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Automation Options for Custom-Made Composite Part Production

TU Delft

Automation Options for Custom-Made Composite Part Production

Master Thesis Report

By

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ABSTRACT

This project analyses the feasibility of the integration of an automation system for custom-made composite part production at the superyacht equipment manufacturer Rondal BV. An analysis of the current prepreg production is performed to understand the automation opportunities and production requirements. Nesting, kitting, protective film removal and the laminating of the plies as well as de-bulking preparation for the laminate were identified as potential automation areas. The analysis also considers the labour time and cost efficiency of the production.

Various automation techniques currently applied in other composite manufacturing industries have been considered and analysed for their feasibility to the Rondal product manufacture. The focus of the analysis was to keep the current manufacturing steps, while reducing labour hours and lead time. The proposed system has also been assessed in terms of its future advancement by considering its current state of development within the industry. Based on this analysis the most appropriate automation solution is the “Pick and Place (P&P) cell” concept. Its capabilities and flexibility recommend it as a suitable candidate to be implemented in the automated manufacture of the variety of Rondal products.

Challenges of each individual equipment within the P&P cell and their interactions are described in detail. Predictions for the automation equipment except for the film removal tool where able to be obtained through literature and interviews with experts in the industry. Due to the lack of available literature information fitting this specific application, on the protective film removal process, a large proportion of this project was dedicated to the development of this tool. In contrast to previous developments, this project uses shock cooling as a solution to detach the protective film from the prepreg.

Implementation of a P&P cell concept was further investigated by the ability of the robot to reach all equipment without affecting the work flow throughout the Rondal workshop. Regulations and other layout restrictions have been considered for the final layout proposal. In order to align the manual and the automation process effectively, common mechanized process steps have been integrated for the use of both approaches.

The effectiveness of the chosen automation system was demonstrated by analysing cost and time statistics of the on-site process, as well as observations of a computer-assisted process simulation. As a result, lead time saving of up to 5 work days per product type as well as labour time reduction of up to 50% were determined. However, the economic analysis showed that the investment into the P&P automation system is not feasible given the current volume of production. On the basis of these conclusions, recommendations have been made to Rondal, proving potential production changes that could lead to an effective integration of automation at their facilities.

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AFP - [Automatic Fibre Placement]
ATL - [Automatic Tape Laying]
ERP - [Enterprise resource planning]
FW - [Filament Winding]
NDT - [Non-Destructive Testing]
NLR - [National Aerospace Centre]
Prepreg - [Resin Pre-impregnated fibre mats]
P&P - [Pick and Place]
P&S - [Pick and Sort]
UD - [Unidirectional Directional fibre mats]
USP - [Unique Selling Point]

CHAPTER 1 - INTRODUCTION

This introductory section provides an overview on the aims of the project at the company Rondal BV. Emphasis is also given to the meaning of automation and its current role in the marine industry.

1.1. AIMS OF THE PROJECT

The aim of this project is to investigate the current composite automated manufacturing systems and choose the most suitable system for the production application of the various products at Rondal. The current production pathway was analysed and its development needs and requirements were determined. These are compared to the current state of composite automation. Based on that analysis the best suiting technology for Rondal is chosen and recommendations for the process implementation are given. The intentions of the automation system are to improve the health-related working conditions of Rondals employees, promote product quality and production capacity as well as reducing cost and delivery time to the customer.

These aims lead to the following research question that this project is trying to address:

"What is the most suitable automation option for the production of Rondal's custom-made equipment and *how can it be implemented into their existing production process?"*

A boundary condition set for this project, is that no major production process redesign is performed. The current process is taken as a basis for the automation integration. The objective is to ultimately provide a report that demonstrates the research, analysis and evidence to highlight the investment potential into the automation system. The analysis points out challenges to face to make an implementation in the Rondal production possible. A series of contact persons and companies that can support and help realize such an automation system will also be provided in this report.

1.1.1. SUPPLEMENTARY QUESTIONS

The supplementary questions are categorizing in three main topics which are answered throughout the report:

1. Suitability of the current production process for automation
    - Can all custom-made parts be classified into process families that follow a common production pattern?
    - What are the quality, cost and time standards for products produced in the current setting?
2. Analysis of existing automation technologies
    - How do the current automation systems for composites compare to one another?
    - Can they be combined with assembly or finishing automation?
    - Can a simple pre-existing or so-called 'off-the-shelf' solution be fitted to the custom-made automation environment?
    - In what way do the current production processes have to be adjusted to accommodate for the new technology?
3. Enabling smooth production transition
    - What potential sources of problems can be identifies prohibiting a smooth transition of production?

1.2. RONDAL BV

Rondal BV produces customized equipment for superyachts, such as rigging and doors. More important for this project, Rondal develops booms, rudders, superstructures, masts and other equipment out of composite material since 1996. Over these 20 years they have been the pioneer developers of the OOA (Out Of Autoclave) and VBO (Vacuum Bag Only) pre-impregnated (prepreg) composite materials which are now commonly used in the composite manufacturing industry.

Rondal is a sister company of Royal Huisman and are working hand in hand with them. However, to be able obtain orders from other Superyacht builders, they require a different company name. One of Rondal’s most known market products is their ability to manufacture masts in one piece. This provides great structural advantages, making them thereby an attractive and widely used product to yacht builders. Thus far, the longest mast was produced to a length of 73 m.

Rondal aims to stay up to par with constant development in the field. They have been working in collaboration with Gurit and the National Aerospace Center (NLR) for many years to keep up with development and research into the composite production processes. Now, they are looking to invest into an automated system for their own labour and time intensive production process. The venture of the purchase is an investment into the future and a mean to stay ahead of the competition.

They gaol is to gain more market potential out of their products by reducing delivery time to customers and simultaneously save labour cost within the overall production process. Furthermore, they aim to improve the health-related work environment of their workers by minimizing repetitive motions that could impact their back and joints. The hope is to further motivate the workforce by assigning them to tasks with variety and to allocate the work forces to more value-adding tasks within the custom-made part production, which cannot be automated. Finally, the integration of an automation system will also enhance the quality to a constantly reliable high standard given by the use of a robot.

1.3. DEFINING AUTOMATION

The ISO 8373 standards on Robots and Robotic Devices provide concrete definitions for terms related to automation. This project is developed based on the understanding of these definitions (ISO, 2012). Autonomy is the ability to perform a given task based on current state and sensing, without human intervention. A robot itself is defined as an actuated mechanism in two or more axes with a degree of autonomy, moving within its environment to perform intended task. They are classified into industrial and service robots. The differences between the two are as follows:

Industrial robots	**Service robots**
Automatically controlled, reprogrammable and multidisciplinary in three or more axes, which are either fixed in place or mobile, for industrial automation application.	Performs useful tasks for humans or equipment excluding automation applications. These can for instance be professional service robots that help workers accomplish their tasks.

As described by Groover (2008) an automated manufacturing system, as it is aimed for in this project, can use some degree of human participation. However, this human intervention must be of a lower degree than the corresponding manual process. Especially, in one-of-a-kind production semi-automated systems, also referred to as mechanized systems, are often the favoured solution (Andritsos & Perez-Prat, 2000). The main reason for which automation is of interest is the reduction of labour hours and lead time, increase of productivity, creation of a constant quality product and reduction of the scrap material per component (Bjornsson, Thuswalder, & Johansen, 2014). Gant (2006) analysis states that whilst manual processes have between 20-40% of scrap material. Automation is able to reduce that to only produced 3-10% scrap. Additionally, the resulting quality of the product is constant and therefore more reliable and predictable (Grant, 2006). The implementation of automation can either simply automate tasks that have before been done manually or provide new options to redesign the production processes to eliminate process steps.

1.3.1. AUTOMATION IN THE SHIPBUILDING INDUSTRY

Andritsos and Perez-Prat (2000) state that most development research on robotics and automation of manufacturing systems has been performed for large volume production. This is a contrasting application to the requirement in the small volume and specialised shipbuilding industry. The differences between these two industrial uses of automation are based on the following aspects (Andritsos & Perez-Prat, 2000):

High Volume Industrial Automation	**Shipyard automation**
• Repeatability over thousands of cycles	• One-of-a-kind operations
• Planning an optimization through simulation or trial and error testing	• Planning and optimization can only be performed through simulation
• Reliability is more important than accuracy	• The payloads can get very high
• Procedure can easily be taught	• Complex, teaching is more difficult

These differences make full automation with high volume machinery difficult to apply in shipyards (Andritsos & Perez-Prat, 2000). Yet, over 50% of shipyards have some form of automation procedure of their production process. This is often in form of mechanization where the manual work is made significantly easier through collaboration with technology. The application areas for these are welding, special processes such as cutting, and assembling including mechanical attachments or bonding.

Due to the nature of steel construction work of the ship building industry, the main focus has been placed on the automation of the welding process. Lee (2014) argues that one of the major reasons for this is that this automation reduces the exposure of the working force to hazardous circumstances within enclosed spaces. Through automation work, in the double bottom of hulls for instance, the amount of accidents is significantly reduced. It should be noted that other areas also provide opportunities for automation, for example in cutting, assembly and surface finish areas.

CHAPTER 2 - COMPOSITE PRODUCTION

This chapter provides insights into specifics of the different types of products manufactured at Rondal. Details about the manufacturing methods are explained and quality requirements are determined to set a comparative baseline for the characteristics of the automation system. This chapter also identifies areas in which some form of automation is already integrated within the current production.

2.1. PRODUCT OVERVIEW

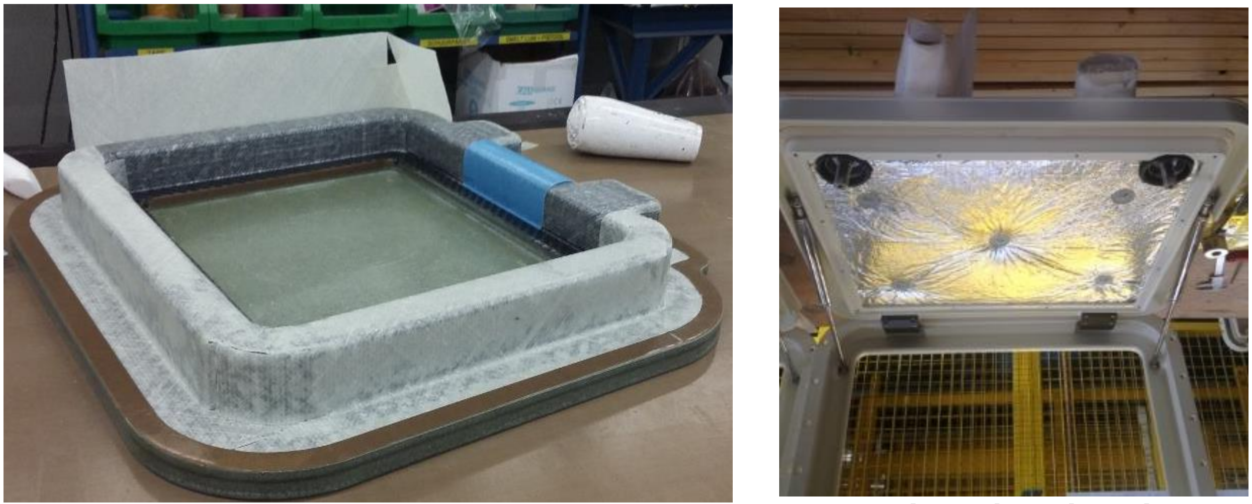
A product overview is given by not only describing the various types of products manufactured but also by describing the materials used for their manufacture. This overview also provides quantitative information on the demand of the products and is of importance to develop an understanding of the production at Rondal. A thorough knowledge of the manufactured products helps to determine in later stages of the project, which automation process can be applicable to the variety of products.

2.1.1. PRODUCT TYPE

This section presents the five different categories of Rondal products. These are placed into different categories based on their manufacturing processes, including the single mould, the hollow, the flat and the outsourced products. All of these are assembled together to form the fifth type or final product.

2.1.1.1. TYPE 1 - SINGLE MOULD PRODUCTS

Single-mould products are classified as type 1 products. Some products might even require a core material as part of their laminate, others only local reinforcements. These can either come in the form of simple shapes such as for the mast inner shell, or more complex as required for the hatches (Figure 1). So far, it has been a challenge to manufacture the hatches cost effectively. To improve this, Rondal has designed a new product concept in which a certain number of hatches are standardized and kept on stock to help reduce their overall lead-time. This provides an increased opportunity for automation.



Sample Hatch in Production

Sample Hatch Finals Product

Figure 1: Sample Hatch

2.1.1.2. TYPE 2 - HOLLOW PRODUCTS

Type 2 products are hollow structures and are manufactured using an inner bladder, made from a sealed vacuum bag. These need a top and a bottom mould, which are assembled before curing. Hence, they require an extra assembly step to bring both sides together. These parts also often require local reinforcement such as seen in the mast spreader manufacture (Figure 2). This two-mould process simpler than to use expensive sacrificial core mandrels.

Spreader Base Product out of Mould

Sample Two Mould Spreader Production

Spreader Tip Product out of Mould

Figure 2: Sample Spreader

2.1.1.3. TYPE 3 – PLATES

Type 3 products are flat products with a significant thickness between 10 mm to 100mm. These plates are laminated into larger assemblies. The laminate is manufactured at Rondal in large rectangular shapes. Once cured, the plate is sent to an external company for waterjet cutting it towards the desired shape. The process is very simple but time consuming especially with regards to de-bulking (removing air between the individual layers) of the numerous layers.

Lug Plate

Assembly of Lug Plate on Mast

Waste Product after Waterjet Cutout

Assembly of the Vang and Gooseneck Plates with Foam Core inserts

Figure 3: Sample Plate

2.1.1.4. TYPE 4 - FULLY-OUTSOURCED PRODUCTS

The 4th type of products is fully outsourced and directly used in the manufacture of the type 5 end products. These products are tubes and pipes that are either braided or feature filament winding (these processes are later explained in section 3.2.2 and 3.2.3), usually manufacture out of glass fibre. Outsourcing is a much more cost-efficient solution than manufacturing them at the yard. Typical examples include the cable tubes along the length of the mast.

Figure 4: Inner Mast Assembly from Outsourced products

2.1.1.5. TYPE 5 - ASSEMBLED PRODUCTS

This product an assembly of the previously described product types. It is categorized as a different type since its production steps differs to form any of the previously explained processes.

The assembled skeleton is used as a base on which the laminate thickness is added. For instance, the mast production uses the inner shells (type 1) and assembles them to form the length of the mast. Before closing the mast shell, which is done by gluing the top into place, products type 4 are inserted within the mast. Once the shell is finished, its thickness is built up on top of the shell along the entire length of the mast. This is referred to as 'one piece' manufacture. Further, Type 2 and 3 products are then laminated onto the exterior of the most shell. Even though product type 5 is the most time-consuming product in the overall perspective, it is also the most challenging to automate due to its distinct assembly processes.

Within this shell process, two types the outer shell lamination can be identified. This is the outward laminate shell, as it is done on the mast, and the inward laminated shell, as it is done on the boom, to ensure a smooth mould surface is kept on the outer surface of the part.

Outer Mast Laminate Layup

Local Reinforcement Laminate Layup

Figure 5: Mast Outer Laminate

The integration of an automation system could potentially prevent products from having to be outsourced. A braiding machine for instance, would make it possible to manufacture the tubing that is currently outsources. In that case it becomes cost effective to manufacture these products in house. This project mainly focuses on finding a direct automation application to produce types 1-3, because those are of a higher volume and have the most repetitive tasks within their manufacture., thereby making them more suited for automation. The application for product type categorised 4-5 are considered in a more conceptual manner since their automation is more difficult to achieve in a cost-effective manner.

2.1.2. MATERIAL

Knowing the material out of which the products are manufactured, is the basis to understand the time-consuming tasks in the manual production as well as the process steps of future automation technology. The material used in Rondal production is pre-impregnated mats of both carbon and glass fibres. This material, commonly referred to as prepreg, comes in different types and orientations. Carbon prepreg is generally only used in high structural performance composites for the aerospace and high-performance car industry due to its high durability and considerable material cost. Rondal uses carbon fibre prepreg either with a unidirectional (UD) orientation 0° or in a woven state, where fibres are either intertwined at 0°/90° or +/- 45. Glass fibre prepreg is also used in some cases, but only a woven state.

Prepreg is stored in freezers to delay the chemical reaction of the pre-catalysed resin that causes them to harden during the curing process. The shelf life of a roll of prepreg lies between 6 to 8 weeks from the date it has been taken out of the freezer. After that the material hardens on its own and no longer forms the bonds required within a laminate.

The UD material is the mostly used laminating material for all parts. This woven material is mostly used as an outer skin layer to every composite product, acting as outer protection against commonly occurring delamination. The UD fabric has all the fibres lying next to each other, so it can easily sustain post processing, for instance drilling. Under the same conditions, the UD materials can suffer delamination, which once occurred in one fibre, can spread along the entire length of the product. The intertwined fibres of the woven fabric prevent that and thereby make post processing of the material significantly easier.

