where Atlas Copco:H (2017) adds that diamond blades are many times used with the tool to cut the material. Atlas Copco:J (2017) further states that the LSV 39, which is a developed version of the LSV 38 is currently being used by a wind blade manufacturing plant in the American market.
Table 5. Shows tools used by the visited plants within the polishing process.

<table>
<thead>
<tr>
<th>GRINDERS/ SANDERS</th>
<th>Plant A</th>
<th>Plant B</th>
<th>Plant C</th>
<th>Plant D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Brand</strong></td>
<td>-</td>
<td>Atlas Copco</td>
<td>Atlas Copco</td>
<td>Atlas Copco</td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td>Electric</td>
<td>Pneumatic</td>
<td>Pneumatic</td>
<td>Pneumatic</td>
</tr>
<tr>
<td><strong>Notes</strong></td>
<td>Electric tools are used because of lower price</td>
<td>Model: LSV38</td>
<td>Model: 3650</td>
<td>Knowledge of tool structure and functionality</td>
</tr>
</tbody>
</table>

Previously, many plants used orbital sanders for the polishing of the blades, but it is no longer that common (Atlas Copco: G, 2017). Other sanders which could be used for this purpose are the Atlas Copco LSO and LST series, however these are also not considered as commonly used within blade manufacturing (Atlas Copco: H, 2017). A common challenge with sanders within blade manufacturing is that they are too powerful and remove too much material. An example of this is the GTG25, where such feedback has been received.

Plant D uses both the Atlas Copco LSV38 grinder as well as grinders and sanders from Dynabrade. The used tools are all hand held and manual (Plant D, 2017). Also in the case of the sanders and grinders, Plant D (2017) state that they use tools from Dynabrade due to their technical knowledge of the Dynabrade tools, where they can repair and rebuild the tools within the plant when necessary. In addition to these tools, the plant is currently testing a tool called Flex-trim. It is a manual tool that uses a sanding brush. During use, the sanding brush leans on the surface of the blade and is attached to a long handle which the operator can hold in a standing position. It is not possible to lift the tool to sand an object in a vertical position, only in a horizontal position. The sanding brush of the tool is built with rows of “regular” sanding paper and brushes, placed in every other layer. The plant is testing this with the purpose to reduce the sanding time of the polishing process and have learnt that it decreases the time for polishing with 50 percent. However, as Plant D produces very large blades, they prefer to position the blades vertically in order to be able to reach the entire surface. It is not possible to use the Flex-trim solution with this type of positioning. Plant D found the Flex-trim tool by searching for efficient sanding solutions on Google. Furthermore, Plant D believes that while the trend of automation within material removal is increasing, it is not applicable to the large blades which the plant produces. They argue that a manual tool which is larger and weighs less would be preferable. The manual solution will thereby increase the efficiency as well as the ergonomics for the operators.

Most visited plants use pneumatic tools during the material removal process of the blades (Plant B, 2017; Plant C, 2017; Plant D, 2017). When buying tools for large productions and plants, price in relation to performance becomes increasingly important (Company B, 2017). Parameters such as tool cost, operation time, hourly cost for the operator and time for replacement of abrasives should be taken into account when calculating cost per produced item.
In this way it is possible to calculate whether it is economically beneficial to buy a product which is more expensive but for instance delivers a higher efficiency and has a longer lifetime. However, it is common that customers choose to buy cheaper alternatives even though such calculations show that a more expensive tool will be more economically beneficial in the long run. With regards to the wind turbine industry, Atlas Copco:H (2017) argues that the tendency to pay more for quality tools such as handheld grinders from Atlas Copco is decreasing. Plant A uses electrical grinders which are much cheaper in comparison to pneumatic tools, even though electrical tools have significantly shorter lifespans and get torn out within a month of usage within blade manufacturing. Plant A simply believe that the tools from Atlas Copco are too high priced. Plant A uses electric tools even though the use of electric tools in the blade manufacturing environment could be problematic and increase risks in regards to safety at the plant. This is mainly due to the cables of such tool which could cause the operator an electric shock if it is accidentally cut off. Furthermore, according to Atlas Copco:H (2017), the most requested task by customers in regards to pneumatic tool is to reduce the energy consumption of the tools which is due to its air consumption, as they believe it is too expensive.

Atlas Copco:F (2017) contradicts this statement by arguing that electric tools are not competing with pneumatic tools. The electric tools are heavier with a shorter lifespan and are believed to only attract smaller manufacturers who want to keep down their investment costs (Atlas Copco:G, 2017; Company F, 2017). Furthermore, the electric tools are louder and have a higher degree of vibrations. The pneumatic tools however, are stronger, have a significantly longer lifespan, lower sound level as well as vibration level. In accordance to Atlas Copco:F (2017), Company F (2017) states that electric tools are more often used by smaller workshops which have chosen not to invest in air driven tools, mainly due to its high costs. However, electric tools are rarely used in the wind industry due to its tough environment which would leave the electric tools with rather short life spans.

Atlas Copco has recently developed a tool together with a Danish company working with abrasives (Atlas Copco:G, 2017). The tool is manually operated and differentiates itself from regular material removal tools such as sanders by not using a sanding blade, but a sanding brush. The sanding brush is built in a circular form where several rows of brushes are attached on the outside of a cylindrical metal form. Each row consists of a layer of sanding paper and a layer of a brush, as can be seen in Figure 12.

![Figure 12. Shows a sanding brush (Scandicsand ApS, 2017).](image)
The hand held sand brush tool is claimed to have five times higher efficiency than a regular sander which decreases the time consumption of the material removal process (Atlas Copco:G, 2017). Furthermore, the hand held sand brush tool has eliminated the vibrations, which is a common problem among material removal tools. By doing so, health problems caused by vibrations such as white fingers among operators can be prevented. Company C (2017) argues that one can easily buy a cheaper sanding tool from a hardware store, but that the quality of it would not last and its lifecycle would be rather short. This hand held sand brush tool has been tested in rather tough conditions and still works. While it might be more expensive that the hardware tools, the quality is significantly higher, it has more features and a longer lifecycle. Atlas Copco has currently sold 60 of these tools through their sales at the Danish abrasive company, however the tools in currently not published in the Atlas Copco catalogue.

Atlas Copco is also currently developing another manual sanding tool, similar to the Flex Trim solution described earlier, together with the same company (Atlas Copco:G, 2017; Company C, 2017). The tool uses a sanding brush which leans on the surface of a workpiece and is attached to a long handle which the operator can hold in a standing position. The tool cannot be held in some angles, for example an operator cannot hold it up in the air, whereas it can only be used in a horizontal position. The sanding brush of the tool is built with rows of “regular” sanding paper and brushes, placed in every other layer. Currently the tool is only a prototype and is being tested. Some challenges with the tool have been that it jumps a lot if not enough weight is applied by the operator, which in turn leaves marks on the workpiece. This is an area which is to be solved in order for all operators to be able to handle the machine regardless of their size and/or strength. This can either be done by adding more weight on the tool or by finding the right combination of the rpm of the tool and the used abrasives. This tool is currently being tested at one blade manufacturing plant.

4.4.1.2 Analysis

According to literature, the material removal process within blade manufacturing involves tools for cutting of the excess glue from the blades, grinding the edges and sanding the blade smooth. To be able to perform these lines of actions, tools such as circular cutters, grinders and sanders are needed. These actions as well as the needed tools for this are confirmed by the empirical data. In the literature Atlas Copco (2015) states that the most common tools used within the wind blade manufacturing from their product range are tools from the LSV, GTG, LCS and LST/LSO series. This can be partly confirmed by empirical data which shows that tools from the LSV, GTG and LCS series were used or had previously been used by the visited plants. The LSV 38 grinder was used at three of the four visited plants, which can indicate that it is a commonly used tool within the material removal process of blade manufacturing. Furthermore, contradictingly to found literature, the LST and LSO series were considered as not commonly used for the sanding of blades in the gathered empirical data (Atlas Copco:G, 2017; Atlas Copco:H, 2017).