To be noted is that UD material is normally used from either 300 mm or 400 mm wide material rolls. The material does exist in wider rolls of 1270 mm width. This is less frequently used since those rolls are very heavy and take up a large amount of space within the freezer. The smaller rolls can be stacked on top of one another or other products to optimize space use. The thinner material is easier to handle and is thus the preferred choice of material among the workers.

The prepreg used at Rondal has two particularities when comparing to the standard prepreg used in the industry. The differences lie in the protective film and resin the fibres are impregnate with. This resin is suited for special low temperature curing and only needs to be heated up to 80°C for the curing process to start. It also does not require the pressure of an autoclave oven to cure (Gurit, 2012). Rondal generally cure their products at around 90-95°C.

Most prepregs are protected by packing paper to shield the material from contamination with impurities. The packaging paper is ridged and easy to remove. When initially placing the ply in the mould the top protective layer is kept on, so that the material is less sticky before it is removed, leading to faster shaping. The backing paper is too rigid to be properly formed into the double curved mould surfaces, so Rondal uses thin polibacks. They are transparent plastic films, more flexible than the paper. The UD material features protective film, on both the bottom and the top sides of the mat, while woven material only have it on the outer side. The example below explains how to interpret the different name descriptions.

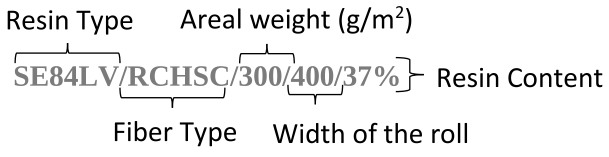


Table 1 provides an overview of all the different types of prepregs used in production at Rondal. The list of materials provides an indication of the cost of prepreg which will later be used for the process and cost comparison of the automated and the manual processes. Additionally, the ranges of material roll lengths provided, suggest the amount of material the automation system can be feed, if it is to use the current selection of prepregs used.

Table 1: List of Materials used at Rondal

Material Type	Cost (€) per m^2	Material per roll length (m)
SE84LV/RC416T/1270/42%	29.97	25
SE84LV/RC200T/1270/42%	26.29	50
SE84LV/RCHSC/300/400/37% (Blue backing film)	14.58	150
SE84LV/RCHSC/300/400/37% (Green backing film)	40.31	150
SPARPREG/HSC/600/300/34+/-3%/2DPE (1240 width)	18.80	250 (120)
SE84LV/RE291QH4/1000/39%	13.28	50
SE84LV/XE905/1270/35%+/-3%	29.61	15
SE84LV/XC411/1270/40%	26.05	30

2.1.3. QUANTITATIVE DEMAND

The products considered in this project do not span the whole portfolio that Rondal manufactures. Due to the custom-made nature of the company it is difficult to categorize every product. Still, even though the products are custom made in size and design, the production method remains similar. This leads to the identification of a series of repeating base products, which form the base for the analysis carried out in the current project. The products that fit this category need to have been manufactured three times in a similar manner and are, thus, likely to be produced again in the future. A full summary of all parts with more detailed information is provided in appendix II. The following quantitative descriptions assume a single manufacture of each product kind. This section has been added to this report for completeness, to be able to relate to specifically which kind of products are considered in this project. The relevant areas for the progression of the research are summarized at the end of this section.

2.1.3.1. MAST

Since 1998, 22 masts (incl. mizzen masts) ranging between 50-73 m, have been manufactured and four have been planned for the upcoming year. The mast consists of subparts that are produced in different manners. The parameters relevant for the process analysis are the number of parts required per unit (mast, boom, hatches), the thickness and the number of plies required.

(a) MAST SHAFT

The mast starts with the making of the shell. The small inner products are glued into place within, before the shell sides are closed. They are combined by means of the backing strip which connects them. Once closed the thick outer layer is laminated onto the shell to form the one-piece mast product. Table 2 provides an overview of these parts, along with an approximation of their average number required for one mast and their thicknesses.

Table 2: Products Making up the Outer and Inner Laminate

Part Name	Number per mast	Thickness (mm)	Number of layers
Shell front	15	3	12
Shell back	15	3	12
Backing strips	30	3	12
Backing strip connection profile	15	3	12
Extender box	1	x	x
Outer laminate	1	35	64

(b) SPREADERS

The spreaders are the second largest components on the mast. They need to be hollow to allow devices, such as radar or light cables to be pulled through them. Dependent upon the length of the mast, 4-5 sets of spreaders are needed with sizes between 1.8m and 7m. Addons are later laminated onto the main spreader structure. The backing plates, which makes it possible to attach the spreader to the mast, fall into this category. The vertical spreader tubes, as well as the radar platform also count to these add-on products that make up the final spreader. Table 3 summarizes the different parts required for the spreader manufacture.

Table 3: Products Making up the Spreader

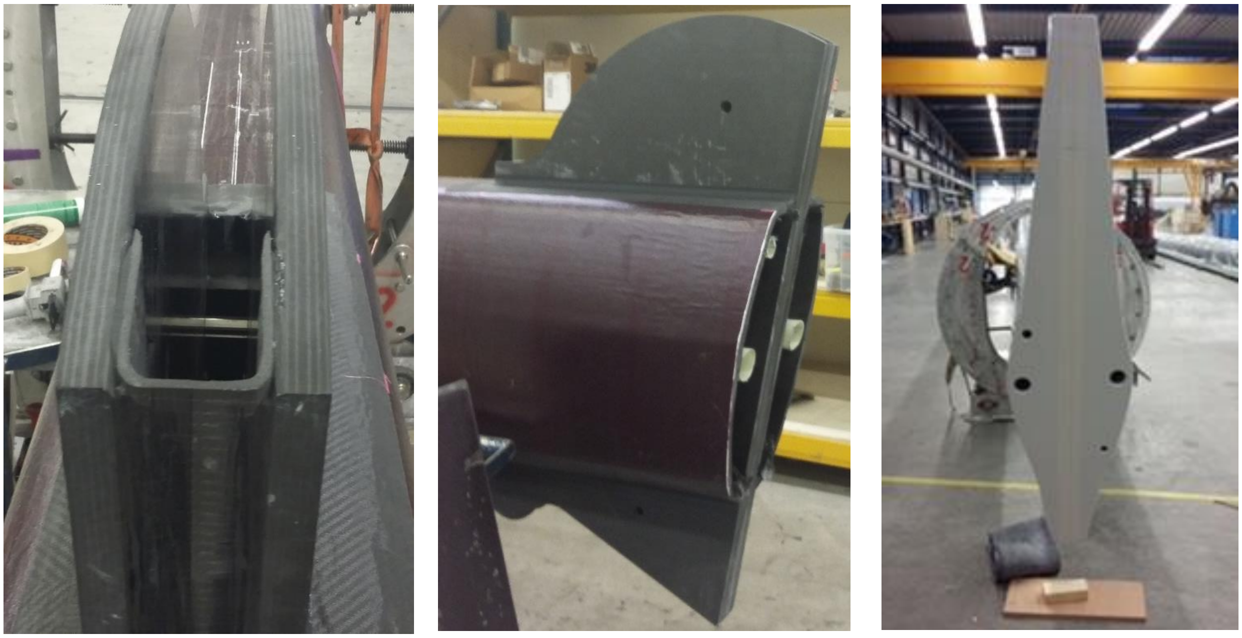
Part Name	Number per mast	Thickness (mm)	Number of layers
Spreaders	10	10 (base)	75 (including patches)
Backing plate	10	30	162 (including patches)
Vertical spreader tubes	10	4	15
Radar platform	2	14 (base)	15 (including patches)
Dome platform	2	14 (base)	15 (including patches)

(c) MASTHEAD

The masthead consists of three main composite parts: the U-Shape, the top plate and the side plate. The U-shape profile connects the two side plates as seen in Figure 6- The mast top plate is attached flat onto it, covering up the hollow shell and preventing water from entering.

Table 4: Products Making up the Masthead

Part Name	Number per mast	Thickness (mm)	Number of layers
U-shape	1	3	12
Top plate	1	14	37
Side plates	2	25	82



Assembled U-Shape Assembled Masthead Side Plates Assembled Mast Top Plate

Figure 6: Mast Head Assembly

(d) LUG PLATES

The three types of plates that are used in the mast assembly are the gooseneck lug, the vang lug and the mandrel lug. These are thick laminates that constitute connection pieces between the mast and other sailing equipment such as the boom or the halliard to hoist the sail. These locations are under high stress and require much material strength. The varieties of average plate thicknesses used in the mast production are given in Table 5.

Table 5: Different Mast Lugs Used in the Mast Manufacture

Part Name	Number per mast	Thickness (mm)	Number of plies
Gooseneck lug	2	62	106
Vang lug	2	62	53
Mandrel lug	2	34	66
Forestay lug	1	25	44
Forestay web	10	12	25

(e) OTHER

This section contains all other products that were not classified into any of the previous subcategories. They include the tube, running along the length of the mast for electrical cables, its connector to the mast and a sensor box. These parts are made of glass fibre prepreg and serve the purpose of organizing the inner part of the mast. The last small is an adapted imprint of the outer shell to form the ventilation cover. It prevents debris and large amount of water to enter the mast at openings. The specification for the described part are provided in Table 6.

Table 6: Other Parts Required for the Mast Manufacture

Part Name	Number per mast	Thickness (mm)	Number of plies
Tube	38 on average (dependent on mast length)	Outsourced	Outsourced
Connector for tube	10	3	12
Sensor box	4	3	12
Ventilation cover	4	3	12

2.1.3.2. BOOM

The following are the most commonly encountered products in the production of a boom.

(a) BOOM STRUCTURE

The boom consists of two sides, the port and the starboard side. These are connected through bulkheads and the floorplate. The guide roller arms, which are made upon an imprint shape of the inner boom, make reefing of the sail possible. The end of the boom is formed by a cover, which is cut off from the main boom structure. Another component is the mandrel around which the sail is wound. This mandrel is an outsourced product. Table 7 summarises the main components of a boom.

Table 7: Products that Make up the Boom

Part Name	Number per boom	Thickness (mm)	Number of plies
Port side	1	20	11
Starboard side	1	20	11
Floor	1	3	9
Bulkheads	6	10	67
Guide roller arms	4	53	161
Mandrel	1	Outsourced	Outsourced
Cover plate	1	52	96
Aft bulkhead	1	20	34
Patch plate	1	8	14
Gooseneck sheaverbox plate	2	8	14
Gooseneck sheaverbox horizontal spacer	3	8	14
Gooseneck sheaverbox vertical spacer	6	8	14
Gooseneck Patch plate outhaul	16	8	14
Gooseneck sheaverbox bearing plate	4	8	14
Preventer sheaverbox top plate	1	8	14
Preventer sheaverbox spacer	11	8	14
Preventer sheaverbox bearing plate	4	8	14
Main sheet sheaver plates	6	8	14
Main sheet top plate	1	8	14
Main sheet sheaver box spacer	4	8	14
Main sheet sheavebox web	4	8	14
Gooseneck inside/ outside cheek plate	4	13	22
Gooseneck web	6	13	22
Flush padeye web	2	13	22
Plate end cover	6	13	22

(b) TUBES AND HOUSINGS

A number of pipes and housings are included in the assembly of the boom. These are summarized in table 8. Most of these parts are made of glass fibre composite.

Table 8: Pipes and Housing for Boom

Part Name	Number per boom	Thickness (mm)	Number of plies
Connection tube	3	Outsourced	Outsourced
Electrics tube (Figure 4)	2x length of boom	Outsourced	Outsourced
Boom light housing	1	3	12
Van tube	1	10	Outsourced
Tang	1	26	87

2.1.3.3. HATCHES

There are many different types of hatches, ranging from deck - and sailor locker - to lazarette -, crane - and lift keel inspection hatches. The components out of which all these different hatches are made are: the gutter, the hatch sections, and the cover plate. Table 9 gives a summary of the hatch parts.

Table 9. Products that Make up Hatches

Part Name	Number per hatch	Thickness (mm)	Number of plies
Cover plate (Figure 1b)	1	4	
Hatch section	1	4 (base)	41 (including patches)
Gutter (Figure 1a)	1	3	8

2.1.3.4. RUDDERS

Six types of rudders have been manufactured with lengths varying from 4.5m to 7.5m. A rudder consists of a rudderstock, which is made out of an inner shell, and outer build-up laminate. The rudder blade is wrapped around a foam core and the rudderstock. Table 10 lists all parts required for the rudder manufacture.

Table 10: Products that Make up a Rudder

Part Name	Number per rudder	Thickness (mm)	Number of plies
Rudder stock shell	1	3	11
Rudder stock outer laminate	1	50	106
Backing strip	2	2	6
Plates for bearing housing	4	5	22
Rudder blade	1	3	7

Table 11 summarizes all the presented products and indicates under which product category they fall. The number of parts column includes duplicate of the same product, that are required for the end product. It can be seen that the flat plates are the most numerous within the product type. This is due to the fact that many of them are cut out of the same manufactured plates. If only the manufacturer plates are considered, these add up to 20 different manufactured parts.

Table 11: Number of Parts Per Product Type

Ranking	Category	Type of different parts	Number of parts	% of total parts
1	Product Type 3	30	112	38%
2	Product Type 1	20	106	36%
3	Product Type 2	8	40	13%
4	Product Type 4	7	32	11%
5	Product Type 5	5	5	2%

This comparison only analyses the quantitative aspect of the products. The percentage of parts produced for the flat plates for instance, is 41 % of the total. This does not mean that the qualitative time (or value added to the end product) is spent on those plates. Many of the type 3 products are small and their labour time is minimal when compared to the type 5-, assembly products. Their parts might only constitute 2 % of the total products but their significance for the mast production is shown to be at least 6 % of the composite labour time performed on the entire composite mast (Table 12). Another example concerns the spreader manufacture. Together with the other hollow products they make up 13 % of the quantity of parts produced yet the spreaders take 17 % of the composite labour time and thereby nearly 5 % of the entire mast cost. This is further elaborated in section 4.1.

2.2. MANUFACTURING METHODS

This section points out commonalities between product types. The main two production techniques are briefly described, then the detailed production steps are illustrated using flow charts.

2.2.1. PREPREG IN AUTOCLAVE

Throughout this process the prepreg is moulded into the desired shape and cured under pressure in an autoclave oven. The parts manufactured through this method have a size restriction, since the moulds have to fit into the autoclave. Autoclaves are normally used at temperatures between 120°C and 180°C. However, Rondal usually cures their products around 90°C-95°C with 3 atmospheres of pressure. This is due to the low temperature curing resin they use (Gurit, 2012).

Figure 7: Rondal's Autoclave Oven

2.2.2. OUT OF AUTOCLAVE (OOA)/ VACUUM BAG ONLY (VBO)

In the introduction, it was mentioned that Rondal pioneered the OOA with VBO approach together with the composite development and material provider Gurit over 20 years ago. One of the most important aspects of the OOA with VBO lies in the low temperature curing prepreg that is used for all their products. The main difference to the autoclave method is that no external pressure is added during the cure process. Since the products are not placed in the autoclave, the size restriction is no longer present. This method makes it possible to manufacture products such as 70m long masts. The oven consists of chambers that are lifted over the product and its mould. The chambers are attached to each other surrounding the product (view Figure 8). The air inside the oven is heated to curing temperature. The mast production has a dedicated hall that can be turned into one giant oven.

Figure 8: Movable Oven for OOA

2.2.3. PROCESS STEPS

For the research of this project, the identification of the commonalities within the processes, shown through flow charts, has high relevance since is helps to filters out the steps for automation. This section briefly explains the most important tasks of the production process to help better understand details about it. The tasks only relate to labour hours of the manual manufacture.

2.2.3.1. STEP DESCRIPTIONS

The steps described include engineering work, cutting, kitting, laminating, de-bulking and preparation for cure as well as the de-moulding action after the cure has occurred.

(a) ENGINEERING WORK

The engineer needs to develop the product design, calculate specific strengths and create drawings that is checked and approved by a classification society. This is a lengthy process, but it is not considered part of the actual composite manufacture. Before any physical manufacturing can start, the work preparation department will have to order all equipment required for the manufacture, such as material or the moulds.

(b) CUTTING

The cutting process is the first physical step of the composite manufacture. It includes tasks such as the removal of the material roll from the freezer (the day before use, to be able to give it time de defreeze) and the nesting of the plies that need to be cut. Further tasks are lifting of the roll (approx. 80kg) onto the cutting table and the adjustment of the material into the correct position. These tasks might seem trivial but do add up to a considerable working time. Once all is in place the cutter can start cutting. The cut plies and the waste material need to be taken off the table before a new round of cutting can be initiated.

(c) KITTING

The kitting process can be performed when the plies are taken off the cutter. It is however identified as an individual process since it is an important step in achieving efficient and error free laminate. The workers need to identify the material and orientation of the cut ply and follow the work instructions to kit the plies in the correct order, or so-called stacking sequence. Once all the plies are stacked in order the kit is complete and can be brought to the work station.

(d) LAMINATING

The laminating of the plies consists of many individual subsequent steps. To start off with the ply is placed together with its backing film in the correct location on the stack. Then if needed for a UD ply the bottom backing film is removed carefully. The next step I is the ply consolidation by putting pressure on the top surface, it takes out air between layers whilst squeezing the ply into every corner of the mould. The top protective film is then finally removed and any overhanging flange is cut off. To finish the cycle a mark is placed on the work instruction to indicate the ply has been placed. This step becomes extremely important with the thicker laminates of several hundred plies, as it can happen that one forgets what ply has just been laminated in the overall stack. If one of the orientations is missed or swapped the entire laminate could be out of balance and end up impacting the material properties. The same counts for forgetting to remove all the protective film.

(e) DE-BULKING

De-bulking is a way to extract air trapped within the laminate. During the process, a vacuum is created surrounding the part, just as the consolidation step during laminating. The preparation to achieve this includes cutting the vacuum envelope bag and flow mesh (allowing the air to be drawn out of the sealed bag) and seal the envelope along all edges. Depending on the process these materials can be reused. The rule of thumb is: for every 5 layers of prepreg the product is debulked for 1h. Naturally, the removal of the de-bulking material is also part of the tasks that need to be accomplished before laminating can be resumed.

(f) PREPARE FOR CURE

Once all plies have been laminated the product needs to be prepared for curing. This is a very similar process to the de-bulking preparation, except that a few more materials are added. A further bleeder helps absorb any excess resin. Also, a better seal is required during the cure to prevent any air leaks leaving voids in the product. Some product processes already used this seal strip (tacky tape) during the de-bulking process, but not all do. Once the part is set under vacuum, it is lifted onto a surface that is pushed into autoclave. Alternatively, the oven is lifted onto the prepared part. Curing is usually done overnight.

(g) DEMOULDING

When the product part is removed from the autoclave/oven it needs to cool before all consumable material, wrapped around the mould/plate, can be removed. When dealing with mould products, the next step is to carefully demould them. One final step is required for the hollow products; it is to remove the vacuum bag within. From there on the product can be forwarded to further processing.

2.2.3.2. PROCESS FLOW CHARTS

This section provides the flow charts of each different process type to clearly illustrate the commonalities between the process approaches. Three sections of processes were identified as common to several products. Therefore, these are placed in separately flow charts: product manufacture from a two-piece mould (Figure 11), from a one-piece mould (Figure 12) and the composite subpart assembly (Figure 10).

Based on the given descriptions in Figure 9 the flow charts of the individual product processes should be self-explanatory.

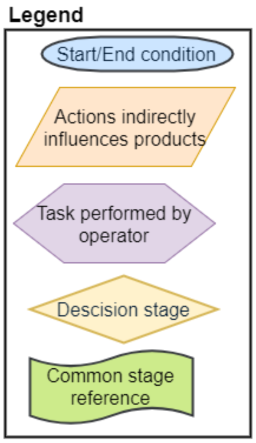


Figure 9: Legend for the Process Flow Charts

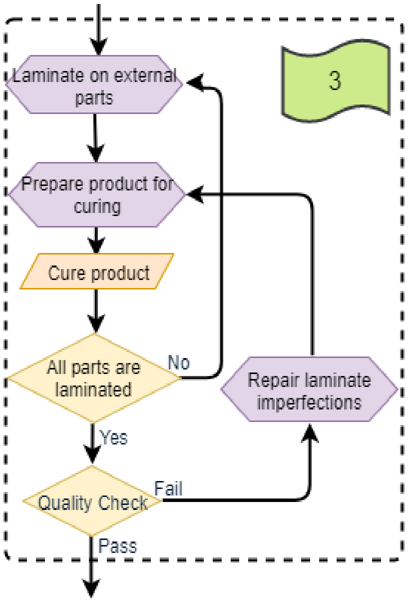


Figure 10: Composite Subpart Assembly Process

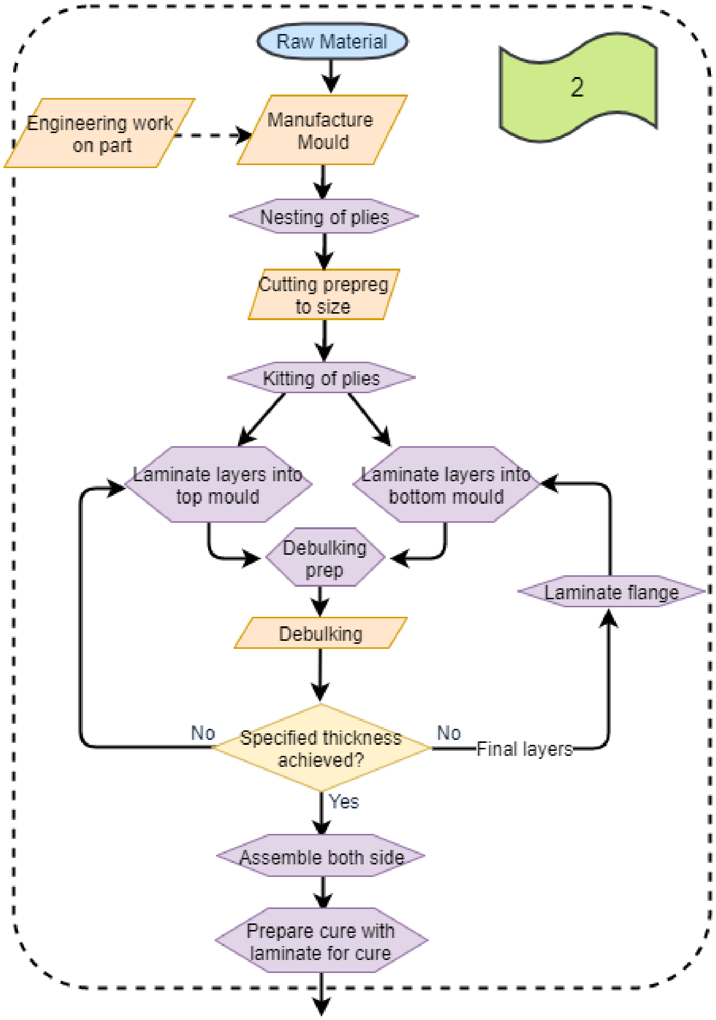


Figure 11: Product Manufacture Flow Chart from a Two Piece Mould

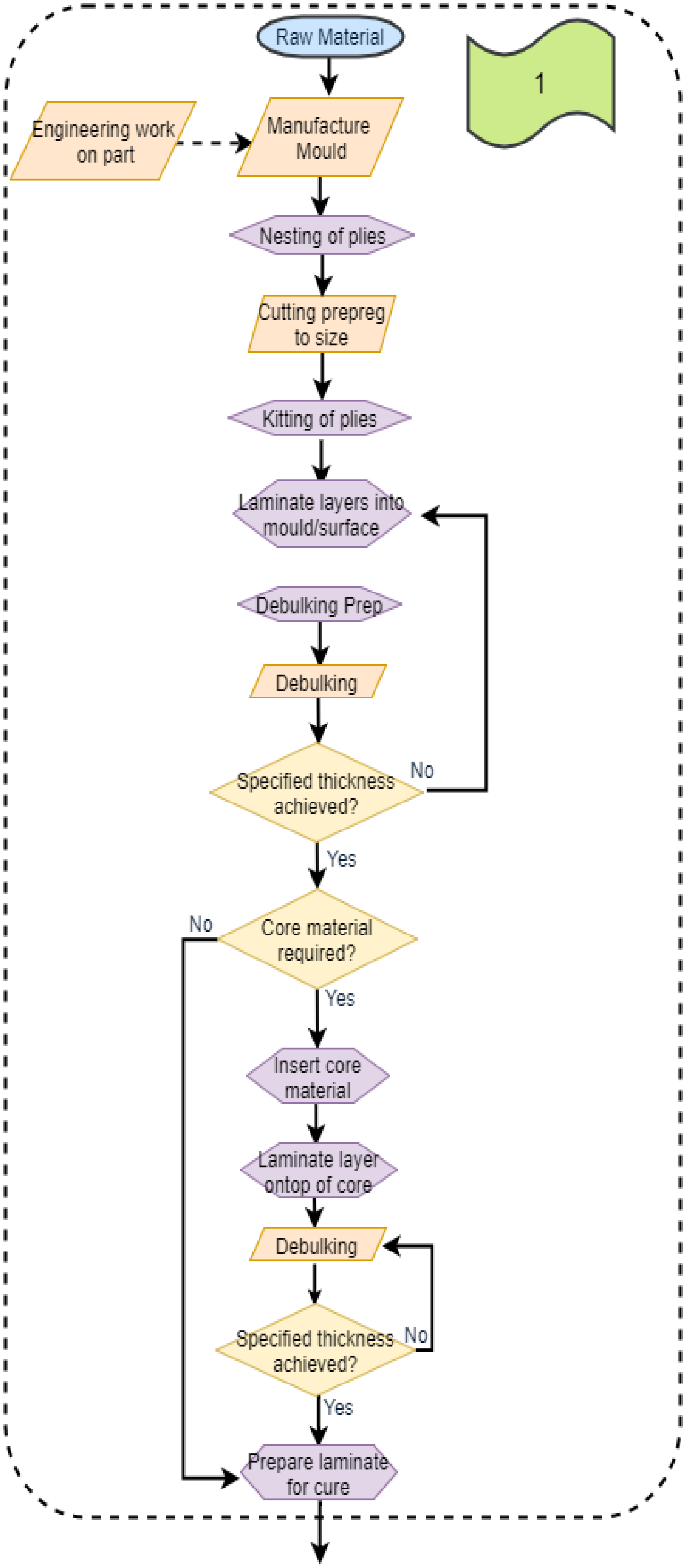


Figure 12: Product Manufacture Flow Chart for a Single-Piece or Flat Surface Part

The three previously indicated flow charts are used as building blocks for the full process Flow chart of the different part Types. For type 4 products no flow chart has been made since they are fully outsourced and therefore their process could not be observed.

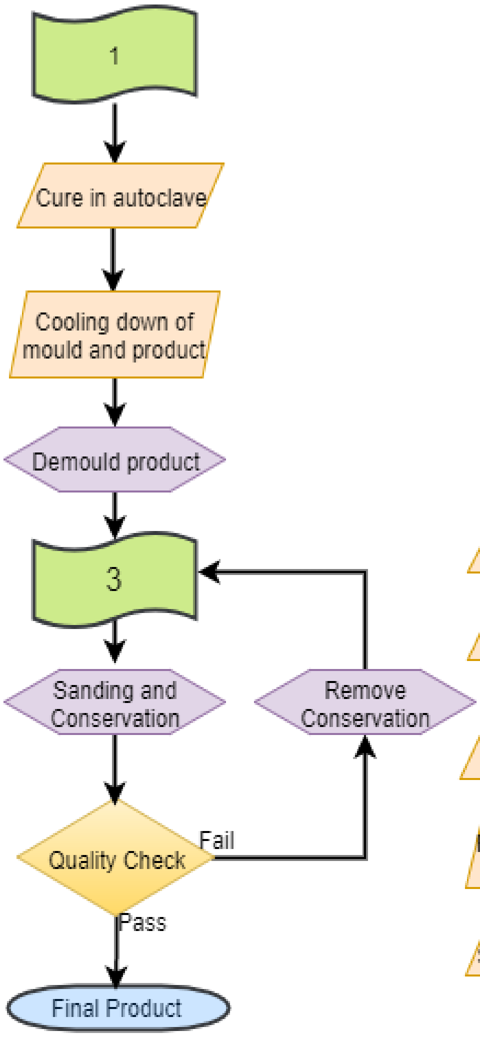


Figure 13: Single Mould Process Flow Chart

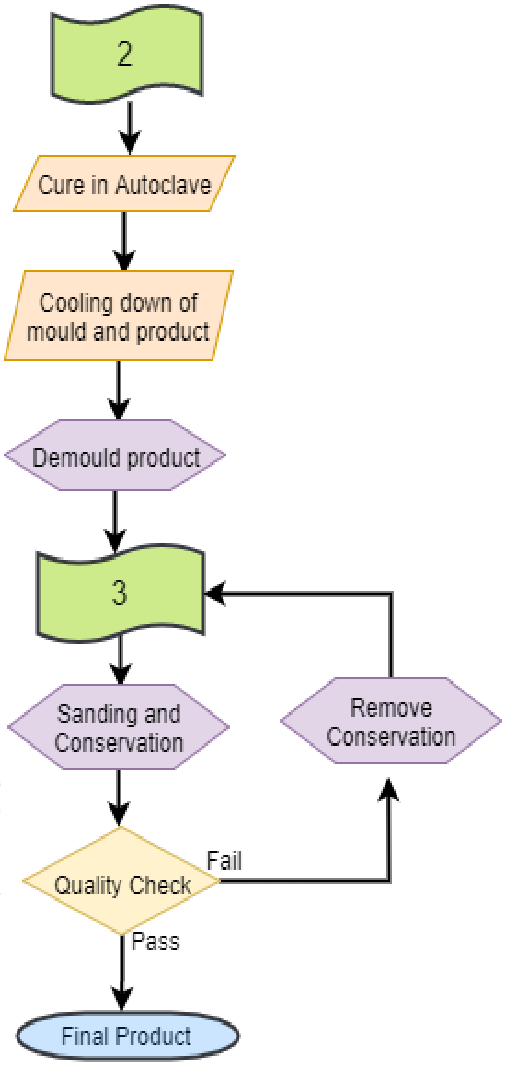


Figure 14: Hollow Products Process Flow Chart

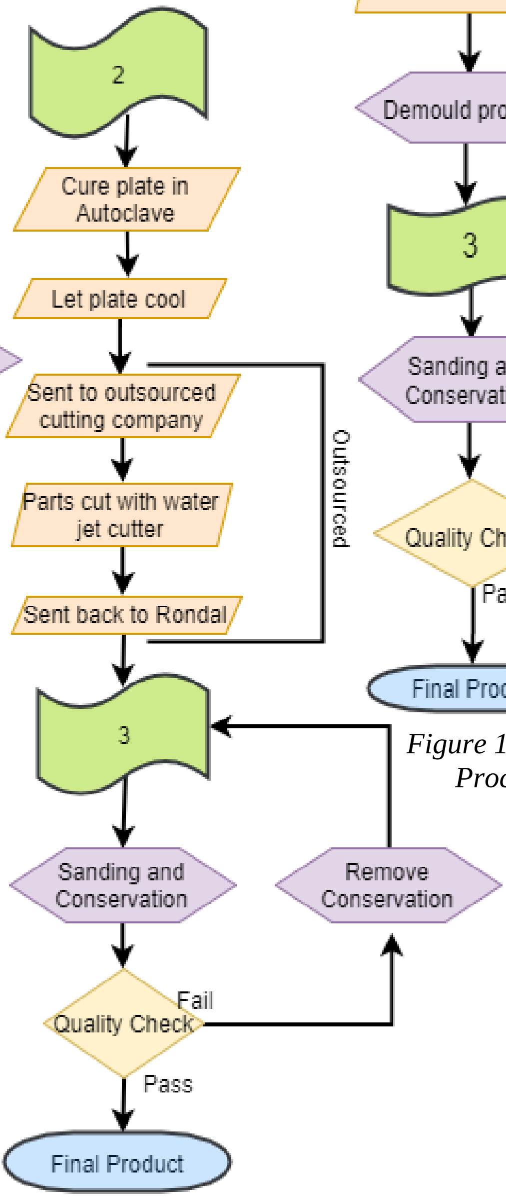


Figure 15: Flat Plate Process Flow Chart

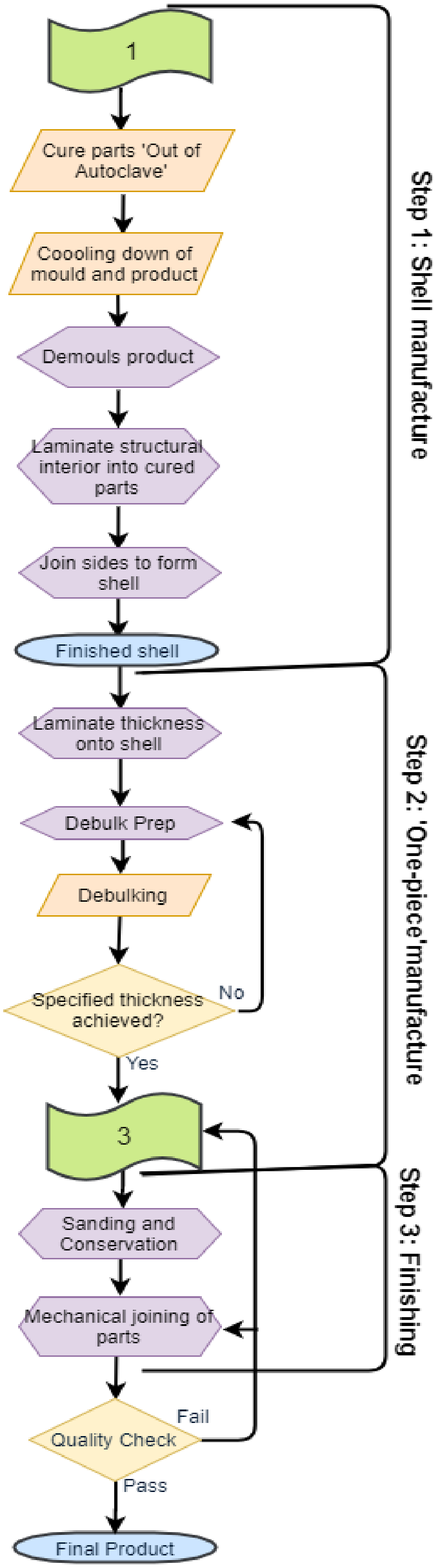


Figure 16: Assembly Products Process Flow Chart

2.2.4. PRODUCTION PARTICULARITIES

This section points out details about the production process that have not been mentioned in the method description but are relevant in later analysis. As mentioned in section 2.1.2 most of the UD material is used from 300-400mm wide rolls. This makes handling of the material easier, but it also means that a larger number of plies is required to produce the same product, as seen in the comparison in CHAPTER 5.