Empirical data shows that manual labor, and in turn the use of manual tools, are most common within blade manufacturing, as all plants used manual tools during cutting and grinding operations (Plant A, 2017; Plant B, 2017; Plant D, 2017). Only Plant C used the LCS 10 tool
from Atlas Copco for the cutting off excess glue, while Plant D had previously used the GTG 21 with a diamond blade to cut the excess glue but had later changed to tools from Dynabrade. Plant B rebuilds and uses grinders from Chicago Pneumatic as cutters for their cutting operations. The lack of usage of Atlas Copco tools during the cutting operations could indicate that they are not optimal for the specific operation of cutting excess glue from blades. However, this could also be a price issue.

As mentioned, grinding was a manual operation at all visited plants, while sanding was a manual operation within all visited plants except for Plant C. While Plant B, Plant C and Plant D use the LSV 38, Plant C and Plant D also use manual grinders and sanders from a brand called Dynabrade. While the use of tools from Dynabrade is explained by having greater knowledge of the tool and a better prize, no indications or conclusions can be made in regards to its benefits or disadvantages in regards to grinding and sanding tools from Atlas Copco.

While all visited plants use pneumatic manual tools, Plant A uses electrical manual tools due to their lower investment costs. Empirical data states that it is common to buy cheaper alternatives even though calculations show that a more expensive pneumatic tool will be more economically beneficial in the long run (Company B, 2017). However it is further argued that this behavior is less common within blade manufacturing and more common at smaller companies and workshops, whereas the use of electric tools in the blade manufacturing environment could be problematic due to their short lifespan, bad ergonomic conditions and their increased risks in regards to safety at the plant (Atlas Copco:F, 2017; Atlas Copco:G, 2017; Atlas Copco:H, 2017; Company F, 2017). Therefore it can be concluded that while Plant A have chosen to use electrical tools within their material removal process in blade manufacturing, it is not a common phenomenon among blade manufacturers due to their lack of applicability to the industry as well as lack of safety.

While Plant A, Plant B and Plant C are looking to increase the level of automation within their material removal process, Plant D believes that automation is not applicable to the large blades which the plant produces. They argue that a manual tool which is larger and can increase the efficiency and productivity of the sanding process and which weighs less for increased operator ergonomics would be preferable. Empirical data also shows that Atlas Copco has developed and are continuously developing material removal solutions to match this criteria. The hand held sand brush tool which has been developed is claimed to have five times higher efficiency than a regular sander. It also eliminates the vibrations, and thereby increases the ergonomic aspects of the tool in comparison to a regular sander. This can indicate that Atlas Copco have identified the need for more efficient manual tools, with improved ergonomics within the material removal process of blade manufacturing.

Based on literature as well as empirical data it can be concluded that most development within manual material removal tools is being done in the area of sanding. Improvements are mainly needed in the area of efficiency, and in turn improved productivity as well as improved ergonomic aspects. It is therefore concluded that an improved manual sanding tool should be more efficient to reduce the time it takes for sanding a blade, it should improve ergonomic aspects in regards to vibrations but also weight as well as improved operating position which has according to empirical data been explained as the level between shoulder and knee length.
4.4.2 Automated Solutions

The gathered empirical data regarding automation and automated material removal solutions within wind blade manufacturing has been presented in this chapter. Furthermore, an analysis of this areas has been conducted.

4.4.2.1 Empirical Data

Optimization through automation within blade manufacturing has been identified as an increasing trend, where robotic solutions are being used to a higher extent in the material removal process (Atlas Copco:G, 2017). Atlas Copco:G (2017) suggests that the trend within material removal tools such as sanders, grinders and cutters are moving towards automation or semi-automation. The three main factors that have driven this trend are time, quality and cost (Atlas Copco:G, 2017; Plant A, 2017; Plant B, 2017; Plant C, 2017; Plant D, 2017). The material removal process has been identified as the most or one of the most time consuming processes, where all visited blade manufacturing plants are aiming towards lowering the time spent on this specific process (Plant A, 2017; Plant B, 2017; Plant C, 2017; Plant D, 2017).

Atlas Copco:H (2017) suggests that automated grinding and sanding would create a leaner surface and provide higher quality blades. A significant challenge with having manual labor within the material removal process is that the quality of the outcome of the process is highly dependent on the skill of the operator who is operating the material removal tool. This means that the quality and outcome of this process can vary greatly depending on the skill level of the operator conducting the operation. Having manual labor also creates the risk of defects within the process caused by human errors. For example Atlas Copco:H (2017) suggests that if an operator is tired or not attentive during their work there is an increased risk for cracks or splintering occurring during the material process of the blades, whereas the reparation of the occurred defects is rather time consuming. The variety of skill level among the operators of a plant as well as the risk of human error during manual labor causes an inconsistency in quality in the production of the blades. This is an aspect which blade manufacturers want to overcome, which could be done through the implementation of automation within this process.

According to Atlas Copco:H (2017), a fully automated process would preferably transport the blade from the molding process directly into a machine with implemented dust extraction to grind the blade from all sides. This type of solution would not only be beneficial in regards to efficiency, quality and cost but would also improve the health conditions for operators within the plants. However, the full automation of the material removal process is met with doubt among the visited plants. While the implementation of some degree of automation within the material removal process of blade manufacturing has been identified as a trend within all visited plants, they also seem to agree upon the fact that this process cannot be fully automated (Plant A, 2017; Plant B, 2017; Plant C, 2017; Plant D, 2017). Plant B (2017) believe that a fully automated solution would be too difficult and expensive to implement, due to the great variety of blades as well as the great variety of problems and defects that might occur on the different blades. Plant B has therefore been looking into implementing semi-automated solutions. Company C (2017) states that material removal tools with a certain level of automation are more attractive to the blade manufacturing industry rather than manually steered tools, as the
automated machines deliver a unified sanding result in regards to quality which is what the industry is looking for.

Plant D (2017) state that since the plant produces rather large blades, it is believed that the application of automated solutions within the material removal process would be difficult. They are interested in solutions that can be applied to the blades when in a vertical (not flat) position and are more interested in manual solutions with tools which are larger and more efficient, but also ergonomically beneficial for the operators. However it is added that if an automated solution which can be applied to large blades was developed, they would of course be interested in getting it. In general, they believe that automatic processes would help then decrease the time for their different manual processes, where the optimization of their different processes is currently their main concern. The material removal process of Plant A is currently manual where no automated solutions have been applied (Plant A, 2017). Plant A mainly claims that this is because they do not know of any other solutions, but are interested in investigating automated solutions with the main purpose of decreasing costs. Plant C (2017) which have designed their own semi-automatic solution for the sanding of the blades state that the semi-automatic sander will most likely never be fully automatic. The plant thinks that there will always be a need for an operator to check if everything is working well and to adjust the machine. Another aspect for not having a fully automated machine is the safety aspect. The benefits of the semi-automatic sander is that it has increased the quality of the blade, it has reduced the polishing time with 22 hours and it has improved the ergonomic aspects such as vibrations, dust and uncomfortable operating positions for operators. The solution was initially built to improve the health-aspects for the operators.

Company C (2017) suggests that while the trend towards fully automatic and semi-automatic machines within blade manufacturing will increase within Europe and USA, this will not apply to countries which are considered to have cheap labor. Due to the cheap labor, Company C (2017) states that it is the manual tools which will most likely grow. However, as the wages within these countries increase, they will also move towards more automated solutions. This statement is partly contradicted by Atlas Copco:G (2017) who argues that only 2 percent of the value of an entire wind turbine goes to paying the operators’ salaries, meaning that the switch to automation within the material removal process is mainly due to increased quality and efficiency, whereas salary costs are not as important. However, a problem with the implementation of automated machines within manufacturing is that the operators understand that it will reduce the need for labor (Company C, 2017). This causes an environment where operators claim that the machines do not work correctly or decrease their productivity even if this is not the case, in order to avoid its full implementation within their plant and in turn keep their job.