For example, a plate of 3m in length and 1.3m in width is to be manufactured. Instead of being able to place a single 0° ply, 4 plies have to be placed with the last one having to be cut to size. This has a larger impact on the 90° and the 45° orientations. Considering this approach for the thick laminate of flat plates this increases the number of plies laminated. From Figure 17 it can be seen that ply handling for the lamination of such large plates is performed by two workers. This enables to have more control over the ply and hence achieving a more accurate laminate layup with a more effectively spend time.

Figure 17: Laminating Process of a Flat Plate

Another particularity of the complex shaped mould products is that the plies are cut oversize on the cutter. This leaves a margin of about 100 mm on all sides to compensate for any inaccuracy in cutting and ply deformation when handling the ply. Each individual ply is cut a second time into shape once it is in the mould.

Some of the current production processes require large amount of post processing. The design of the process does not provide the opportunity to make all production steps simultaneously. It is important to be aware of these extra steps to be able to determine if automation can include these measures into the main manufacture. It might be possible that the process requires minor redesigns, which can include these secondary processing steps into the main process. One post processing example is the spreader manufacture. After demoulding of the spreader, the backing plate needs to be laminated on, to be able to later assemble it to with the mast. The lamination of each of these backing plates takes on average an additional 80h of labour work per project (Appendix II). The design of the moulds often causes improper curing at the tips of the spreaders where the inner bladder cannot be reached. It is pinched into place by the narrow tip casing bridging of the inner bag. This causes the pressure not to be spread evenly across the inner surface of the spreader and hence the laminate cures unevenly.

2.3. QUALITY REQUIREMENTS

The relevance of the product quality determination is to clearly define features the automation system will have to perform to produce products of equivalent or higher quality than the current production. General quality requirements are for instance an undergoing of a non-destructive test (NDT) (e.g. Laser shearography) in which no delamination due to curing or other defect can be present. Another quality standard is that the current manual layup accuracy lies at a tolerance of about 1-2 mm. This is unlike the production in the aerospace industry where the layup accuracy lies at about a 10th of a millimeter. The last more general quality requirement is that most products require areas of local reinforcements where the laminate thickness is thicker than the rest of the product. These are mainly for high stress areas and locations where post processing is required. These local reinforcements are of importance for the structural integrity of the custom-made parts. For completeness of this report the product specific quality requirements are provided in the following subsections.

2.3.1. MAST

The masts' most important properties are in its longitudinal strength. This mainly applies to the mast shaft as well as for the spreaders and makes the laminate layers of 0° paramount. Additionally, the one-piece construction process is essential, as it improves the structural integrity of the mast. Another important factor of the mast is that different locations have different thicknesses of reinforcement. This mast property has to be kept to in the automated process.

The lug plates need to withstand large amounts of stress and are the connection points to major mechanical components of the mast. The plate's strength is important. Impurities in the laminate can cause weaknesses in the shear strength that could result in delamination of the individual plies. The attachment between the connection laminate of the plates and the mast also has to be of highest quality to be able to spread the loads partially.

2.3.2. BOOM

A requirement for the boom manufacturing process is a smooth mould surface on the outer surface. Wrinkles within the surface, as they are occurring on non-mould surfaces, require filling to be applied to smoothen the surface for the conservation. This is usually less durable and requires maintenance. The outer surface of thick laminates is to be made with a mould face. For the newer boom manufactures the interior structure of the laminate encloses a combination of foam and laminate layup to reduce cost and weight over the thickness of the laminate.

2.3.3. HATCHES

Information on hatches is very limited. It is known however that regional reinforcements, especially in the location surrounding the hinges, are significantly thicker than the rest of the laminate. Therefore, the right positioning of these patches is important.

2.3.4. RUDDERS

The rudderstock is surrounded by foam core, to form the shell around which the rudder laminate self is built up. A solid connection between the stock and the foam is vital to prevent separation when high stresses are acting upon the rudderstock during sailing of the vessel.

2.4. AUTOMATION WITHIN THE CURRENT MANUFACTURE

The automation or mechanization of the current process extends to automated cutting of the prepreg layers and a handheld laser projection tool for the positioning of the reinforcement patches in relation to the mould. Additionally, thee nesting of the plies is done automatically using the nesting software Alphacam Advanced Profiling, which converts the dxf drawing files into files the cutting machine can read.

Figure 18: Currently Installed Cutter at Rondal

CHAPTER 3 - AUTOMATION OPTIONS

This chapter touches presents automation opportunities regarding cutting surface finish and post composite manufacturing process assembly of parts. It also gives detailed descriptions on the automation opportunities of composite automation options that are in use in other industries to show the application options available for the Rondal production. This chapter thereby provides an overall completeness to the report by demonstrating a variety of automation options. Further research analysis is continued in CHAPTER 4.

3.1. CUTTING AUTOMATION

The cutting processes are already automated in most yards. This mainly applies to flat cutting in form of gas-, plasma-arc, gouging, laser and water jet cutting (Eyres & Bruce, 2012). However, many of these cutting methods are not applicable for composite materials due to the extremely high heat exposure, which would impact the composites structural integrity. In their uncured state both prepreg and dry fibres are still soft which means a cutting bladed automation system is sufficient. Yet once cured the thick laminates is cut with waterjet cutters.

A great example for the successful integration of automation into the marine industry is the German yacht builder Bavaria (Bavaria Yachts, 2016). It is known for the incorporation of five custom-built Maka CNC machines used to trim, drill and profiling its deck mouldings into their production. This initially high investment proved itself invaluable for the company. Together with their ‘built-to-order’ manufacturing model, Bavaria managed to underbid their competitors in price and achieve much higher production numbers (Blundel & Thatcher, 2003). The manufacture approach of such series yacht construction is performed based on takt times. The yachts are moved along workstations of different teams or robots to perform a series of tasks before they are move to the next step. As such it is a line production in which the vessel moves along a ‘belt’ path. This is an example for high volume manufacture, in comparison to the custom-made manufacturing of Rondal where every product is custom made.

3.2. COMPOSITE MANUFACTURE AUTOMATION

The use of composites materials in the marine industry is especially applied to Navy military and offshore construction, due to its lightweight and non-magnetic properties (Selvaraju & Ilaiyavel, 2011). Furthermore, the yachting industry has also set a foothold into the composite production, where mainly the smaller yachts are now primarily made of glass reinforced polymers (GRP). Nevertheless, as can be seen by the Rondal business strategy, composite materials also become increasingly more popular in the superyacht industry. However, for large parts with high material thickness that are needed on superyachts, the layer-by-layer production of composites becomes an extremely labour-intensive and time-consuming production process. For this reason, the automation of this sector becomes very attractive to improve and stay ahead of competition.

The aerospace industry has invested vast amount of time and money into the research and development of automated composite manufacturing systems. This is due to the fact that the aerospace structures are much more dependent upon high performance quality of the material than the marine industry is. These somewhat ‘off-the-shelf’ automation technologies can be applied to the Rondal production. This section provides a brief overview over different processes that can be considered.

3.2.1. PULLTRUSION AND PULLFORMING

Pulltrusion is a continuous composite manufacturing designed for high volume production of parts with constant cross section. The fabric, either roving or mats, is dispensed and guided in position onto the die which provides the product with its final shape. Following the insertion of the dry fibres into the injection chamber, they are wet with high pressure resin before being pulled into and through the die. In most cases, the die is heated and performs the curing process as the composite runs along it. During the curing, the product shrinks slightly and detaches itself from the die wall, making it easy to pull out and cut to length (Barbero, 2011).

Pullforming is a similar process with the difference that it is produced one cross-section at the time. The fibres are lead from an impregnation bath directly into a mould that is closed around it and heated. Once cured, the part is released and the material for the following cross-section is pulled into place. (Barbero, 2011). A cost-effective production is still limited to a high volume of parts with relatively few changes in cross-section. Additionally, the parts are cured per die which does not mean that the part length is equal to a die length, but rather a part can be created out of several die lengths. Even a mould changeover might occur throughout the production. This can however create a weak point in the part.

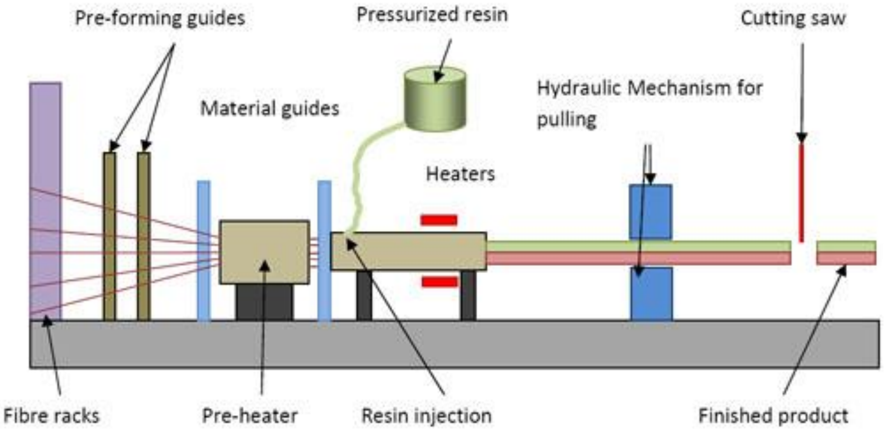


Figure 19: Pulltrusion Process (Sen, 2016)

3.2.2. FILAMENT WINDING (FW)

Filament winding (FW) is a continuous fibre process mostly associated with the fabrication of cylindrical shapes (Grant, 2006). The process is described by Figure 20. Alike the pull-processes, the fibre tows are taken off racks and are impregnated, usually through a resin basin. These are then lead through a delivery guide that controls the slip angle of the fibre and thereby determines the fibre orientation. The guider runs back and forward along the length of the mandrel. The wound fibres around the mandrel, result in a helical pattern. A set of rollers ensures sufficient tension on the fibres during the winding process. The nature of this process only allows orientations between 5º and 90º (Barbero, 2011). Using special tricks such as end of mandrel pins; smaller angles can also be achieved. This also means that the fibres are no longer continuous throughout the entire part, since the ends with the pins is cut off during post processing. FW on cylindrical shapes is the most common process and is straight forward to program. However, as the shapes become more complex the slip angles for the different orientations must be calculated accordingly making the winding program and mandrel rotation much more complex. The deposition rate of such complex parts is still reported to be between 5 and 90 kg/hr, which is much faster than manual layup. (Strong, 2008).

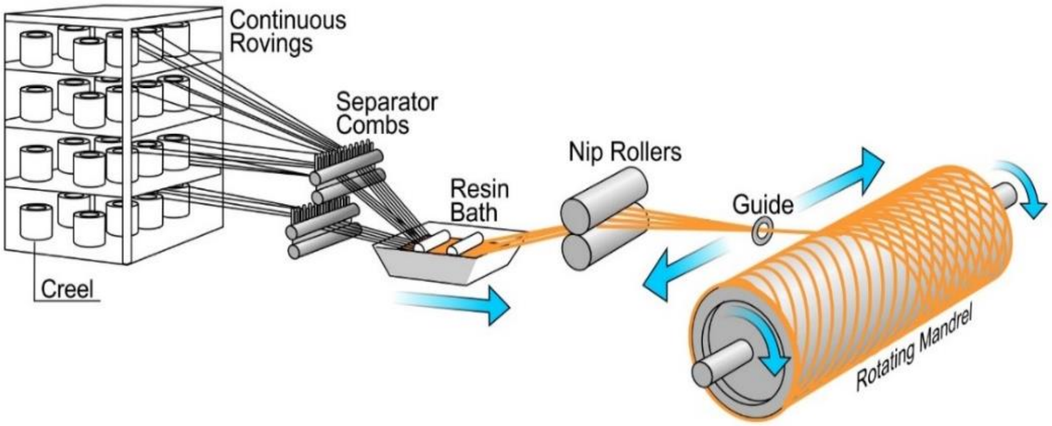


Figure 20: Filament Winding Process (Nuplex Industries Ltd., 2014)

3.2.3. BRAIDING

Braiding makes use of individual tows and intertwines them with one another to form a tight fabric around the shape of the mould to form a final product (see Figure 21). These tows are taken off spindles and are impregnated before they are braided around the mould, with the help of bobbins. The process can be set-up into either vertical or horizontal braids. The length of the part is only limited by the length of the mandrel around which the tows are braided. As long as the space surrounding the machine allows it, products of any length can be braided. The main limitation is the diameter of the surrounding circle into which the spindles are placed (Carey J. , 2016). There are a vast variety of fibre orientation combinations that can easily be reached with the combined use of different numbers of spindles. Even 0° can be reached as long as they are placed under a braided layer. The preoperational work required for the programming of the machine can be based upon an excel sheet and is fast in comparison to other automation alternatives (De Kruijk, 2016). The curing process can be either in or out of autoclave cure. (Fröhlich, 2016)

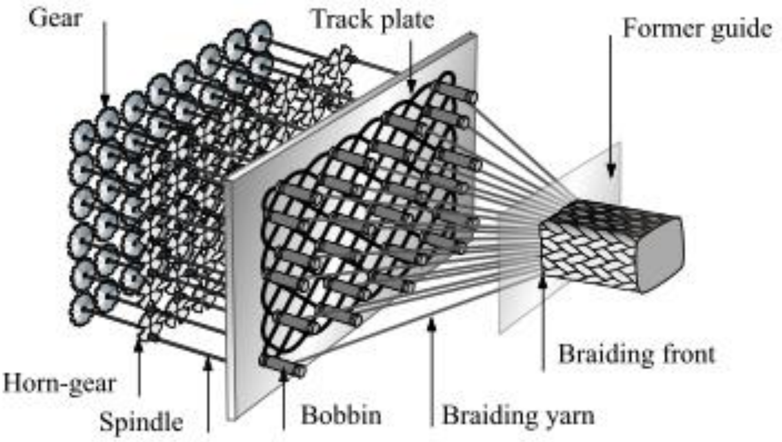


Figure 21: Braiding Process (Tada, 2007)

3.2.4. AUTOMATED TAPE LAYING (ATL)

Both concepts of the automated tape layers (ATL) and the fibre placement (AFP) systems have been around since the 1960s. The ATL system is now well developed and commonly used in the aerospace industry. However, it implies the purchase of large and heavy equipment (Bjornsson, 2014). A movable head is attached to the gantry crane and is in contact with the mould surface. It places fibre tapes of widths between

0.3cm (1/8”) and 1.3cm (1/2”) with consolidation pressure onto the laminate surface. The use of the gantry crane is the most common method for large parts. Recently the technology has developed through the attachment of the movable head to a robot arm. All orientations can be achieved with the UD material. It is simply applied onto the laminate in a different direction. This automation system provides the opportunity to create locally reinforced parches, as the product requires it. The machines are specifically programmed for no material overlap between the tapes. The ATL technology is split into three different categories:

- Single-phase (most used in industry)
- Two-phase
- Dual-phase

Whilst the single phase cuts the material on the gantry machine by stopping for the cut, the two-phase technology cuts the material to size off-line and spools it onto a ‘cassette’. The cassette is then labelled with a barcode for the machine to read and delivered to the tape laying head. The two-phase method is a faster operation since it provides the machine to lay the material at full speed. The dual-phase combines these first two methods in one head for different applications on different axis, making it the most versatile of the three technologies.

The ATL is primarily designed for relatively large and flat moulds, making it difficult to cope with smaller details within a mould (Grant, 2006). Yet, the wider the material, the less curvature can be draped onto the laminate without having buckles and wrinkles in the final layup. It is difficult to predict ATL deposition rates since they are highly dependent upon the complexity of the component, but testing rates between 8.6 and 13 kg/h have been recorded (Lukaszewicz, Ward, & Potter, 2012). Figure 22 gives A visual representation of an ATL on a gantry.

Figure 22: ATL Process Set-up on a Gantry Crane

3.2.5. AUTOMATIC FIBRE PLACEMENT (AFP)

The AFP process was originally based on FW at the same time as aiming to surpass the production limitations provided by the ATL process. Instead of winging continuous fibres or placing tapes into a mandrel, AFP places multiple tows with a low tension onto the surface. This process results in the ability to cope with much more complex shapes than the previous two automation processes. One band of material usually consists of 12-32 individual tows, but the thickness can be ‘changed on the fly’ during the process to adapt to design requirements (Grant, 2006). The delivery of the tows along a curved path is defined as the steering of the tows. The smaller tapes enable even less material waste compared to the ATP. Yet the AFP market price is higher since it requires more cutting processing. It is worth noting that the small tapes also reduce the dimensional accuracy since there are more issues regarding the gaps between the tows. To be able to obtain a similar laydown rate as the ATL, several tows need to be placed simultaneously (Lukaszewicz, Ward, & Potter, 2012).