Company C (2017) argues that there are a lot of potential application areas for semi-automatic sanders, whereas they are now mainly cost and quality efficient for sanding large workpieces with contours that do not only have a plain and straight surface. Atlas Copco does currently not offer automated or semi-automated tools within their material removal product segment. Atlas Copco:G (2017) therefore believes that the introduction of this will be a challenge for the company.
Atlas Copco:G (2017) mentions that one blade manufacturing company is currently using an automated solution in the form of material removal robots which are enabled to move alongside a blade due to an installed rail system at a specific part of the plant. However this type of system is seen as “outdated” and can only sand around 50 percent of a blade automatically, whereas the rest needs to be sanded manually. According to Atlas Copco:G (2017), mobile material removal robots and solutions are more relevant to the blade manufacturing industry and it is believed that companies with stationary solutions will be switching to mobile solutions. This is mainly due to the increasing size of the blades where Atlas Copco:G (2017) and Company C (2017) suggest that moving the blades between different stations within the plant will not be feasible and therefore the machine needs to adapt to the position of the blade. Furthermore, Company C (2017) states that with the increasing size of the blades and the difficulties of transportation within the plants, a fully automatic solution where the blade is placed at a certain position and processed by an automated material removal machine based on sensors, would not be applicable. It is important that the material removal process functions correctly in order to achieve a high quality result, whereas the slightest mistake could create a need for reparation of the blade.

The semi-automatic sanding machines that companies such as Blade Treatment and Eltronic have developed are smaller than the stationary fully automatic machines and more applicable within blade manufacturing as they are mobile; “The whole idea with the semi-automatic sanding machines is that instead of having to take the blade to the sanding machines, the sanding machines come to the blade. Before when the blades were smaller, they were moved around a lot, but as the blades are growing bigger this is no longer possible.” (Company C, 2017). The semi-automated sanders from these two companies are rather similar, where the only difference that Company C (2017) have identified is that the Eltronic machines are hydraulic while the Blade Treatment machines have a server engine that applies pressure on the blade. According to Company C (2017), the semi-automatic sanders have decreased the sanding of a blade with around 4 to 5 hours in comparison to the use of manual sanders. However the machines only sand around 80 percent of the surface of a blade, whereas the rest needs to be sanded manually. This is due to the fact that some parts of the blade are sensitive and need to be sanded carefully in order to avoid defects, but some spots of the blade are also hard to reach for a semi-automated machine. It is further stated that there are currently only a few of these semi-automatic sanding machines which are used in the manufacturing of blades, around 10 of them that Company C (2017) knows of where 7-8 are from Blade Treatment and 2-3 are from Eltronic. Blade Treatment currently has 3-4 machines in production. The machines that Eltronic has currently sold are currently used by a rather large actor within blade manufacturing as well as the overall wind turbine industry, where it is believed that Eltronic might have a larger order flow coming from the same company.

The semi-automated sanders are programmed with the dimensions and the design of the blade which is to be sanded, and need to be reprogrammed for different models or sizes of blades (Company C, 2017). Company C (2017) however mentions that reprogramming can be expensive. The semi-automated machines are not manually steered, but have sensors which can read the surface of the blade and thereby apply the relevant pressure on the blade during the sanding process. There are currently no manually steered semi-automated machines available
in the market. Company C believes this is due to the increased risk of occurring defects, for example if the brush does not have the right angle in regards to the blade surface it might remove too much material from certain parts of the blade and thereby cause defects.

There are both positive and negative aspects of these semi-automated machines (Company C, 2017). The machines are rather expensive, around 2.5-5 million SEK and therefore require higher investment costs. However it is added that when selling products to the wind industry, more focus should be put on increasing productivity, efficiency and quality, where less focus should be on lowering investment costs. Another problematic aspect with the semi-automated sanding machines is the reparation and maintenance of them, as this knowledge will most likely not be available internally within the plant and external help will be required; “If a regular grinder or sander breaks down the operator can just take another one and continue the work while the other one is repaired. But if the semi-automatic machine breaks down it is not easily replaced and the production will stop until someone can come to the plant and fix it.” (Company C, 2017). This can be seen as a reliability problem with the machines, as the time which it takes to repair a broken down machine is not known, whereas the production has to be delayed during this time. However, the semi-automated machines significantly reduce the sanding time of the blade and thereby increase the lead time of the production of the blades. Furthermore, the semi-automated machines also increases the quality of the sanding of the blades as well as keeps a consistent quality as the quality of the sanding will no longer depend on the skill of the operator and eliminates defects caused by human error.

Currently there is high variation of wind blade models for wind turbines (Atlas Copco:G, 2017). The variation is dependent on both design as well as size, where each model is developed for a certain kind of environment depending on where the wind turbine is to be situated. However, most blade manufacturers are currently decreasing the variety of their blade models in an attempt to standardize the production and in turn increase the production volumes and decrease costs. Plant A (2017) states that while they have previously focused on high variety within their product offering in regards to both size and design, they are now focusing on decreasing the number of product models as well as standardizing all remaining models. The standardization and decrease in variety of blade models is also crucial in regards to an increasing level of automation within the processes. Sanding solutions with a certain level of automation have to be programmed with the dimensions and the design of the blade which is to be sanded, and also need to be reprogrammed for different models or sizes of blades (Atlas Copco:G, 2017; Company C, 2017). To reprogram the machines is both time consuming as well as expensive, whereas decreasing the variety of blade models makes it beneficial.

4.4.2.2 Analysis

Literature states that automation is a key factor for blade manufacturers to be able to increase their production volumes while keeping it financially feasible by decreasing its costs (Wind Energy Initiative, 2017; ETIP Wind, 2016), where automated material removal and finishing solutions is predicted to increase within coming years (Nolet, 2011). Similarly, this increasing automation trend was identified in the empirical data where it was seen that robotic solutions are being used to a higher extent in the material removal process and where all visited plans
aimed towards this type of solution. Furthermore, the decrease of time spent on the time consuming material removal process was expressed as a crucial matter at all visited plants. This proves to be consistent with literature where it is explained as currently being a labor intensive and time consuming process.

According to Sainz (2015), the implementation of automation within the material removal process of blade manufacturing contributes to cost reduction, increased productivity, improved quality as well as improved health conditions for operators as direct contact to dust and chemicals can be avoided. This is confirmed by empirical data which states its benefits in regards to efficiency, quality, cost and operator health. Empirical data further states that manual labor is highly dependent on operator skills, is time consuming, causes inconsistent quality and increases the risk of defects caused by human error.

As blade sizes are growing, empirical data claims that the application of automation becomes more difficult, and further claims that there is instead a need for manual material removal solutions which are more efficient and more ergonomic for the operators. This is partly consistent with literature according to Goch, Knapp and Härtig (2012). However in contradiction to this, authors such as Handelsman and Zald (2010), Guillermin and Shankar (2012) and Sainz (2015) argue that the increasing size of the blades is a significant aspect which is driving blade manufacturing towards automation and further claim that manual labor will no longer be applicable due to the large size of the blades. These statements are contradictory in regards to the level of automation that can be applied to the manufacturing process of large blades, however they are consistent in arguing that manual labor using classic hand held tools such as regular cutters, grinders and sanders are no longer feasible due to the large size of the blades. Furthermore, with increasing blade sizes, follows decreasing mobility. Literature and empirical data both indicate that automated material removal solutions in the form of stationary robots are outdated and no longer feasible in terms of accessibility, whereas a solution within this area needs to be mobile. However, empirical data gathered from visited plants indicate that the blades are transported between some of the different steps of the blade manufacturing process. Furthermore, during the material removal process, most plants use a central dust extracting system which is installed where such tasks are performed.

Literature states that while automation is beneficial in many ways, it decreases the level of flexibility within the processes in comparison to manual labor (Composites Manufacturing, 2012). Literature further states that there is currently a high variety of blade models in the market which prevents the application of serial production through automation (Kaczmarek et al., 2016). High variety in products need a higher level of flexibility within the process (Hagelberg, 2015). This reasoning is highly consistent to gathered empirical data which indicates that fully automated processes would not be applicable to the material removal process of blade manufacturing, where semi-automated solutions would be a better fit as it contributes to a higher level of flexibility. Furthermore, empirical data shows that blade manufacturers are currently decreasing the variety of their blade models in an attempt to standardize the production which is a crucial step towards reaching an increased level of automation within the process. However, all visited plants have at least two different models of blades which are manufactured at the plants. This concludes that while variations are decreasing, any automated
material removal solutions will need to be adaptable to at least two blade models, which should preferably be done without the need for reprogramming as it is both time consuming and expensive according to empirical findings.

Gathered literature, theory and empirical data, can conclude that the material removal process of blade manufacturing is a time consuming and labor intensive process, where the main aim is currently to increase the efficiency, quality and operator health conditions while decreasing its costs. It is further concluded that automation can contribute to achieving these criteria and is therefore an increasing trend within blade manufacturing. According to the analysis of literature, theory and empirical data, a solution within the material removal process needs to be applicable to large blades and therefore needs to be mobile for improved accessibility. Furthermore the solutions needs to be semi-automatic, as there is still a need for flexibility within the process due to variations in the blade models. The solution also needs to be programmed to be able to sand at least two different blade models without the need for reprogramming. Lastly the solution should perform the material removal operation more efficiently and thereby increase productivity, providing a result with higher and more consistent quality, lower costs and eliminate exposure to dust and other chemicals within the material removal process.
4.5 Analysis Summary

In the analysis summary, a summary of the conducted analysis has been presented. The summary is divided into three areas based on each sub-research question of this thesis.

4.5.1 How will new market trends impact the manufacturing processes within the wind blade industry?

The market for wind energy systems has grown tremendously during the past 15 years and is expected to keep growing in the next decade. However, the industry faces some major challenges, mainly concerning costs, reliability and energy capture, especially related to the offshore segment. Empirical data indicate that cost reduction is the main priority among blade manufacturing plants within Europe. Historically, these plants has focused more on improving quality but reduced subsidies within the industry has forced manufacturers to decrease production costs in order to reach the competitive threshold and be able to compete with conventional energy forms. However, in order to increase the efficiency of the blade structures, it is necessary to not only focus on decreasing the costs but to also focus on increasing its lifetime. This is particularly important within the offshore segment as a decreased availability generates high maintenance costs. In order to increase the lifetime of wind turbines it is crucial to develop lighter blades which are stronger and stiffer. It is the use of new and improved materials together with improved methods of life prediction and defect identification which are key to optimizing the lifetime of a wind turbine and its components. Furthermore, changes towards lighter materials, such as carbon fiber, could be necessary in order to enable manufacturing of blades with an increased size and a larger energy capture. As of today, wind turbines do not gather as much energy as they potentially could due to their size and the weight of the blades. A main objective for wind turbine manufacturers is to increase the rated power of each wind turbine which results in continuously increased blade sizes. This is a fact not only for the offshore segment but also for the onshore segment as new onshore capacity will, to a high extent, consist of the repowering of older and smaller wind turbines. In 2012 the maximum length of rotor blades was limited to 70 meters but by the end of this decade, the maximum length is foreseen to reach 110 meters (Goch, Knapp and Härtig, 2012).

4.5.2 What are the underlying customer needs within the manufacturing processes of wind turbine blades?

As only 2 percent of the value of an entire wind turbine goes to paying the operators’ salaries, the greatest potential in regards to possible cost reductions within blade manufacturing is related to an increased efficiency and productivity rate. The material removal process is considered as the most or one of the most time consuming parts of the blade manufacturing process and all visited plants expressed a will to increase the efficiency within these steps in order to reduce the manufacturing time. Thus, there is a need for more efficient material removal solutions.

As the wind energy sector keeps growing along with the number of workers enrolled in the industry, safety and health aspects become a prime concern. Wind blade operators are exposed to a number of hazards whereas injuries due to manual handling such as heavy lifting, injuries due to machinery usage such as white fingers and exposure to hazardous chemicals and dust
have been identified as the most problematic in this study. Both literature and empirical data support the fact that ergonomics is important in order to keep the operators healthy and reduce work related injuries even though the mindset towards ergonomics differ between different plants. An injured operator results in both direct and indirect costs for the company. Thus, proactive ergonomic interventions are sometimes necessary in order to support organizational goals such as profitability. However, the importance of sustaining good health conditions among operators usually becomes less important in regions where operators can easily be replaced.

Literature supports other ergonomic benefits such as improved quality and productivity since healthy and alert operators are able to sustain a higher and more consistent productivity rate. Ergonomic issues such as uncomfortable operator positions involving heavy machinery do not only increase the risk for injuries but also affects the quality and time needed to perform certain tasks. However, the benefits generated by ergonomic as well as high quality products with higher efficiency often have to be seen in a longer perspective in order to become economically profitable. The perception created by this study is that most, but not all, European blade manufacturing plants do take on a longer perspective and weigh investment costs against performance and ergonomic aspects when buying tools. For instance, three out of four visited plants did buy pneumatic quality tools due to higher efficiency, longer lifetime and better ergonomic attributes. However, one plant chose to buy cheaper electrical material removal tools with a significantly lower lifetime even though the use of electrical tools in these applications could be considered as a safety concern. The current cost focus within the industry may affect these choices and makes it even more important for tool suppliers to offer solutions which are economically justified.

The white finger illness caused by vibrations is now a known phenomenon and most employers care more and more about vibration levels when buying tools. It is important for employers to prevent the white finger illness since it shortens the working lifetime of the operators and may prevent operators from maintaining a high and consistent productivity rate. Furthermore, in 2005 regulations regarding hand-arm vibration was introduced in the European Union, restricting the amount of vibrations that an operator can be exposed to during the work day. Regulations in combination with an awareness of the white finger illness could have increased the demand for tools with low vibration levels. However, as for ergonomics in general, the extent of which companies care about vibration levels varies between different plants and regions.

Literature as well as empirical findings indicate that dust generated from material removal operations of GFRP is a problem when appearing in direct contact with the lungs or with the skin of the operator. However, plants using a fully functioning central dust extraction solution in combination with protection clothes did not perceive this to be an issue. Literature suggests otherwise, studies investigating finishing processes involving repairing defects and sanding down imperfections have revealed skin related issues among other health concerns. Problems such as the stopping of menstrual cycles, severe headaches, nosebleeds and dizziness, as well as throat and eye irritation have been reported. These symptoms occurred even though all workers wore gloves, overalls and safety glasses. The chemicals penetrated through the
protective equipment and were not sufficient to prevent these symptoms. Furthermore, health problems due to dust and chemicals are predicted to grow as the blades get larger. Dust from GFRP is not only harmful for the human body but also for the tools (Plant B, 2017). In order to extend the lifetime of the tool it is important to keep the dust extraction module separated from critical parts within the tool. The dust extraction module must be located externally, otherwise the dust will destroy the tool from the inside and the entire machinery will break.

4.5.3 What kind of material removal tools are needed to support the development of the blade manufacturing processes?

Literature states that automation is a key factor for blade manufacturers in order to increase production volumes while reducing costs (Wind Energy Initiative, 2017; ETIP Wind, 2016). Empirical findings partly support this statement since all visited plans in this study, more or less, aim towards implementing automated solutions to a higher extent. Manual processes are not only time consuming but also highly dependent on operator skills which causes inconsistent quality and a risk of defects due to human error. According to Sainz (2015), the implementation of automation within the material removal process of blade manufacturing contributes to cost reduction, increased productivity and improved quality as well as improved health conditions for operators as direct contact to dust and chemicals can be avoided. Aligned with this statement, the European Agency for Safety and Health at Work (2013) suggests an increased automation of manufacturing processes where operators are eliminated from the manufacturing process as much as possible through the use of robotics, in order to increase the safety and health conditions among operators within wind turbine manufacturing. Furthermore, the European Agency for Safety and Health at Work states that this is increasingly important, as the wind turbine systems get larger.