Most AFP heads have a black tube attached through which the tows are arranged head to the head. This method prevents to have a heavy head with creels on it that is less agile (Lindbäck, Johansen, & Björnsson, 2012). The set-up of the AFP system used to be on gantry cranes but like ATL, this has developed to the robot arm set-up which reduces the investment cost of the system. The combined movement of head and mandrel of the AFP can be moved strategically to obtain an optimal placement procedure programmed by software. This can only be achieved using a rotating mandrel. The software that controls these complex movement combinations have much in common with the control of numerical control (NC) machining tools (Reinforced plastics, 2011). Yet the programming is still very complex and can take 2-3 weeks per part by a qualified programmer (De Kruijk, 2016).

To be able to adapt the product production process to manufacture product using AFP, requires changes in the product design which can be very time consuming and expensive to do. Changing the process from a female mould to a mandrel for convex placement is 7–10 times as expensive (Morey, 2009). This shows that for some components, the manufacture via this automation system is not feasible (Björnsson, Lindback, & Johansen, 2013).

The mandrels used in all these automation processes require a geometry such that the mandrel can sustain its self-weight and the load from the AFP/ATL head. The maximal deflection the mandrel can experience should be less than 1 mm and a minimal natural frequency higher than 15 Hz. All this is to ensure a sufficient stiffness doing the placement process (Kumar, et al., 2014).

The mandrels can be made either in form of core materials that stay in the mould or removable moulds. The removable mandrels are either in form of collapsible or sacrificial cores. The collapsible mandrels are often metallic with a fold up mechanism integrated within. This design increases their cost and their use is mostly worthwhile for high volume production. There are also collapsible cores in form inflatable or memory bladders, yet these take an extensive manufacturing process to be produced. These sacrificial cores can be cast, shaped with a CNC or printed into shape. The cast materials usually cannot withstand the heat in the autoclave since they are designed to be melted out once the part is cured. Fused Deposition Modeling (FDM) core is mostly 3D printing which makes it thereby a fast process reducing lead time up to 85% and labour time up to 95% (Stratasys, 2014). Nevertheless, it is also very much restricted by the size of the printer. In contrast to the cast material, the FDM process is compatible for the autoclave and is water-soluble, which makes the core removal process easy (Stratasys, 2008). The CNC option generally makes use of foam, which is later ice-blasted out of the part. (De Kruijk, 2016).
An AFP head mounted on a robot arm can be seen in Figure 23.

Figure 23:AFP Process (Automated Dynamics Performance Composites, 2016)

3.2.6. PICK-AND-PLACE CONCEPT (P&P)

The main difference of the Pick-and-Place (P&P) solution is that it is combining various technologies into one working robot cell, whereas all other previously described options are one piece of equipment.

The P&P concept is a well-developed technology in automation application in the high-volume production of many industries. These advances have nevertheless only recently been applied to composite applications in form of R&D projects (Lindbäck, Johansen, & Björnsson, 2012). Different automated cells have been developed at NRL, Airborne, SICOMP with SAAB Aerostructures and KTH Stockholm where robots performs automated cutting, stacking, de-bulking and forming action. This process is not yet wide spread within the composite manufacturing industry but has great potential due to the simplicity of the process. It does not require major engineering adaptation to the manufacturing process. Instead, the robot imitates the steps taken during the manual manufacture of the parts. It picks up the material from a cutting machine, stacks the plies on top of each other to create the flat laminate, debulks it and proceeds to place it onto the mould on which it is formed into shape (Bjornsson, 2014).

The P&P system has the advantage of being able to perform a variety of different tasks by simply using a different tool head. The motion of the robot itself is simple and does not need to follow a surface path as for instance the AFP, which makes the programming of this system easier and faster. This shows that even though the concept of the system is not widely used, it is economically viable (Buckingham & Newell, 1996). The applications for this kind of automation are especially beneficial for applications in which orientation, shape and target locations as well as type of the products are frequently changing (van Delden, Umrysh, Risario, & Hess, 2012).

The disciplines of a P&P system are split into a variety of different function areas. These are gripping, lifting, the removal of the protective layer, placement, de-bulking and the hot drape forming process. Figure 24 illustrates the order in which the tasks are performed by the robot. The three most important elements out of these are picking, sorting of the plies and the laminating step (Ehinger & Reinhart, 2014). An other piece of equipment that can be added to such a set-up is a hot drape forming equipment (HDF). It allows the stacked prepreg plies to be shaped by draping the lamiante into the mould using a heat and a pressure membrane. This would make it possible to full automation of larger variety of products. The HDF equipment can not only improve the laminating speed, but also allows a constant quality reliance (Sorrentino & Bellini, 2016).

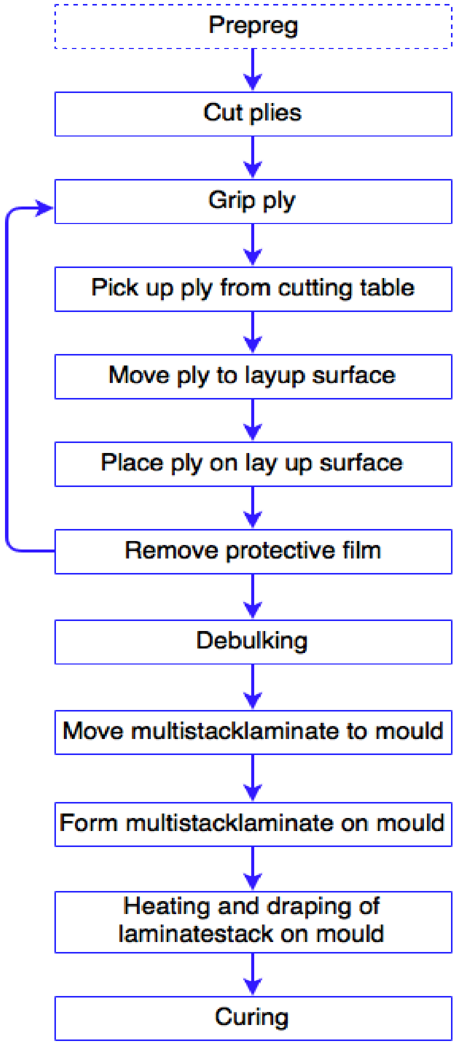


Figure 25: P&P Step Flow Chart (Björnsson, Lindbäck, Eklund, & Jonsson, 2015)

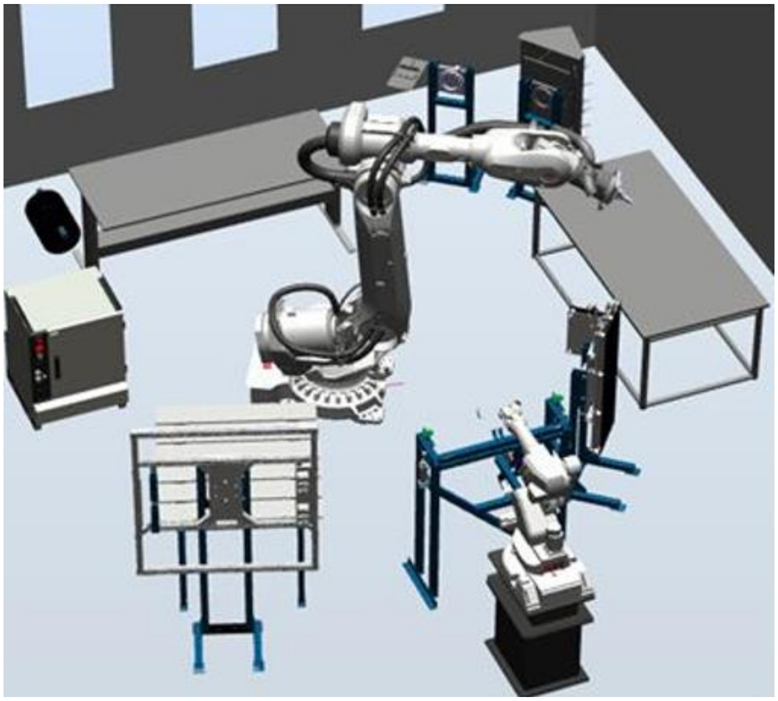


Figure 24: P&P Concept Cell (Björnsson, et al., 2015)

3.3. ASSEMBLY AND SURFACE FINISH AUTOMATION

Hertling, Hog, et al. (1996) describe that robots for surface finish and spray-painting are widely used in industrial settings. However, the range of application for these are restricted to a small number of preprogramed standard products. With large components, the issue of these types of automation is that programming the actual tasks takes longer than the conservation task.

Yet it is possible to develop quick release tools for the automation options making use of a robot arm as their main source manoeuvrability. For these types of assembly or finishing setting one would have to either isolate individual tasks from the production to be performed or work in form of a robot-human collaboration. This topic is later address in more detail.

CHAPTER 4 - CHOICE OF AUTOMATION

The decision of production automatization is a process in which many different factors must be considered. A feasibility analysis was performed to ensure that the automation system is suitable. According to Frans van de Ven, the former director at Airborne Composite Automation, it often occurs that complex automations systems are purchased but cannot be implemented to their full potential. The identification of the most useful automation is key to determine the technology used to automate. One part of guaranteeing that this is achieved is by identifying the right actions to be automated, followed by determining the technology used to automate. Another vital part is also fully integrating these systems into the overall workflow of the manufacture. (Bergeron, 2016)

This section aims to identify the actions that are to be automated by answering functionality questions such as: What is to be automated? What takes the most time? Or what are routine steps and what is the importance of accuracy and precision in the manufacture? In this section, the information from the previous chapter on the technologies options is used to compare them to one another and analyse it to be able to conclude the most suitable method. To do so, a more thorough cost and labour time analysis is performed

4.1. CURRENT PROCESS COST AND LABOUR TIME ANALYSIS

The following analysis has been done based on comparison of percentage impact of different production entities within the mast, boom and rudder production. The data obtained for this analysis is subjected to the person that logged and what tasks are part of the logged time. Additionally, it is difficult to directly compare the cost and labour times to one another due to one-off manufacture of the products. This has been taken into consideration by not comparing the direct cost value but instead calculating the percentage of each entity on the overall project. The calculations are based on data from 4-5 projects, dependent upon the availability. The average of these percentage impacts has then been calculated from the given projects to provide a general overview of the production.

Even though the obtained values are not of detailed accuracy they are of sufficient use to be able to serve as a basis for a later comparison of processes. A more detailed analysis of the entire range of products is advised to be performed, if this research is to be used as a basis for an automation system purchase.

4.1.1. MAST

The data recording of the mast production only allowed the detailed collection of four data sets, with mast length variation between 58m and 72 m.

Table 12, like all other tables found in this section, represents a percentile comparison of labour requirement and cost of different tasks with regards to the overall production of the part. The second and third columns provide the percentage of each of the task costs compared to the overall cost given in column one. So, whilst the overall mast cost represents 100% of its cost, the plate material only represents 0.4% of the total mast cost in column two. The way the data has been available does not distinguish between specific areas, some cost might be covered several times within different categories in the rows, which is why the percentages do not add up to 100% of the production costs.

The third column also considers the composite production cost. Continuing along the table, the fourth column provides the average labour hours spent on the different tasks, whilst the last two columns are equivalent to the second and third, except that they consider the indicated labour time, and not the cost. The

‘X’ in the table are either due to irrelevance to the row, for instance material cost is not related to labour times, or a lack of data available within the Rondal system to make any estimations on the task.

It can be seen in Table 12 that within the mast manufacture most of cost goes the prepreg. It adds up to one third of the total mast production cost. This cost cannot be reduced significantly because this material is needed for the design of the part. Only the waste material of 4 % could possibly be reduced by altering the production process. It is also clear from this table that the labour work is the second most significant cost of the total mast production cost. It makes up 16,4% of the overall price and close to a third of the composite production cost.

Further, when comparing the impact of the different product types it can be seen that type 5 (represented by the outer build up laminate) makes the most significant impact with 7% of the overall cost and 27% of the composite labour hours. In contrast, the spreaders (type 2) only get up to 2,6% of the total cost and nearly 8% of the labour time. The type 3 products are referred to by the plates and make up only 1.9% of the cost and 3,1% of the labour cost.

Table 12: Cost and Labour Time Analysis of Mast Production

Mast	Cost	% of overall	% of composite work	Labour time (h)	%of overall	% of composite work
Overall	€ 1 320 000	100%	X	12700	100%	X
Total composite	€ 735 000	55.7%	100%	5900	46.5%	100%
Composite (mould prep, laminate, cure)	€ 626 000	47.4%	85.2%	3300	26.0%	55.9%
Labour cost composites	€ 217 000	16.4%	29.5%	X	X	X
Labour cost spreader	€ 52 200	4.0%	7.1%	1000	7.9%	17.9%
Material cost	€ 409 000	31.0%	55.7%	X	X	X
Scrap cost (15% of material)	€ 53 400	4.0%	7.3%	X	X	X
Assembly Composite	€ 43 600	3.3%	5.9%	800	6.3%	13.6%
Work preparation	€ 21 800	1.7%	X	300	2.4%	5.1%
Cutting	€ 9 000	0.7%	X	200	1.6%	3.4%
Conservation	€ 76 500	5.8%	X	1200	9.4%	20.3%
Plates material	€ 5 700	0.4%	0.8%	X	X	X
Labour cost plates	€ 14 000	1.4%	2.5%	300	2.4%	5.1%
Overall plate cost	€ 20 600	1.6%	2.8%	400	3.1%	6.8%
Outer build up laminate	€ 95 200	7.2%	12.9%	1641	12.9%	27.8%

4.1.2. BOOM

The same approach as discussed in section 4.1.1 is now applied to the data obtained from the boom production. From these calculated values, it can be seen that the labour intensity for both the boom and the mast are both making up 30% of the composite production cost. Additionally, type 3/flat products have percentage wise a higher impact in the boom manufacture than in the mast manufacture.

Table 13: Cost and Labour Time Analysis of Boom Production

Boom	Cost	% of overall	% of composite work	Labour time (h)	% of overall	% of composite work
Overall	€ 620 000	100%	X	6100	100%	X
Total composite	€ 190 000	30.6%	100.0%	2800	45.9%	100%
Composite (mould prep, laminate, cure)	€ 159 000	25.6%	83.7%	1500	24.6%	53.6%
Labour cost composites	€ 63 400	10.2%	33.4%	X	X	X
Mould (internal only)	€ 7 900	1.3%	4.2%	200	3.3%	7.1%
Material cost	€ 81 800	13.2%	43.1%	X	X	X
Scrap cost (15% of material)	€ 9 600	1.5%	5.1%	X	X	X
Assembly composites	€ 21 200	3.4%	11.2%	400	6.6%	14.3%
Work preparation	€ 14 000	2.3%	7.4%	250	4.1%	8.9%
Cutting	€ 6 200	1.0%	3.3%	100	1.6%	3.6%
Conservation	€ 43 300	7.0%	22.8%	800	13.1%	28.6%
Quality improvement work	€ 4 500	0.7%	2.4%	X	X	X
Plates material	€ 2 900	0.5%	1.5%	X	X	X
Labour cost plates	€ 6 700	1.1%	3.5%	125	2.0%	4.5%
Overall plate cost	€ 11 700	1.8%	6.2%	X	X	X

4.1.3. RUDDERS

The data summarized in the *Table 14* is the taken from five manufactured rudders. These vary from 4,6m to 6,4m in length. The reason for which this product was added into the analysis is that it is a product that has become increasingly significant in the production over the past few years.

Table 14: Cost and Labour Time Analysis of Rudder Production

Boom	Cost	%of composite work	Labour time (h)	% of composite work
Overall composite	€ 71 000	100%	761	100%
Composite (lamination & cure)	€ 42 600	60.0%	359	53.3%
Labour cost composites	€ 20 500	28.9%	X	X
Material cost	€ 21 200	29.9%	X	X
Scrap cost (15% of material)	€ 3 300	4.6%	X	X
Work preparation	€ 4 000	5.6%	70	11.6%
Assembly composite	€ 14 000	19.7%	235	22.6%

Due to the small amount of specific data available for the rudders it is difficult to draw conclusions. The composite work only including laminating and curing, which is less than what is included in the composite labour hours of the other two products. Yet, the percentage cost of the rudders is comparably much higher. Additionally, the labour intensity for the rudder is similar to the other two main products (Tables 12 and 13), whilst the material cost is significantly lower with only 30% of its composite cost. This is explained by the fact that rudders are made of a foam core. A more detailed cost and man-hour analysis of the flat plates from mast and boom is provided in the CHAPTER 5, where they are compared directly to the automation process costs.

This analysis concludes that there are significantly more information and data available on the mast and boom products than on any of the other products. The datum become important in later chapters when a direct cost and process comparison is made between the chosen automation method and the manual process.

Therefore, it has been decided that the mast and boom parts are going to be focused on during for the automation application in this project and the production of all other products is kept in mind put not implemented in a full cost analysis

The pie chart in Figure 26 summarizes and illustrates the most important elements of the information gathered in Table 12 through Table 14. The entire chart represents the production costs for boom, mast and rudder. Entities such as the plates, spreaders and outer mast laminate are emphasised to show the labour cost impact of a type 3, type 2, and type 5 products on production costs. The plates do represent all plates (type 3 products) manufactured, whilst the spreader and the outer laminates only represent highly impacting type 2 and 5 products. The 'Other' slice of the pie chart contains all costs that could not explicitly be specified. These can therefore also include composite related costs such as laminating, curing, cutting or quality test costs. The pie chart demonstrates that the automation solution can potentially have an impact on about 15% of the overall cost of the mast, boom and rudder production.

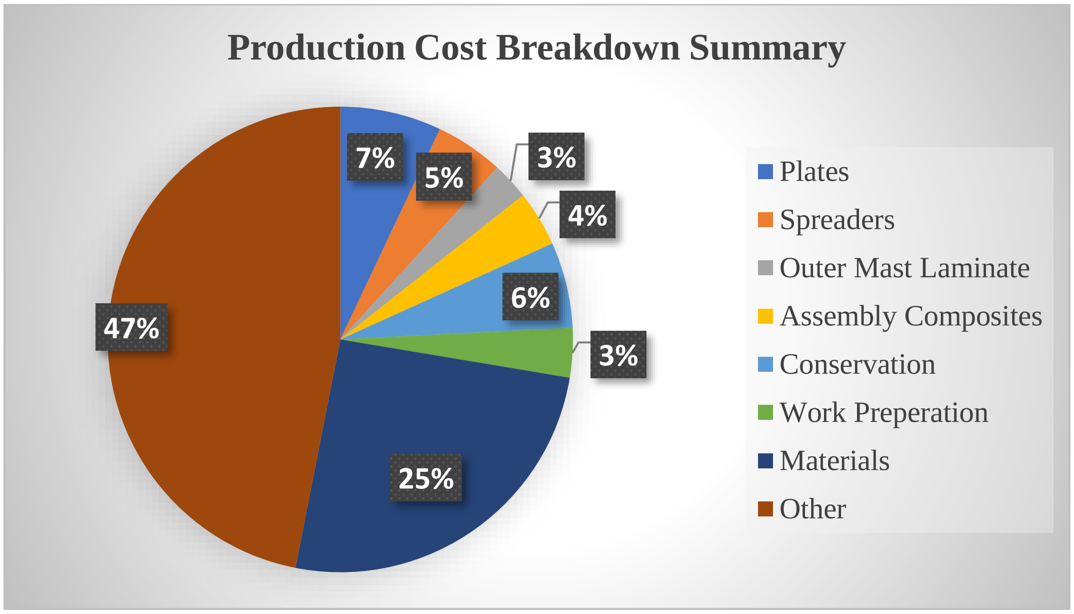


Figure 26: Production Coat Breakdown Summary

4.2. STEPS TO BE AUTOMATED

Based on the automation definition given in CHAPTER 1 - 1, it can be defined that automation tasks can either be fully replaced by an industrial robot or steps of tasks that can be automated to create a semi-automated work environment using a service robot.

The introduction of automation into the process is specifically aimed to reduce the labour hour to obtain a shorter lead-time to the overall products. However, the automation process should also improve health related working conditions for the workers. Further, using a robot for simple yet repetitive action not only allows skilled work force to be reallocated to more complex, value adding tasks, but also ensures a constant quality. Human errors that can be caused by a lack of focus due to fatigue or boredom from repetitive action can cause material waste. Therefore, these steps are to be automated or eliminated through the introduction of a new automated process solution.

The process flow diagrams from the previous chapters (Figure 11 to Figure 16) show numerous common activities over all different types of product. Such routine tasks include cutting, kitting the plies into the correct stacking sequence at the start of the process, preparing the mould, laminating and de-bulking throughout the process and curing as well as conservation towards the end of the process. As can be seen from the average cost and time summary of the mast (Table 12), the added cost for the actions of mould prep, cutting, kitting, laminating, de-bulking and curing make up 47,5% of the mast sales cost, out of which 16.5% of the overall cost is due to labour cost. In view of the fact that number of plies for parts varies between 6 and 588 plies per part, not only the lamination time itself but also the de-bulking time after approximately every 5th ply add up to a large amount of time. With such large numbers, an organized and faultless kitting method becomes vital for a smooth laminating process.

Manufacturing steps such the assembly of composite parts within the shells of entire masts or booms are extremely important since they make up the final functionality of the product. They ensure that lines can run along the length of the mast, to rig the sale or that loads are evenly spread across the different load points on the mast. The assembly of these parts requires flexibility within motion and the ability to access tight spaces for instance to adhere small parts close by to other already assembled parts. This also means that each of these tasks has their own surrounding settings. Robots on the other hand become less useful for this type of tasks since each individuality needs to be adapted in the programming. The labour time that could be saved in these tasks are far exceeded by the amount of time the programming preparation takes. Hence, these assembly tasks are not considered in the automation aims for this project.

A further advantage that automation brings is the movement precision and layup accuracy. It has to be ensured that this factor is exploited to its fullest. In the current process a leeway for layup inaccuracy and deformation of plies during the cutting and kitting process, is created by cutting the plies oversize and adjusting the size of the individual plies once it is placed in the mould. Even though this method ensures a certain level of quality, it also creates waste material and added labour time. With the introduction of automation systems, this safety margin can be reduced significantly. However, the increase in accuracy of layup through automation is not required for some of the parts. This is especially true with regards to the manufacture of flat plates. Some of the edges require a waterjet cut flat edge, which cannot be achieved though the stacking of the plies, no matter how accurate the layup. For those parts, the manual process step of cutting will still have to be performed.

It can be concluded that the most numerous and repetitive current process steps that are to be automated or eliminated are:

1. Cutting, which is already automated
2. Identification of plies
3. Kitting of plies
4. Protective film removal of plies
5. Positioning of plies
6. Consolidation of plies
7. De-bulking of stack

The automation of additional steps such as placing the plies into the mould and hot drape forming them is an additional building block of the automation, that can be later added on to the automation system. But, as such it is not necessarily part of the core automation.

Based on the last two chapters it can be concluded that a well set-up Enterprise Resource Planning (ERP) system, used to log production data, is of extreme importance in the feasibility analysis for an automation system. Only if all data can clearly be analysed, the full achievements of an automation system can be compared to the current production line. Even though, the analysis performed on the current data was able to identify some major focus points, a more in-depth analysis of the individual products is highly recommended to obtain a better understanding on what the automation system will actually be used for. To do so, a more detailed log within the ERP system is necessary.

4.3. COMPARISON OF OPTIONS

The information gathered in CHAPTER 3 about the various automation options is summarized and evaluated for their advantages and drawbacks in Table 15 and Table 16. Most sources of this information are indicated within the tables. All other information has been gathered from interviews with experts such as Joachim de Kijlk[1] from the Netherlands Aerospace Center (NLR), Tahira Ahmed[2] from Airborne Composites and researcher Rik Tonnaer[3] from the TU Delft Aerospace faculty.

Table 15: Automation Options Dis/Advantages Part I

Process	Advantages	Disadvantages
Pull-Processes	• Fast and economic	• Limited to constant cross sections
	• Resin content can be accurately controlled	• Limited to small cross sections and relatively small parts if compared to what Rondal is producing
	• Material cost is minimized since only the required material is taken of the creel	• Fibre in orientations other than the longitudinal directions have to be added through bidirectional stitched material
	• Good surface finish or the product	• Low fibre volume content 0.3-0.45
	• Can manufacture any length	• Wall thickness of product is limits to 12mm due to curing limitation
	• No shelf life of material (dry fibres)	• Heated die cost can be very high
Reference	(Barbero, 2011)	
Filament Winding	• Resin content controlled	• Resin with low viscosity are needed
	• Process can be fast and economical	• Process limited to component with convex shapes
	• Complex pattern can be wound for better load bearing	• Mandrel cost for components can be high
	• Continuous fibre process means particularly good strength properties	• Outer surface of component is not smoothly finished
		• Longitudinal orientation is more complex to achieve, usually only wound between 5 and 90 degrees
		• Additional engineering work must be completed to create a program and to calculate the slip angles.
Reference	(Barbero, 2011), (Stong, 2008)	

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Table 16:Automation Options Dis/Advantages Part II

Process	Advantages	Disadvantages
Automated Fibre Placement	• Long parts can be manufactured with the fibres running continuously along the length	• Some parts can only be made if the moulds are changed from female mould to a rotating convex mandrel, due to sharp corners in the mould. This mandrel base convex placement is 7–10x more expensive than a female mould
	• All orientations achievable	• High capital cost
	• Manufacture with local reinforcement	• Core material needs to be placed either manually or by a different robot
	• Most shape, even from complex moulds	• Can have issues with tow overlapping and gaps
	• Can manufacture most shape, even from complex moulds	• Higher material cost than most other option since the material has to be pre-cut into small strips before it is inserted into the head
References	(Grant, 2006), (Lukaszewicz, Ward, & Potter, 2012), (Lindbäck, Johansen, & Björnsson, 2012), (Reinforced plastics, 2011), (Morey, 2009), (Björnsson, Lindback, & Johansen, 2013), (Kumar, et al., 2014)	
Automated Tape Laying	• All orientations can be achieved	• Only UD material can be used no weave
	• Is able to manufacture with local reinforcement	• Core material needs to be placed either manually or by a different robot
	• Low percentage waste since tapes can be cut to size individually	• Limited to simple moulds due to the thickness of the tape
	• Long parts can be manufactured with the fibres running continuously along the length	• Risk of machine head collision in complex geometries, it is very expensive to repair both a tape head and the tooling
		• High capital cost
References	(Bjornsson, 2014), (Grant, 2006), (Lukaszewicz, Ward, & Potter, 2012).	
Pick and Place Concept	• Robot system cost well developed due to numerous applications in other industrial sectors	• The forming process on top of the mould might result in wrinkling, it will require testing to figure out which moulds can be manufactured
	• Robot head is flexible to accomplish several different types of tasks	• A cell is composed of many more components that need to be interconnected
	• The current process steps can me kept the same	• Limited to the size of the pick and place table
	• Implemented into a cell that performs a series of other tasks	• Steps such as the removal of the protective film are still in development
	• Possible to handle large plies dependent on the robot used	
References	(Lindbäck, Johansen, & Björnsson, 2012), (Bjornsson, 2014), (van Delden, Umrysh, Risario, & Hess, 2012), (Ehinger & Reinhart, 2014). (Björnsson, Lindbäck, Eklund, & Jonsson, 2015).	
Braiding	• Enables near-net-shaped consistency of the fabric, which improves the products impact properties and overall structural properties	• Cannot make parts with majority 0° orientation since every UD layer has to be braided in with a woven layer
	• Components of various different - cross sections and circumferential changes can be produced	• Uniform thickness of the laminate; local patches not possible
	• Holes can easily be integrated, so no drilling needed later	• Core is required around which the material is braided
	• Low scrap material <5%	
	• High productivity	
References	(Maekawa, et al., 1994), (Fröhlich, 2016), (Carey J. P., 2017)	

4.4. OPTIONS APPLICABILITY ON PRODUCT TYPES

The different types of available automation systems have now been described and compared. This section adds onto the previously presented information and relates it to the manufacturing process of products. The decision, on which automation system is to be used, is split into two stages: A quantitative analysis and a qualitative multi-criteria analysis.

4.4.1. QUANTITATIVE ANALYSIS

The quantitative analysis considers the amount of the products types that can be manufactured with each approach. This ensures that the system has potential for expansion. Even though Rondal might only start with applying the system to one specific product type, it should be ensured that this can be elaborated on a wider range of products. The aim of this analysis is to shortlist the three best options that show the most potential. In order to do so a multi-criterial analysis was performed to compare the options. Table 17 and Table 18 provide a summary describing the most important factors for the application of these methods on the product manufacture. The question that is to be answered is: can the automation option be applied on the five previously identified product types?

Table 17: Can the Automation be Applied on Product Types? Part I

Products	**Pull-forming**
Type 1	Yes, but only the parts without local reinforcements or core material. Making it applicable for very few parts.
Type 2	No, it can't deal with local reinforcements, which are crucial for this type of product. Nor can it deal with the amount of shape changes without having to manufacture a die for each part. Such a solution is not feasible.
Type 3	No, it can produce plates but only up to the thickness of about 12mm. Anything over that thickness will not cure properly during the process.
Type 4	Yes, uniform cross section products are ideal for this production method.
Type 5	No, it cannot be used for assembly or external laminate build up.
Products	**FW**
Type 1, 2	Yes, but manufacture possible though a redesign of the process that uses a mandrel.
Type 3	No, it is not able to be manufacture plates without a core material.
Type 4	Yes, this process is ideal for such products.
Type 5	No, it cannot automate assembly. but could help build up the laminate.
Products	**ATL**
Type 1	Yes, but the tapes have difficulties reaching into tight corners. The woven materials cannot be used, as all material must be UD. So, a redesign of the product needs to be done. For the most effective application a resign of the process will also have to be done. This might allow to resolve the process problems and reduce post processing. Such a redesign would probably have the layup be would on a sacrificial core/core mandrel.
Type 2	Same issue as for type 1, but it is even more worthwhile considering a mandrel, since these products can have core material.
Type 3	Yes, it can be manufactured with the current process.
Type 4	Yes, it can be manufactured using a mandrel. However not to the same material properties as the outsourced product since the fibres are not spread continuously around the mandrel.
Type 5	No, it is not possible to automate the assembly of these product types. But yes, it is feasible to automate the local reinforcement layup and the build-up of laminate. The restriction lies in needing specialized equipment that can deal with a large size variation.

Table 18:Can the Automation be Applied on Product Types? Part II

Products	**AFP**
Type 1	Yes, the thinner strips are better to deal with complex shapes so corners can more easily be reached. The woven materials cannot be used, as all material must be UD. So, a redesign of the product needs to be done. For the most effective application a resign of the process will also have to be done. This might allow to resolve the process problems and reduce post processing. Such a redesign would probably have the layup be would on a sacrificial core/core mandrel.
Type 2	Same issue as for type 1, but it is even more worthwhile considering a mandrel, since these products can have core material.
Type 3	Yes, it can be manufactured with current process, however the process will be more time and cost consuming than the ATL approach.
Type 4	Yes, can be manufactured using a mandrel, however not to the same material properties as the outsourced product since the fibres are not spread continuously around the mandrel. Due to the smaller strips, this technology will also be able to deal with smaller parts.
Type 5	No, it is not possible to automate the assembly of these product types. But yes, it is feasible to automate the local reinforcement layup and the build-up of laminate. The restriction lies in needing specialized equipment that can deal with a large size variation. It would be slower than the ATL in that respect.
Products	**P & P**
Type 1,2, 3	Yes, parts can be manufactured using the current production process.
Type 4	No, parts that require a mandrel cannot be made using this method.
Type 5	Yes, the robot tool on the robot arm can be changed to accomplish assembly tasks. A long robot track and specialized robot end effectors would be required to deal with the large size variations. The programming of these tasks for the type 5 products would however be so time extensive that it is not a feasible solution.
Products	**Braiding**
Type 1, 2	Manufacture possible only if surrounding a mandrel, but no local reinforcements possible.
Type 3	No, braiding cannot be manufacture plates without a core material.
Type 4	Yes, this process is ideal for such products.
Type 5	No, the assembly cannot be automated though the barding process. But yes, the braiding can be used to build up outer laminate, if not local reinforcements are necessary. It would also need specialized facilities to deal with the large size products.

The individual products described in 2.1.1 are each compared to the description of automation applicability in Table 17 and Table 18. It was determined how many of the individual products can be manufacture with the different automation options. The numerical results of this analysis are summed up in Table 19, which is hence a summary of all parts that can be manufacture the specific automation technology. ATL, AFP and the P&P are the automation systems able to adapt to the largest part manufacture with 65, 68 and 55 products respectively. The table also shows that some options are mainly suitable for the currently outsources products, not for the in-house production. This brings them therefore into the next stage, the multi-criteria analysis.

Table 19: Number of Product Type Produced per Automation Option

Product	**ATL**	**AFP**	**FW**	**Braiding**	**P&P**	**Pull-forming**
Type 1	19/20	20/20	11/20	11/20	17/20	11/20
Type 2	6/8	6/8	5/8	5/8	5/8	0/8
Type 3	30/30	30/30	0/30	0/30	30/30	22/30
Type 4	5/7	7/7	7/7	7/7	0/7	5/7
Type 5	5/5	5/5	3/5	2/5	3/5	0/5
Total Score	**65/70**	**68/70**	**31/70**	**26/70**	**55/70**	**38/70**

4.4.2. QUALITATIVE ANALYSIS

This second part of the analysis determines which of the short-listed options is most suitable for this project and the direct implementation into the process. Table 20 states how each of these process steps is addressed in the automation options. The ATL and AFP system are very similar to one another, hence it is mostly a general comparison between their and the P&P approach. All information provided in this table is taken from the process description in section 3.2.