Empirical data indicates that the implementation of automation becomes more difficult as blade sizes get larger. This is partly confirmed by literature as Goch, Knapp and Härtig (2012) argue that the development of material removal processes towards automation is hampered by high quality requirements as well as the increasingly growing sizes and weights of the blades. However, Goch, Knapp and Härtig further argue that the automation level and optimization of production infrastructure and processes have lagged behind and manufacturers should be able to increase the automation level within blade manufacturing significantly. Furthermore, other authors have a different view and contradictory believe large blade sizes to be a driving force towards automation (Handelsman and Zald, 2010; Guillermín and Shankar, 2012; Sainz, 2015). As the size of wind turbines increase, it is no longer financially feasible for manufacturers to keep labor intensive processes, thus automation becomes essential in the long term (Guillermín and Shankar, 2012). Even though the attitude towards automated solutions within the production of large blades somewhat differs, it is possible to claim that manual labor using classic hand held tools such as regular cutters, grinders and sanders are no longer feasible due to the large size of the blades. There is a need for more efficient tools which enable processing of a larger area of the blade. Furthermore, there is a need for tools which can be operated in ergonomic positions as well as tools with a decreased weight, decreased vibration levels and a decreased exposure to dust. Moreover, manual tools must be provided with an external dust extraction solution in order to survive environmental condition.
Two other reasons which may lead to hesitation regarding the implementation of automated solutions are high investment costs and reliability aspects (Company C, 2017). Manufacturers need to look at profitability in the long run in order to find automated solutions beneficial. Furthermore, it is not an option for manufacturing plants to close their production due to equipment failures. Manufacturing plants do not want to be dependent on external help in order to keep a continuous production flow. Moreover, literature states that while automation is beneficial in many ways, it decreases the level of flexibility within the processes in comparison to manual labor (Composites Manufacturing, 2012). There is currently a high variety of blade models in the market, which prevents the application of serial production through automation (Kaczmarek et al., 2016). High variety in products need a higher level of flexibility within the process (Hagelberg, 2015). However, empirical data indicate that blade manufacturers are currently decreasing the variety of their blade models in an attempt to standardize the production, which is a crucial step towards reaching an increased level of automation within the process. Even though the varieties are decreasing, all visited plants plan to produce at least two different models of blades, even in the future. Thus, an automated solution needs to be adaptable to at least two blade models, preferably without the need for reprogramming as empirical data indicate that this is both time consuming and expensive. In order to maintain a certain level of flexibility in the system, a fully automated solution would not be applicable to the material removal process of blade manufacturing, whereas a semi-automated solutions could be seen as a better fit.

Empirical data as well as literature indicate that wind blade manufacturers have implemented or are in the process of implementing streamlines and production lines in their manufacturing process, where the blades are moved between different steps of the process (Gardinger, 2016; Vestas, 2015). Empirical data from the visited plants show that the blades were moved one to two times during the process, mainly between the gluing and the first material removal step. However, when a blade is placed in the area which is intended for material removal operations, it is placed there together with other blades which are in the same stage in the blade manufacturing process. The blades which are placed here are seldom moved within this area. Furthermore, to move the blade within this area becomes increasingly difficult as the blades increase in size. Thus, mobile material removal tools which make it possible to alter between different material removal manufacturing steps, without moving the blades, are desirable.
5. Conclusion

How should Atlas Copco support the development of blade manufacturing processes within the wind industry by expanding or developing their product range within material removal tools?

As cost reduction has been identified as the main priority among blade manufacturing plants within Europe, there is a need for economically justified manufacturing solutions which enable an increased productivity rate, see Figure 13. The material removal process is considered as the most or one of the most time consuming parts of the blade manufacturing processes, where all visited plants expressed a will to increase the efficiency within these steps in order to reduce the manufacturing time. Furthermore, the time consumption regarding material removal processes is a growing problem as the blades continuously increase in sizes. Thus, there is a need for more efficient material removal solutions. Furthermore, as the wind energy sector keeps growing along with the number of workers enrolled in the industry, safety and health aspects become a prime concern. Unsustainable ergonomic conditions do not only increase the risk for injuries but also affects the quality and time needed to perform certain tasks.

![Figure 13. Shows the requirements for manual and automated solutions in regards to the customer needs of wind blade manufacturers.](image)

Literature states that automation is a key factor for blade manufacturers in order to increase production volumes while reducing costs. The implementation of automation within the material removal processes contributes to cost reduction, increased productivity and improved quality as well as improved health conditions for operators as direct contact to dust and chemicals can be avoided. Thus, the implementation of automated solutions could enable wind blade manufacturers to deal with future challenges. As wind blade manufacturing plants most likely will continue to produce at least two blade models within the same plant, there is a need for flexibility within the process. Thus, a semi-automated solution is considered to be more applicable than a fully automated solution. Furthermore, as the blades become increasingly difficult to move due to their size, there is a need for mobile material removal tools which can be transported between different blades.
The attitude towards automated solutions differ between different manufacturing plants. Furthermore, some authors argue that the implementation of automation becomes more difficult as blade sizes get larger while others argue that increased sizes make this transformation necessary. Moreover, high investment costs and reliability aspects may lead to hesitation regarding the implementation of automated solutions. However, it is possible to claim that manual labor using classic hand held tools such as regular cutters, grinders and sanders are no longer feasible due to the large size of the blades. There is a need for more efficient tools which enable processing of a larger area of the blade. Furthermore, there is a need for tools which can be operated in ergonomic positions as well as tools with a decreased weight, decreased vibration levels and a decreased exposure to dust. Moreover, manual tools must be provided with an external dust extraction solution in order to survive environmental conditions.

By providing manual and semi-automated tools aligned with the customer needs found in this study, Atlas Copco will be able to support the development of blade manufacturing process within the wind industry.

**5.1 Discussion**

In this thesis, the main focus has been on the development of material removal solutions within wind blade manufacturing. However, it was also found that the need for material removal operations are highly dependent on the molding process which includes the application of glass fiber sheets but also other material such as wood or carbon fiber, as well as the infusion of resin in the mold. If the molding process was to improve, where it would result in the molded blades having less excess material, the need for material removal operations would decrease significantly. This means that if an improved molding method for wind blades was to be developed, this would have a negative impact on the need and development of material removal solutions within this segment, and in turn have a negative effect on the material removal product range of Atlas Copco towards the wind energy segment. No in depth investigation has been done in the area of new molding methods or techniques. Therefore, no statement or comment can be given regarding the current or future development within this area. However, further investigation in this area is believed to be of interest for Atlas Copco and is recommended.

When analyzing the empirical data and the literature, there are contradicting statements about the effect which the increasing blade sizes will have on the applicability of automated solutions within the material removal process. While some sources argue that increasing blade sizes will make it difficult or even not possible to apply automated solutions, others argue that the increasing blade sizes will instead create a crucial need for automated solutions. No research has been conducted in the application of automated solutions based on the blade size, and therefore no statement regarding this area can be made. Knowledge of the applicability of automated material removal solutions on different blade sizes is however identified as crucial during the development of new material removal solutions. Therefore, further research in this area is suggested.

Both literature and empirical data indicate a future change of material for the wind blades. While some visited plants state that there will be an increased use of carbon fiber, others state that there will be a material change but are not willing to share any information regarding the
material which will be used. The change in blade material might affect the choice of material removal tools which are used. However, no research has been conducted on how the changed material of the blades would affect the tools which are used within the material removal process. Research in this area may however be relevant during the development of material removal tools towards this segment.

Two main aspects have been identified as restraints during the plant visits; the level of honesty and the language barrier. When asked about aspects such as ergonomics and working conditions for the operators, some plants were not perceived to give truthful answers. This perception is mainly based on the fact that the answers could be contradictory to previous answers regarding the same area. To overcome this situation, questions were reformulated in different ways and asked. For example, instead of asking whether the ergonomic conditions of the plant were considered problematic, questions regarding working hours, shifts and rotation within the plants were asked. This approach was identified to give more truthful answers, where conclusions regarding the ergonomic conditions of the plant could be made based on these answers. This method has not affected the ethical aspects within this research, where the respondents were always aware of the purpose of the research and the questions that were asked within the area of ergonomics and working conditions were clearly stated. Any conclusions that have been made based on this information, is based on the analysis which has been done on the empirical data as well as literature for the purpose which was communicated to each respondent.

Furthermore, there was a significant language barrier that needed to be overcome at all plant visits. While some three of the four plant guides had basic knowledge in the English language, one of the plant guides did not speak any English. The language barrier made it more difficult to communicate, where it is believed to have affected the gathered empirical data. We attempted to overcome this problem by asking the same question in different ways, and by using different words during the times where it was noted that our question had not been fully understood in the right way. This approach was helpful the majority of times, however the risk of misunderstandings or misperceptions is still significant. Both of these restraining aspects could have affected the empirical data and in turn the analysis and solutions of these thesis.