Table 20: Qualitative Comparison between ATL, AFP and P&P

Process	ATL AFP	P & P
Cutting	• Cuts the strips into the needed size on the lay-up head	• Cutting is performed on the cutting table, like in the manual process.
Identification of plies	• Does not need to identify plies. Identification of orientation is programmed within the code.	• Plies are identified through the preprogramed connection between cutter and robot
Kitting plies	• Does not need kitting since no plies are handled	• Has not yet been implemented into the industry
Protective film removal	• The film is removed before it is head to the layup head	• Only research project has developed a working removal tool, in industry it has not yet been implemented
Positioning plies	• The start and end of the strip layup are precisely controlled through the program.	• Requires less coordinate inputs since it is done by ply instead of by strips.
Consolidation of plies	• The strips are consolidated during the layup process.	• Only research facilities have developed working consolidation tools.
De-bulking of stack	• Most de-bulking technology is mechanized but not completely automated.	• The NLR P&R uses a membrane, based automated de-bulking/hot drape forming machine.

The qualitative analysis ranks these three options based on ten criteria. It is difficult to judge in what way each of the criteria has a higher importance than the other within the overall scope of the application. For this reason, the concordance technique has been applied to obtain an understanding of the dominance of one automation option in judging upon these criteria. This method takes into consideration every criterion without giving them a specific ranking score. The information for the application of this technique is taken from Chapter 14 of Rogers and Duffer on Engineering Project Appraisal: The Evaluation of Alternative Development Schemes (2012). The ten criteria are:

I. Ability to implement with current process

As Björnsson *et al* (2013) describes, some of these processes might require redesigning of the part to be able to apply the process. This project description limits such a redesign to a minimum to make one automation option applicable. It thereby solely focuses on the implementation of the technology. The workers are familiar with the end result and therefore faster adapt to the technology. A negative aspect of this limitation is that process flaws such as the inability to add the backing plates to the spreader structure during the main manufacturing process, will not be able to be resolved with the implementation of the technology.

II. Reduction of labour

The more steps are automated the more labour is reduced and can be refocused on other products. Yet, the more steps are automated the more programming needs to be done to prepare every custom-made part production. It is known from the literature review that the programming adaptation for ATL and AFP process is very extensive, since it includes many simultaneous steps such as trimming, consolidation, or even heating of the prepreg in the right orientations. P&P on the other hand also includes numerous tasks but are is easier to program since they occur consecutively. The P&P motions are easier to program since they imitate the human process.

III. Specialist knowledge required

The specialist knowledge to prepare the work for the automation production is directly correlated to the reduction of labour. The automation system reduces the labour requirement only looking at the physical production. Yet, if the implementation requires new personnel to be hired with the skills to be perform the work preparation this labour time saving has become redundant. It is the aim to choose a system that can be implemented without any major addition of new skill requirements to the company. This is mainly achieved through the P&P option.

IV. Lead-time saving

The lead-time saving is closely related to the reduction of labour; however, it also considers the amount of time it takes for the process to be produced and the reallocation of the labour into other tasks. The reason for which the ATL/AFP processes are considered slower than the P&P is that they lay up the laminate in smaller steps and are hence assumed on average to take longer than placing the entire ply at once with the P&P.

V. Number of products

As previously analysed in the quantitative analysis in section 4.4.1, the number of total part manufactured by each automation option is still a factor in the final decision making.

VI. Investment cost

Even after thorough investigation, only limited information has been obtained concerning the investment cost of the technologies. Investment cost is a significant factor to be able to create a realistic scenario for a return of investment in later stages of the project, which is why even the limited information is considered in these criteria.

VII. Facility requirement

The facility requirements consist of area requirements of the workshop available for the implementation of the automation system, but also structural integrity of the workshop floor to carry the equipment. The latter one is not of such high importance since the Rondals' workshop is on the ground floor and designed for the movement of equipment with weights alike the one for the automation systems. Other facility requirements are; access to power or other resources like vacuum or compressed air at the location of installation. Aspects such as security fencing surrounding the equipment are also still necessary and are considered in this criterion. The P&P option requires most facility space since it needs to have access to a cutting table, Sorting station, film removal space and stacking space all within the reach of the robot.

VIII. Running cost

The running cost replace the labour cost of the manual work. This includes the power used to run the robot but also maintenance costs and safely equipment that needs to be set-up for the entire apparatus to run smoothly within the production.

IX. Scrap material

The scrap material adds to the overall product cost of the production. The P&P option does not impact the current process it also does not majorly reduce the amount of waste material during the production. The other two methods on the other hand both cut the material strips close to size so that only minimal trimming is required and thereby reduces the amount of waste material.

X. State of development

At the initial implementation stage, the state of technological development does not play an important role. This changes once the first steps of the technology are implemented successfully. ATL and AFP processes are commonly used in industry so, their problem resolution and further development is faster to achieve. The P&P technology is a new concept within the composite industry. Implementing that technology means that further progress of application is slower.

The detailed concordance analysis is provided in appendix III. The following points are a brief description of the steps taken to reach the final dominance scores.

1. Compare every criterion to one another from every option available by giving it a concordance score of either 1= better or 0= worse
2. Split the criterion into two groups of immediate and long-term relevance and calculate a normalized value for each.
3. Multiply the concordance score with the normalize weight for each option and log the resulting value in a matrix
4. Subtract the column scores from the row scores to obtain an overall value of dominance

The concordance analysis results are represented in the Table 21. The results show that the P&P has the highest, most dominant score, for the given criteria. On second place is ATL with a lower negative score than AFP.

Table 21: Concordance Dominance Score for Choosing the Automation Option

Options	Row score - Column score
ATL	-0,12
AFP	-0,71
P&P	0,82

This dominance score for P&P does not mean that it this option has the most impact on the overall production. It rather considers the method providing the greatest potential for a start-up of automation. This choice also provides sufficient data to be able to compare the automated process to the manual choice via a simulation.

The choices for step 1 of the concordance analysis are of higher certainty for some criteria than for others. Whilst the ability to implement the automation with the current process, the number of products produced, the facilities requirements, the scrap material and the state of development of the automation system are fairly set criteria, most others are subjective decisions based on opinionated reasoning from experts. An analysis has been performed assuming that all these subjective criteria were to be wrong. The results show a change in dominance scores of the ATL, AFP and P&P options to -0.118, 0.354 and 0.059 respectively. This means that if 100% of the uncertain estimations are wrong then the choice of automation could deviate to the AFP solution. These results provide an understanding of the sensitivity of the result but do not change the final automation choice, since the gap between the dominance of the original calculations are significantly supporting the choice for P&P.

CHAPTER 5 - CONCEPT OF AUTOMATION PROCESS

The previous chapter has shown an analysis of the different automation options and in which way these can be applied to the manufactured products. The P&P concept, with its individual pieces of equipment, makes it the most flexible and most suitable option. It is able to fully automate the flat plate production and partly automate the single mould, hollow products and small amounts of the Assembled product type production. As the automation develops these latter ones have a potential for full automation as well. This section is elaborating on specifics of the P&P concepts and points out possible challenges that need to be considered when developing the automation system. In this first step, the most suitable test product is chosen out. This allows detailed focus to be placed on the production of one part, which can later serve as a basis for a comparison.

The flow chart in Figure 27 demonstrates the automated process of the concept. It is placed at the beginning of this chapter to provide an understanding of the overall system before diving into specifics of each individual step. The flow chart can be separated into two main sections; the kitting process from steps 1 to 6 and the laminating process from steps 7a to 10. The partially automated products only use the kitting process of the automation system whilst the fully automated products further continue into the laminating stage.

To be able to provide specific examples on the application of the automation system, a sample product is chosen that provides the best features to demonstrate the advantages of the automation. This sample product is determined in the first section of this chapter. The thereafter following sections, describe the current state of development of the concept as well as requirements the final concept needs to meet. Only once this frame work information is set, will the chapter elaborate in more detail on the individual equipment that make up the robot cell.

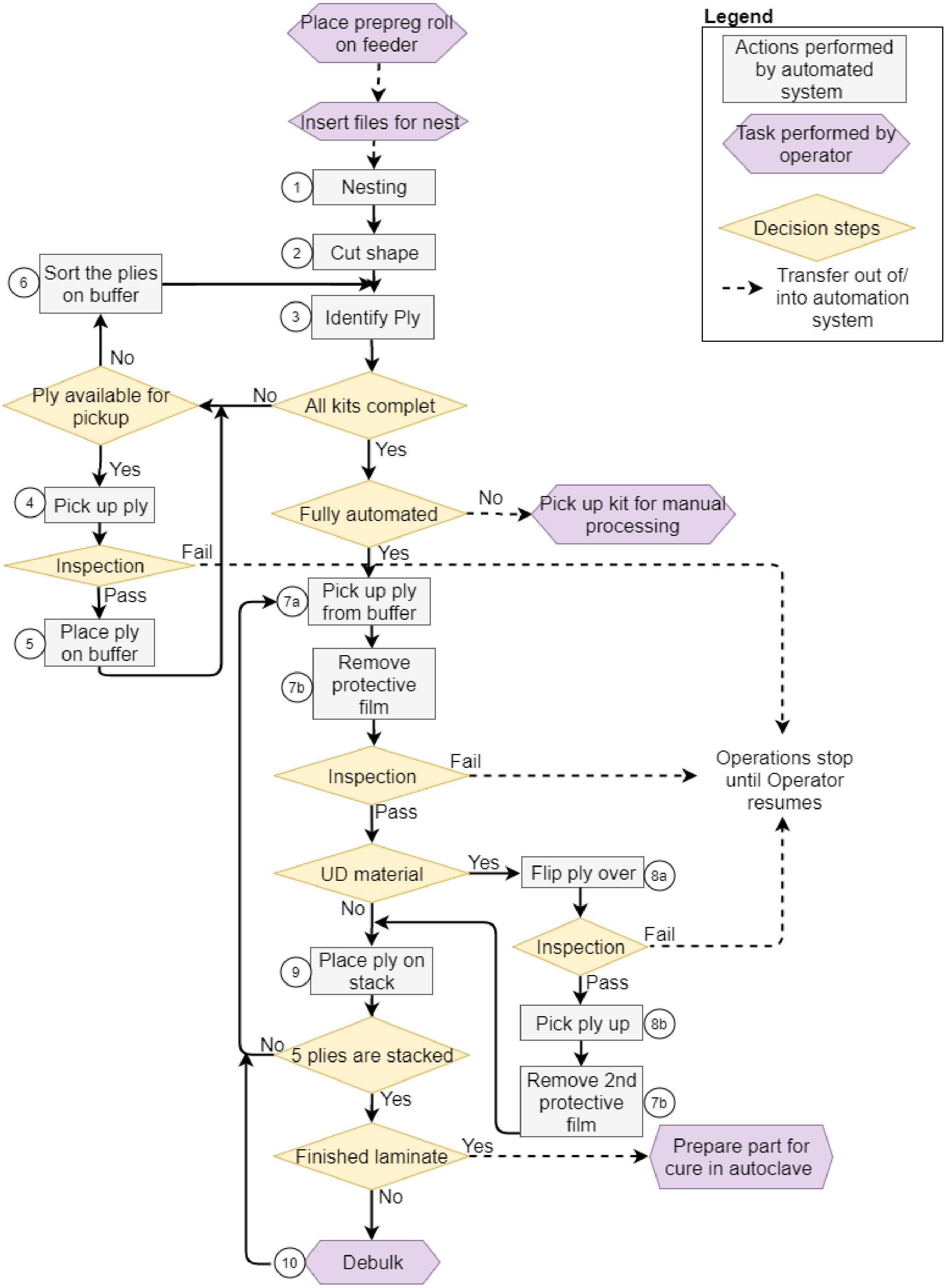


Figure 27: Flow Chart of the P&P Automation System

5.1. SAMPLE PRODUCT

The actual impact of the automation can only be determined if a direct comparison to the manual process can be made. To make this possible a specific sample product is chosen to focus upon. A second concordance analysis has been performed, to determine which of the products is best demonstrated through the P&P concept. The criterion for the analysis are:

- To perform each of the automation steps
- To repeat the steps numerously with orientation alterations
- To produce the largest number of parts
- Data availability for comparison
- Cost impact
- Potential of full automation

The ability of the sample part to nest the plies part effectively can also be viewed as an important criterion, especially concerning waste reduction. The nesting is however not considered as a criterion in the concordance analysis since that would require specific comparative data that is not available.

These criterions were compared to one another based on their applicability on three different products. The results can be seen in Table 22, where product Type 3 (plates) is the most dominant of the three products. Type 2 are the second choice for sample product with its small negative value (Appendix III). Yet, this does not mean that Type 3 products are the dominant product within the production. As previously concluded in CHAPTER 4 most other product types do have a larger impact on the production process itself.

Table 22:Concordance Dominance Score for Choosing the Automation Option

Options	Row score - Column score
Single Mould Product Type 1	-0,7
Hollow Products Type 2	-0,2
Plate Products Type 3	0,9

In contrast to the concordance analysis performed in the last chapter this one only has one criterion with a higher uncertainty and that is the cost impact. This is due to the fact that most others are based on the previously performed current process analysis. Therefore the plate solution is even under changing circumstances the most dominant solution.

A detailed cost and time analysis of the plate production has been performed and are presented in section 7.1.2. The most complete information was gathered on the mast plates. This information concludes that the masthead side plates have the highest labour and overall cost per part. So, the plate manufactured for the masthead side plate is to be modelled for this concept description.

The laminate plate made for the waterjet cut of the side plate has dimensions of 1800mm by 900mm. Other than the two outer skin layers it is made of SE84LV-SPAR 600 material (view Figure 29). As described in section 2.1.2. As previously described in section2.2.4. currently all plies of the SPAR 600 material are cut from 300mm wide strips. The simulation of the ply cutting is performed on plies cut from the 300mm wide rolls. In addition to that, a second simulation is run with a wider roll of 1240mm width. This aims to show a direct process improvement in number of ply reduction as seen from Figure 28 and Figure 30. The corresponding number of plies required to build up the laminate thickness are given in Table 23. The difference in ply number between the thinner and the wider material approach is 228 plies.

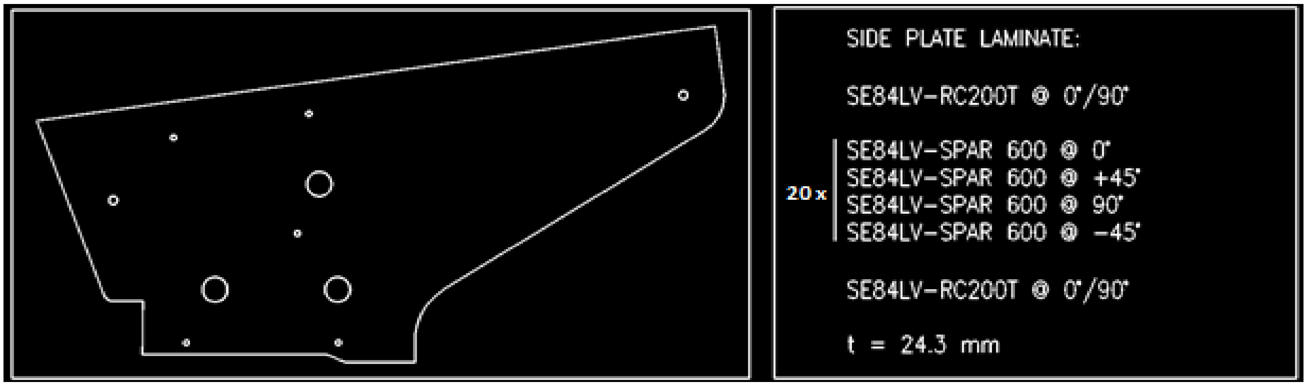


Figure 29: Laminating Instructions for The Masthead Side Plate Manufacture

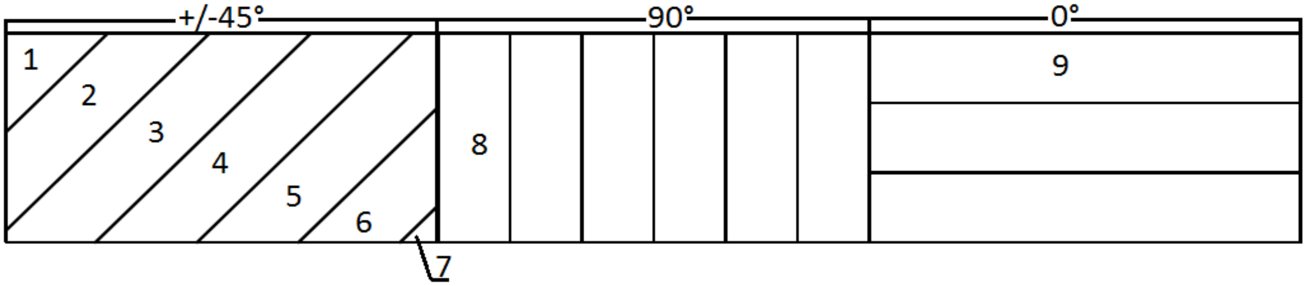


Figure 28: Ply Arrangement for the Laminate of the Masthead Side Plate (meterial roll width 300mm)