During one of the plant visits a Non Disclosure Agreement (NDA) had to be signed in order to be granted approval to enter the plant. This means that by agreeing to this NDA, we were restricted in the way were we could not share in depth information regarding the different manufacturing solutions of the plant. Therefore, some empirical data which were retrieved from the plant visits has not been presented or addressed in this thesis. We believe that the exclusion of this empirical data has had an effect on the analysis as well as the solution of this thesis, as we have not been able to consider all aspects of the conducted visits. Furthermore, even though some empirical data was excluded from the report and therefore should also be excluded during the analysis and solution, we as the authors of this thesis might have been biased due to the fact that we have knowledge of this data, whereas it may have affected the analysis as well as the solution.

The plant visits were delimited to be within Europe, due to geographical restrictions in regards to traveling. However, all visited plants were located in different areas and many times within different countries within Europe. This follows a difference in culture within the plants and may
thereby have affected their views and attitudes towards different aspects of the manufacturing process such as working conditions, health and safety of the operators and their view on automation. The cultural aspects may have affected the gathered empirical data in regards to the level of importance of the different aspects of manufacturing, and may in turn affected our results. However, as this research was set to cover the European region, the difference in culture and views and their effect on our results are highly relevant.

5.2 Suggested Solution

In the conclusion, some requirements regarding manual as well as automated tools have been presented, which are based on the customer needs of wind blade manufacturers. By analyzing these requirements, some suggestions in regards to material removal solutions which correspond to these requirements have been identified in a future state map; semi-automatic sanding machine, FlexTrim and FlexArm (see Figure 14).

![Figure 14. Shows the future state of the tools used in the sanding process of Step 3 of the blade manufacturing process, and their level of automation.](image)

A semi-automatic sanding machine is suggested as one of the applicable material removal solutions for wind blade manufacturing. The semi-automatic sanding machine is mobile, can process a larger area of the blade at a faster pace and provide higher quality. This makes it significantly faster and more efficient than regular manual sanders and it also increases its accessibility. The consistent sanding also increases the quality as it is no longer dependent on operator skill which is the case when using manual tools. Furthermore, it significantly decreases the number of operators needed during the material removal process to only one, whereas this operator does not need to stand right next to the machine. This lowers the operator’s exposure
to dust during the material removal process. In regards to automation level, the semi-automatic sanding machine is as the name suggests semi-automated. This increases the level of flexibility within the material removal process in comparison to fully automated solutions. As have been earlier mentioned, two companies which produce these kind of semi-automatic sanders are Eltronic and Blade Treatment. Where Eltronic’s device is also claimed to be adaptable to each workpiece and does not require preprogramming to identify the shape of a blade. Furthermore, even though the investment costs are significantly higher for the semi-automated sanding machine in comparison to a regular sander, it is claimed to reduce the operation costs for the material removal process, which would suggest a long term financial feasibility.

In regards to manual solutions, two suggestions have been presented. The first suggestion is the FlexTrim Blade Sander tool. The tool has a sanding width of 300 mm consisting of strips of flexible brushes and sanding material, which ensures that the material is pressed evenly on the surface of the blade. This means that the Blade Sander can process a larger area of the blade which increases its efficiency, while it also increases the quality of the blade due to the evenly pressed sanding brush on the surface of the blade. As the tool increases the efficiency of the sanding process and decreases the time for the sanding operation, it is also claimed to decrease the costs and total production time for a blade. Furthermore, the Blade Sander is formed in the shape of a lawn mower where it can be moved back and forth on the surface of a blade with the use of a handle. This means that operators can use the tool while standing in an upright position, which increases the ergonomic conditions for the operator. The Blade Sander also has a dust control system, which decreases the operator’s exposure to dust during the sanding.

Lastly, a second suggestion for a manual solution has been presented. The second suggestion is a combination of a material removal tool and the FlexArm solution Flexarm Gimbal. The Flexarm Gimbal is a support arm which is developed to work with heavy hand grinders, where it enables smooth grinding with significantly less effort. This gives the operators better ergonomic conditions during the material removal process. However the Flexarm Gimbal is currently designed to work with manual hand held grinders, whereas the developed requirements for manual tools state that there is a need to not only improve ergonomic conditions for operators but also increase the efficiency of the tool. For this purpose, it is suggested that Atlas Copco develops a sanding and/or grinding tool with a significantly wider width which can process a larger area of a blade than a regular manual sander or grinder. This tool is further suggested to use sanding brushes as they are claimed to reduce the vibrations of the sanding operation. Furthermore this developed tool needs to be attachable to the Flexarm Gimbal solution.

5.3 Empirical and Theoretical Contribution

The empirical contribution of this thesis was mainly in the area of wind blade manufacturing processes, the material removal tools used at the manufacturing, the level of automation within the plants as well as their attitude towards it, and data regarding trends within wind blade manufacturing. The main empirical contribution is however in the area of material removal tools within wind blade manufacturing, where the contribution includes the developments in
this area such as automation, increased ergonomics and health aspects, increased efficiency, reliability and resulted quality, and decreased costs.

The theoretical contribution of this thesis involves the importance of ergonomic aspects within manufacturing, the application of automation within manufacturing processes and the Systems Perspective Framework which shows the connection between the industrial, functional and individual level of a phenomenon, which in this case was the wind energy industry.

5.4 Generalizability

The conclusion of this thesis suggests the application of manual as well as automated material removal tools within the material removal process of wind blade manufacturing. The solutions have been based on the analysis of gathered empirical data from plant visits as well as interviews and literature in the researched area. As this thesis was delimited to focus on the European wind blade manufacturing market, the application of the suggested solutions have not been analyzed in terms of applicability to other geographical markets. Three material removal solutions have been suggested based on the customer need criteria which was identified during the research. This variation of solutions suggest a variation in customer needs among different plants, which is believed to reflect the European market. This research included four plant visits within Europe and does therefore not represent the entire European wind blade manufacturing market, but rather a part of it. However, due to the various geographical locations of the visited plants within Europe which includes a variety of cultures and ways of working, generalizability in the research is indicated but not concluded.

5.5 Limitations and Further Work

Many limitations were experienced during the writing of this thesis. While around seven to eight plant visits had been planned, only four plant visits were conducted. This was mainly due to the fact that many plants were not willing to arrange such visits, or simply stated that they do not have the time to do so. Furthermore, it was found that the level of confidentiality within the blade manufacturing industry is rather high where many plants do not want to arrange visits due to the fact that they are afraid that confidential information may be leaked outside of the plant. In order to increase the generalizability of the result from this type of research, it is suggested to increase the amount of visited plants during further work. This might mean that there is a need to extend the time-span of the conducted work as flexibility is required in order to conduct a plant visit.

As mentioned in the discussion, research in the area of the development of materials used for blade molding, the applicability of automation on larger blades and the development of the molding process has not been conducted. These areas are however identified as important aspects in regards to the development of new solutions within wind blade manufacturing. Therefore these areas have been suggested for further work within this area of study.
References


Atlas Copco:J (2017) Interview with Regional Sales Manager - Wind Segment. Interview conducted on: 2017-02-17


Company B (2017) Interview with Product manager of Abrasives company. Interview conducted on: 2017-03-10

Company C (2017) Interview with Owner of Abrasives company. Interview conducted on: 2017-02-23


Appendix

Appendix 1 – Pre-study; Foundry Vs. Wind Energy

The foundry market and the wind segment are both industries which are facing great future market changes. Atlas Copco offers material removal tools such as cutters, sanders and grinders within both of these segments and are looking to develop their offering to meet the changes within these markets. A pre-study was conducted in order to identify which of these markets has the most potential for development and expansion in regards to the Atlas Copco material removal product offering.

Foundry

The foundry market is currently facing some major changes, mainly in regards to used materials and manufacturing methods. Trends show that lighter metal materials such as aluminum are being used to a greater extent (Heuss et al., 2012). However the main factor of change in this market in regards to the use of material removal tools are the changing and developing manufacturing methods. Atlas Copco:B (2017) argues that there has been a significant increase in quality and precision in the traditional casting methods, which in turn decreases the need for following processing operations such as material removal. Furthermore, additive manufacturing (AM) in the form of 3D printing of metals has been a growing phenomenon (Atlas Copco:B, 2017; Atlas Copco:C, 2017). There has also been an increased use of 3D printing for sand molds used for traditional casting methods, which in turn increases the quality of the castings (Zelinski, 2014).

AM processes have been identified to have some advantages in comparison to conventional manufacturing processes (Huang et al, 2012). The advantages are for instance material efficiency, resource efficiency, part flexibility and production flexibility. This means that AM uses less material in comparison to subtractive manufacturing where large amounts of material needs to be removed. This in turn means that less resources such as tools to remove the excess material is needed within AM (Atlas Copco:B, 2017; Atlas Copco:C, 2017). However, Huang et al. (2012) argues that there are also some negative aspects with AM technology such as size limitations, imperfections and cost. Where it is therefore considered to have difficulties when competing with conventional manufacturing, such as casting.

Currently, AM is mainly used for prototyping for instance within the automotive industry however Herzog et al. (2016) argues that AM can be considered in regards to serial production. Furthermore Cohen et al. (2014) argues that larger objects with higher printed quality in the form of precision and resolution will be enabled through 3D printing. These aspects contribute to AM being another alternative to conventional manufacturing. According to Wohlers Report there was a 75.8 percent increase in sold metal 3D printers between the years of 2012 and 2013 (Knapp, 2014). Whereas Grunewald (2016) argues that the market for metal 3D printers is the fastest growing segment.
Wind Energy

The wind energy market has been expanding at a significant pace during recent years and is anticipated to keep growing. According to Statistiska Centralbyrån, the amount of electricity generated from wind power increased with 44.8 percent in Sweden during 2015 (Kulin & Enmalm, 2016). This significant growth within wind energy is based on several aspects such as an increasing environmental concern, decreasing generation costs and an increased stability in environmental regulations (Global Wind Energy Council, 2016). Furthermore, the Paris Agreement for Climate Change has set to achieve an emission free energy sector for the year of 2050, which in turn contributes to the increasing trend of renewable energy sources such as wind energy. According to McKinsey, renewable energy sources such as solar and wind energy are expected to grow up to five times by the year 2050 (Nyquist, 2016).

The wind energy market is identified to be an innovative industry which is open to change and continuously strives to develop new and more efficient solutions (Atlas Copco:B, 2017). One of the recent developments within wind turbines is the increasing size of the rotor blades which can generate more energy by increasing the productivity (Atlas Copco:B, 2017; Howard, 2012; Engström et al., 2010).

Atlas Copco:D (2017) argues that the wind turbine industry has rather distinct processes, where gaps in their manufacturing processes can easily be identified during an investigation. In order to be able to manage new potential within a process in the best possible way, it is important to clarify and understand the entire process together with the aspects which generate value and is beneficial for the customer. Furthermore, Atlas Copco:B (2017) states that an identified area of improvement within the blade manufacturing process is the sanding of the blades which is in most cases a rather time consuming manual process. It is however added that some manufacturers have implemented automation within this process.

Pre-study Conclusion

The growing market for metal 3D printers and their ability to compete with conventional manufacturing methods such as casting will affect the foundry industry significantly as it will decrease the need for the current material removal operations that follows. Such a scenario would have a negative impact in regards to the sales of material removal tools towards the foundry industry. The significant expansion of the wind energy industry has however been identified to affect the sales and development for material removal solutions in a positive manner. In order to increase the productivity of the wind turbines, a trend towards increasing blade sizes has been identified. Together with the time consuming operation of sanding the blades, this has been identified as an opportunity for expansion within the material removal product range at Atlas Copco. The wind energy industry has therefore been selected as the main area of investigation for this thesis.
References


Appendix 2 – Pre-study Interview Guide

- Please tell us about your role at Atlas Copco.
  - What is your academic and/or work-related background?
  - Which product segments do you work with?
  - How long have you had this role at Atlas Copco?

RnD - Tightening tools

- Which products are included within tightening tools?
- Within which industries are these products used? Who are the customers?
  - Metal fabrication? (mining, foundries, metal production, offshore, rail, non-metal fab)
  - Energy? (wind)
- Has there been any form of product development of any of these products during recent years?
  - How have these products been developed? Example?
  - Why were they further developed?
- Has there been a change (increase/decrease) in the number of sold items within a certain product segment within the last years?
  - If yes: Which segment? What kind of change is it?
  - Why has this change occurred? Can you identify any trends which have affected this change?

Product Manager - Material Removal

- As we understand it, you mainly work with material removal tools, is this correct?
  - Which other product segments do you work with?
- Which industry segments do you work with an focus on?
  - Metal fabrication - mining, foundries, metal production, offshore, rail, non-metal fab?
  - Energy - wind?
- Who are your customers within these segments (product segments as well as industry segments)?
- Has there been a change (increase/decrease) in the number of sold items to certain customers or industries within the last years?
  - If yes: What customer or industry? What kind of change is it?
  - Why has this change occurred? Can you identify any trends which have affected this change?
  - Is this an industry related change or does it only apply to certain customers?
• In the Wind Turbine product folder which you have produced, different manufacturing techniques of wind turbines have been explained. Here it is stated that there are three main manufacturing techniques for wind blades.
  ○ Are there any other manufacturing techniques which are used in this area?
  ○ Are any new manufacturing techniques being developed?
  ○ Have there been any changes in the current manufacturing techniques during recent years?
    ■ If yes: how has this affected development or purchase of your products?

RnD - Metal fabrication

• Which products are included as metal fabrication tools?

• In which industries are these products used?
  ○ Metal fabrication? (mining, foundries, metal production, offshore, rail, non-metal fab)
  ○ Energy? (wind)

• Who are your customers within this segment?

• Has there been any form of product development of any of these products during recent years?
  ○ How have these products been developed? Example?
  ○ Why were they further developed?

• Has there been a change (increase/decrease) in the number of sold items within a certain product segment within the last years?
  ○ If yes: Which segment? What kind of change is it?
  ○ Why has this change occurred? Can you identify any trends which have affected this change?

• Has there been a change (increase/decrease) in the number of sold items to certain customers or industries within the last years?
  ○ If yes: What customer or industry? What kind of change is it?
  ○ Why has this change occurred? Can you identify any trends which have affected this change?
Business Development

- How has the business developed within recent years?
  - Has any recent acquisitions and/or partnerships been done?
  - What types of companies and products have been acquired?

- How does this process work within the company?
  - How are decisions regarding which company to focus on made?

- Which product segments has there been a focus on?
  - In which industries are the specific product segment used?
    - Metal fabrication? (mining, foundries, metal production, offshore, rail, non-metal fab)
    - Energy? (wind)

- Can you identify any trends that indicate an expanding market within any of the mentioned industries?
  - What are the trends? Example?
  - What industries are affected by these trends?

Voice of Customer

- Tell us about the Voice of Customer Process.
  - What type of surveys and/or customer studies are conducted?
  - How often are they conducted?
  - What is achieved during these studies? What is the purpose of these studies?

- Who are your customers within the Wind and the Foundries segments?

- Have any studies been conducted on customers within the Wind and Foundries segments? Which customers?

- How do you proceed with the information gathered from these studies?

- Have specific questions or methods been developed for gathering of data for the Voice of Customer studies?
  - If yes: are they adapted to each product segment or each industry?
  - Can these be applied to future Voice of Customer studies?

- Tell us more about the “Deck of Cards”. How can this be applied to Voice of Customer studies within different product segments and industries?
Appendix 3 – Internal Interview Guide

- Tell us about yourself and your role within Atlas Copco.
- What is your involvement with the wind industry?
- What customers do you work with within the wind segment?
- Do different customers use different blade manufacturing techniques?
  - What are the different manufacturing techniques which are used?
  - Why do different companies use different techniques?
- Have you seen any trends or developments within the manufacturing processes of blades?
  - What are these trends/developments?
  - How have they developed/changed? Example?
    - Why?
- What current challenges have you identified within the wind blade manufacturing industry?
- What challenges do you foresee in the near future within the wind blade manufacturing industry?
- Which are the biggest trends driving this evolution?
  - Why?
  - What are the benefits?
  - Which limitations do you see in this evolution?
Appendix 4 – External Interview Guide

- Tell us about yourself and your role at the company.

- Tell us about the company, their background and their products.
  - What different kinds of products do you have?
  - What are the products used for?
  - Who are your customers?
  - What is your involvement with the wind industry?

- What are the current trends within the sanding industry/sanding brushes?
  - Has there been any changes within the products?
  - (Are these changes applicable to the Atlas Copco tools?)

- How are your products used in the manufacturing of wind turbines?
  - How are they used during manufacturing of blades?

- What challenges are you currently working on within the wind industry?
  - What challenges do you foresee in the near future within the wind industry?

- Which are the biggest trends driving this evolution?
  - Why?
  - What are the benefits?
  - Which limitations do you see in this evolution?

- Have there been any changes in the use of your products within the wind industry?
  - How are your products used differently?
  - Why has the change in usage of your products occurred?
Appendix 5 – Plant Visit Observation Guide

Process and machines/tools

- Is the process divided into: Molding - Gluing - Grinding/sanding - Finishing?
  - If not, what is different? Describe the full blade manufacturing process.

Notes:

Molding

- Does the molding process include:
  - Application of glassfiber sheets? Yes / No
  - Application of wood layer? Yes / No
  - Building of beam? Yes / No
  - Gluing the blade halves together? Yes / No

- What is the level of automation for spreading fiber sheets within the molding process?
  1. Not automated (manual)
  2. Semi-automated
  3. Fully automated

Notes:

- What is the level of automation for gluing the blade halves together?
  1. Not automated (manual)
  2. Semi-automated
  3. Fully automated

Notes:

Material Removal and Finishing

- Does the material removal/finishing process include:
  - Cutting excess glue? Yes / No
  - Grinding of uneven areas of blade? Yes / No
  - Application of glassfibre to glued blade edges? Yes / No
  - Sanding of blade? Yes / No
  - Application of gelcoat on blades? Yes / No
  - Painting the blades? Yes / No
• What is the level of automation for the process of cutting excess glue from the blade?
  1. Not automated (manual)
  2. Semi-automated
  3. Fully automated
   Notes:

• What is the level of automation for the grinding and sanding process of the blade?
  1. Not automated (manual)
  2. Semi-automated
  3. Fully automated
   Notes:

• What tools are used during the grinding and sanding process?
  Cutters:
    ○ LCS?
    ○ Other:
  Grinders:
    ○ LSV 38/39?
    ○ GTG xx?
    ○ Other:
  Sanders:
    ○ LSO?
    ○ LST?
    ○ Orbital sanders?
    ○ Other:

• What is the level of automation for the application of gelcoat and paint on the blade?
  1. Not automated (manual)
  2. Semi-automated
  3. Fully automated
   Notes:
Health and Ergonomic aspects

● Do the operators operate in uncomfortable positions?
  ○ Tool below waist-height  Yes / No
  ○ Tool in level with waist-height  Yes / No
  ○ Tool in level with chest/head height  Yes / No
  ○ Tool above head height  Yes / No

● Do the operators wear relevant protective gear during their work?
  ○ Relevant clothing?  Yes / No
    ■ With airflow (for sanding/grinding)?  Yes / No
  ○ Protection glasses?  Yes / No
  ○ Masks?  Yes / No
  ○ Gloves?  Yes / No

● Level of dust in plant?
  ○ Low (some dust on the ground- no masks needed when entering plant)
  ○ Medium (Dust on the ground and some in the air, masks might be needed)
  ○ High (air filled with dust, masks and protective gear needed)

Plant Layout

● Do they currently have a flow line where the blade is moved between different production steps?
  ○ Yes
  ○ No, the blade remains at the same position during the manufacturing
  ○ Partly, the blade is moved during the following steps:
Appendix 6 – Plant Visit Interview Guide

General

- What is your role in the company?
- What processes do you work with or have knowledge of?
- Can you briefly describe the different steps of the blade manufacturing process?
  - What tools are used within each step? Why, for what purpose?
    ■ Pneumatic or electrical? Why?
    ■ How many of these tools that you use are from Atlas Copco? Why?
    ■ How many of these tools that you use are not from Atlas Copco? Why?
  - What abrasives are used for grinders and sanders?
- Which steps of the process is most time consuming? Why?
- What difficulties or limitations have you identified within these steps?
  - Why is this a difficulty or limitation?
  - How can this step/process/task be changed for the better?
- Have there been any recent development or changes within the processes?
  - What are the changes? Example?
- How do you see your processes evolve in the coming years, any trends?
  - Why do you think it will evolve in this way?
- Have you identified any trends in regards to changes in design and material used on blades? (size, weight etc.)
- How many different varieties of blades are you currently producing in the plant?
  - How many have you produced in the past?
  - How many are you planning to produce in the future?
- Can you describe current plant layout?
  - Are you planning to change the layout of the plant in the future?
  - Why?

Automation

- What steps of the blade manufacturing process are currently performed manually? Why?
  - Have you experienced any challenges with these steps? Example?
  - What are the benefits? Why?
  - Are you currently looking into implementing automated solutions within this area?
    ■ Why/why not?
What kind of automated solution are you looking for?
- Fully automated/semi-automated? Why?
- Do you have any specific requirements or demands?

What steps of the blade manufacturing process are currently performed semi-automatically? Why?
- Have you experienced any challenges with these steps? Example?
- What are the benefits? Why?
- Do you think this step will be automated to a higher extent in the next five years? Ten years?
- What kind of automation solutions are you looking for? Why?

What steps of the blade manufacturing process are currently performed fully automatically? Why?
- Have you experienced any challenges with these steps? Example?
- What are the benefits? Why?
- Does these solutions require reprogramming when alternating between different blade designs? Why? Is this challenging?
- Is it hard to handle the varieties regarding defects of different blades?

Data collection

Are you currently collecting any data from the blade manufacturing process? Why?
- How?

Are you currently using any data collection devices associated with the use of pneumatic tools?
- Timers or accelerometers associated with the use of pneumatic tools?

What kind of data do you collect?
- Why? How is the gathered data used? For what purpose?

How and where is the data stored?

What kind of data would you be interested in collecting?
- Why? For what purpose?

How important is it for you to keep track on following data on a regular basis? (1-5)
- Vibrations
  1 - 2 - 3 - 4 - 5
- Noise level
  1 - 2 - 3 - 4 - 5
- Service intervals
  1 - 2 - 3 - 4 - 5
- Calibration intervals
  1 - 2 - 3 - 4 - 5
- Usage hours for each machine
  1 - 2 - 3 - 4 - 5
- Applied pressure
  1 - 2 - 3 - 4 - 5
- Imbalance within the tool
  1 - 2 - 3 - 4 - 5
- Other:
Ergonomics

- **How important are the following aspects** for you when buying tools? (1-5)
  - Vibration level 1 – 2 – 3 – 4 – 5
  - Noise level 1 – 2 – 3 – 4 – 5
  - Weight 1 – 2 – 3 – 4 – 5
  - Dust extraction 1 – 2 – 3 – 4 – 5
  - Tool guard 1 – 2 – 3 – 4 – 5
  - Price level 1 – 2 – 3 – 4 – 5
  - Life span 1 – 2 – 3 – 4 – 5
  - Power output 1 – 2 – 3 – 4 – 5
  - RPM 1 – 2 – 3 – 4 – 5

- **Is ergonomics an important aspect** for you when buying tools? (1-5)
  1 2 3 4 5
  - Why?
  - How is this reflected in your manufacturing?

- **How do you handle dust** within the plant?
  - Is dust a problem?

- **How do you deal with static electricity** during the grinding/sanding process?
  - Is static electricity a problem?

- What are your current focus, cost reduction or quality improvements?

- What is your turnover rate of operator? (How many years on average do they work at the plant?)

- **How many shifts** do you have for your operators?
  - How many hours are each shift?

- Does an operator operate the same machine and/or process for an entire shift or is there any rotation during a shift?
  - If rotation, for how long does an operator work at the same station?