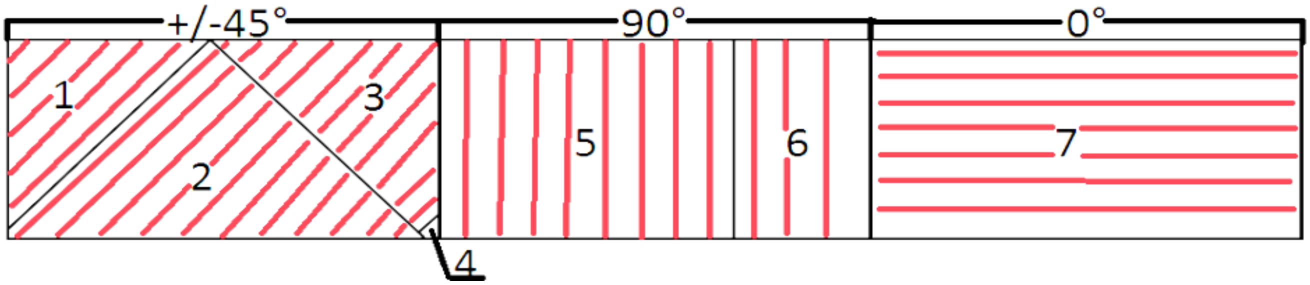


Figure 30: Ply Arrangement for the Laminate of the Masthead Side Plate (roll width 1240mm)

Table 23: Plies Requirement of the Sample Product

Ply type		# of layers	300 mm		1240 mm	
			Type	Plies	Type	Plies
Blocks	20					
Layers UD	+/-45	2	1	40	1	40
			2	40	2	40
			2	40	3	40
			4	40	4	40
			5	40		
			6	40		
			7	40		
	90	1	8	120	5	20
					6	20
	0	1	9	60	7	20
Base	Woven	2		2		2
Sum of plies			462		222	

5.2. STATE OF THE ART OF THE CONCEPT

The two Dutch composite production research institutes, NLR and Airborne Composite Automation, have developed set-ups and systems to comparable to the P&P system that would fit into the Rondal production. It was concluded from the discussion with both firms that the automation solution is not ‘off-the-shelf’, ready to be implemented in production immediately. Each company have developed individual building blocks that make up the process Rondal requires. Both are using vacuum inducing Coanda grippers to handle differently shaped plies handle. The NLR mainly handles dry fibre, therefore their griper flat suction surfaced are not ideal to use with the sticky prepreg. In comparison, Airborne uses suction cups to handle their prepreg. Furthermore, Airborne is currently developing a sorting system that will be able to deal with a large variety of plies and is one of the building blocks for the Rondal process. The NLRs has focused its development on hot drape forming laminates stacks into moulds, which is also a further added building block to the concept. The expertise of both companies will help to realize Rondals’ P&P concept.

5.3. PROCESS REQUIREMENTS

This section addresses specifics about the requirements the automation system needs to meet as well as identifies boundary constrains the system should be built around. Regulations limitations are touched upon, but the main objective of this section is to provide an insight into the robot options and capabilities. It is also clarified which of the equipment is self-developed.

The individual process steps of the concept are identified to be at one of the following five stages: existing ‘off-the-shelf’, existing ‘built-to-order’, under development, self-developed and in use at Rondal. Table 24 helps understand which equipment falls under either of these stages.

Table 24: Summary of Development Source of all Concept Cell Equipment

Equipment	Concept description
Robot	The robot is an ‘off-the-shelf’ piece of equipment and is directly available for delivery, but it need code development adapted to the cell process. So, it is partially existing and partially under development.
Nesting	Nesting software’s are an ‘off -the shelf’ product, usually part of the cutting table.
Cutting Table	The cutting table is also an ‘off-the-shelf’ piece of equipment that can directly be implemented into the production be it manual or automated.
Gripper	A possible prepreg gripper solution has been developed by Airborne. It is as a ‘made-to-order’ product since adaptations will have to be made to the gripper for it to fit the plies. Self-developed suggestions for adaptations are made based on observations during testing.
Sorting Station	The pick and sort process is under development at Airborne. For intellectual property (IP) reasons the actual Airborne solution is not disclosed. The solution presented in the concept is hence a deduction from information gathered though discussions with Airborne. The equipment seen in the description is self-designed in this research project.
Film Removal Tool	The tool is a ‘black box’ in terms of process data, so it is entirely self-designed.
Flip Tool	This apparatus is part of the film removal process, so is also self-designed.
Stacking Table	The stacking tables are already in use at Rondal.
De-bulking Frame	The de-bulking frame is already in use at Rondal. If any additional de-bulking frame is required, these must be ‘built to order’.

5.3.1. ROLE OF OPERATOR

The operator oversees the feeding material into to cell, this means not only at the start of the process but also at any time the material roll is empty and stops the overall process. Once the nesting is complete at the operator can see at what time these change overs are occurring, since the system computes a cutting simulation. So, creating the nest for the plies is also part of the role description of the operator. The information input at this stage is taken from the work instructions. The in charge of the automation system also needs to be available to resolve any process interruption caused by failed process inspections. Resolving such interruptions should generally only involve the adjustment or the rest peeling of a ply. It should allow the automation process to continue once it has been indicated to the system that the problem is resolved. According to the ISO 10218-2 norms a process fault which the operator needs to intervene is not to lead to any loss of safety function in the overall system. Dependent on the task the operator should also be able to teach simple motions to the robot as well as perform a simulation run through of the process in case of an alteration to the process.

The approach of so called ‘lights out factories’ have become more popular in recent years. It provides 27/7 manufacturing opportunity since the robot system are developed in such a way that either very few problems occur or the robot can solve the issues on its own. Only in such circumstances can the process be left completely unsupervised. Most processes such as the one looked at for this application are too complex for the lights out principle to be worth implementing (Anurag, 2016). Additionally, Rondal also does not have the need for such manufacturing since the product volume is not that high.

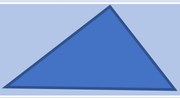
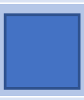
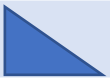
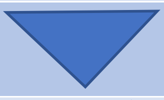
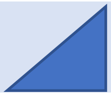
5.3.2. EXTEND OF PROGRAMMING

The desired state of technology of the implementation of this automated system is at an “off-the-shelf” state. As stated in section 5.2, the development is not sufficiently advanced to allow that. The data input to the system is ideally an interface established to feed a range of information initially into the nesting software from which the robot movement information can be deducted by the program.

A sample set of input data for the block within the laminate stack (Figure 29), is provided in the Table 25. The nesting software should label the ply within its program. The nesting software should also be able to position the shapes of the nest based on the number of plies required, the material used and the geometry and orientation of each ply. The cutter can then identify the ply and the information is forwarded to the robot and the gripper to pick-up the ply at the correct location and rotating it. The system should also have an algorithm integrated that identifies the centre line of each ply for the peeling process. This state of implementation minimizes the amount of training needed for the operators.

Teaching the robot movement is another way to adapt this process to a product. It is simple and can easily be instructed to workshop personnel. This is only feasible for many reparative actions with a small variety of plies, such as in the layup of plates. The disadvantage of this approach, is that labour hours need to be assigned to teaching the robot the movements. The teaching limits the decision-making logic of the robot (Mariani & Groover, 2007), so errors are more likely to occur.

Table 25: Input Information for the Program

Ref. Nr.	Place in stacking sequence	Nr. plies required	Material	Orientation	Geometry/ Dimension
1	1	20	SE84LV-SPAR 600	0°	
2	2a	20	SE84LV-SPAR 600	45°	
3	2b	20	SE84LV-SPAR 600	45°	
4	2c	20	SE84LV-SPAR 600	45°	
5	2d	20	SE84LV-SPAR 600	45°	
6	3a	20	SE84LV-SPAR 600	90°	
7	3b	20	SE84LV-SPAR 600	90°	
8	4a	20	SE84LV-SPAR 600	45°	
8	4b	20	SE84LV-SPAR 600	45°	
10	4c	20	SE84LV-SPAR 600	45°	
11	4d	20	SE84LV-SPAR 600	45°	

5.3.3. ROBOT

The robot is one of the largest and most costly piece of equipment within the cell. This section discusses different robot type and looks robot performance properties that are most important for the final implementation.

5.3.3.1. TYPE

The largest industrial robot manufacturers are Fanuc, Yaskawa (Motoman), ABB, Kawasaki, Nachi and KUKA. All of which have between 80.000 to 400.000 industrial robots installed globally (Mantaqim, 2015). Most robot manufacturers offer similar products but specialize in different areas of the world. There are two different types of robots that need to be considered: the robot requiring safety fencing and collaborative robot (Cobots). Fanuc have developed a wide range of Cobots. This prevents the need of safety fencing. Others such as KUKA are manufacturing large industrial robots that do require safety fencing. The KUKA models are the ones in developed composite handling cells in the Netherlands. A robots' main properties are its upon is payload, max. reach, number of axes and its position reliability. Table 26 demonstrates these properties comparing a standard industrial robot and a Cobot. This information is taken from the product brochures of the manufacturers (KUKA, 2017) (FANUC, 2017).

The payload requirement is determined based on considerations such as the weight of the end effector for the plies (further discussed in section 5.4.4) of approximately 30kg Weight of the plies are minimal with the largest ply weighing 1.6kg (600g/m^2). At early stages of the implementation this is the only payload the robot has to carry. This automation system needs to have the potential to be further developed in the future to manufacture mould products. The robot should also be able to lift the largest mould that are the spreader moulds that weigh each up to 100kg. Both mould only have to be lifted together for the preparation of curing and the lifting of the mould into the autoclave. The time-consuming alignment and assembly of the two moulds only required one mould to be lifted on top of the other. Thereby, even though the most flexible payload capacity would be of 240kg, a payload of 140kg would also suffice to be able to automate most of the mould parts. This lower payload provides the opportunity to have a robot with a wider reach, which is of importance due to the large amount of equipment necessary in the cell. By installing a robot of 140kg payload no changes to the system will have to be made for future adaptations.

Table 26 provides the data specification of the largest Cobot with a payload of 35kg. This clearly only meets the requirements of the initial phase of the implementation. The advantages of the Cobot are easy handling, programming and integration as well as less use of workshop space. The safety proportions that need to be taken due to the co-handling of the robot impact the operational speeds. Additionally, reach, payload and accuracy are also reduced with the Cobot. In later stages, this collaboration option could help to create a semi-automated work step where the ply is placed in the mould and manually consolidated.

The industrial robots have the capability to be more accurate at a higher operational speed and even though their system set-up is more multifaceted, it also provides the possibility to program more complex tasks. The addition of the fencing adds to the capital cost and further increases the workshop space required for the automation cell. According to TMrobots (2017) , the return of investment for most industrial applications is usually less than one year. The KUKA industrial robot provides the opportunity to meet the future potential specifications.

Even though the Cobot has advantages to the standard industrial robot it simply cannot deal with the required payload for future potential. This means that a new robot would have to be bought to continue further automation development. Since that is not feasible the fenced industrial robots have been chosen to be implemented into this systems set-up.

An important point concerning the robot speed, is that the robot will not always travel at its maximum speed of 2m/s even when it is in its fully autonomous operational mode. The speed depends on the distance travelled between the process steps. These distances might not always allow the robot to accelerate to its maximum speed before decelerating again for the process step final position. A product flow and movement simulation of the process hence becomes paramount to obtain an understanding of the process times. Extra entities like the linear track unit, the rail upon which the robot is mounted, adds an axis of freedom. But, it possibly also slows down the operational speed when the robot is running over these tracks since additional joint restrictions are added to the system. This is possible to be identified by the robot movement simulation.

Table 26: Comparing Robot Types

Model and Manufacturer	 **KR QUANTEC KR150 R3700 (KUKA**	 **CR-35IA (FANUC)**
Repeatability (mm)	<+/- 0.06	+/- 0.08
Range (mm)	3701	1813
Max speed (mm/s)	2000	250 -750
Max payload(kg)	150	35
Number of axis	6 + 1 (from rail)	6
Mass (kg)	1215	990

The main difference between the Fanuc and the KUKA robots is that Fanuc sells product with their own sensing system integrated.as a way to prevent fencing to be required. They call this a dual trace system. Any sensors added to a KUKA robot will have to be integrated from an external system.

The choice of robot manufacturer is not a choice of performance ability of the robot, since most industrial robots can perform the same task. The brand of the robot is mainly based on the company Rondal chooses to develop their autonomous system. Whilst Airborne and the NLR use KUKA Robots, the system developer Smart robotics/Gibas that partner with the cutting firm Zünd, work with Fanuc robots.

The robot movement simulation that is described in later chapters is using a KUKA robot. This is because there was a larger selection of KUKA robots accessible in the Visual Components Library and therefore gave a wider choice of robot ranges.

5.3.3.2. PERFORMANCE

Table 27: Robot Axis Property

Model	**KR Quantec ultra K**
Axis	**Range**
A1	±185°
A2	+70°/-120°
A3	+155°/-120°
A4	±350°
A5	+125°/-122.5°
A6	±350°
	Velocity
A1	105°/s
A2	101°/s
A3	107°/s
A4	179°/s
A5	172°/s
A6	219°/s

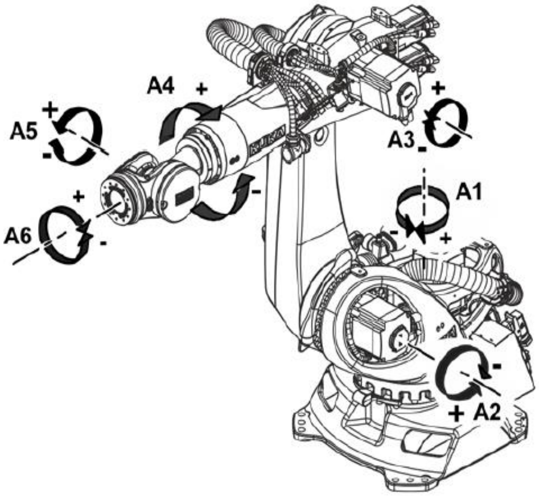
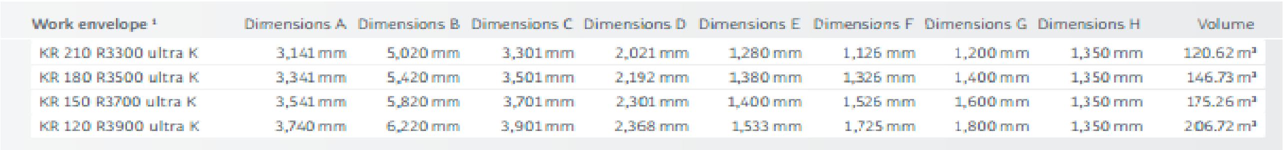


Figure 31: Robot Axis

An industrial robots' performance is measured in two properties repeatability and accuracy. Repeatability is the robots the ability to return to the position it has set off in. Values for this are usually indicated per direction, meaning that for a multiaxial robot these values add. Repeatability is due to loss of motion through for instance backlash, torsional elasticity or friction in the gears. The value in Table 26 let's deduct the reliability about +/- 0.48mm considering all 6 axes. This is an acceptable tolerance since currently a manual layup accuracy of +/- 2 mm is achieved. Accuracy is the ability to displace the tool centre–point (TCP) at a given distance from its start position (Slamani, Nubiola, & Bonev, 2012).

Figure 32 shows the movement ability of the axis. The axes A5, 5 and 6 will most probably be further restricted since tubing for the vacuum/air pressure of the end effector have to be attached. The robot model chosen is very much depend on its reach. Iterations of different robot reaches should be investigated taking into consideration different cell layouts to determine the exact reach requirement. Figure 32 emphasises that a robot maximum reach does not apply into all surrounding directions. Additionally, the reach has a length C but the actual space in which the robot can operate is C-E.

The vast variety of equipment in the cell needs a large robot reach. Robots have a physical limitation to how far it can reach, additionally the wider the reach the costlier the robot becomes. An option to reduce the range requirement of the robot is by adding a linear track unit to the set-up. The minimum length of the travel track for such a unit is 400mm in addition to two standing lengths of the robot making it about 1,5m long. Its maximum velocity is 1.96m/s.



Work envelope ¹	Dimensions A	Dimensions B	Dimensions C	Dimensions D	Dimensions E	Dimensions F	Dimensions G	Dimensions H	Volume
KR 210 R3300 ultra K	3,141 mm	5,020 mm	3,301 mm	2,021 mm	1,280 mm	1,126 mm	1,200 mm	1,350 mm	120.62 m³
KR 180 R3500 ultra K	3,341 mm	5,420 mm	3,501 mm	2,192 mm	1,380 mm	1,326 mm	1,400 mm	1,350 mm	146.73 m³
KR 150 R3700 ultra K	3,541 mm	5,820 mm	3,701 mm	2,301 mm	1,400 mm	1,526 mm	1,600 mm	1,350 mm	175.26 m³
KR 120 R3900 ultra K	3,740 mm	6,220 mm	3,901 mm	2,368 mm	1,533 mm	1,725 mm	1,800 mm	1,350 mm	206.72 m³

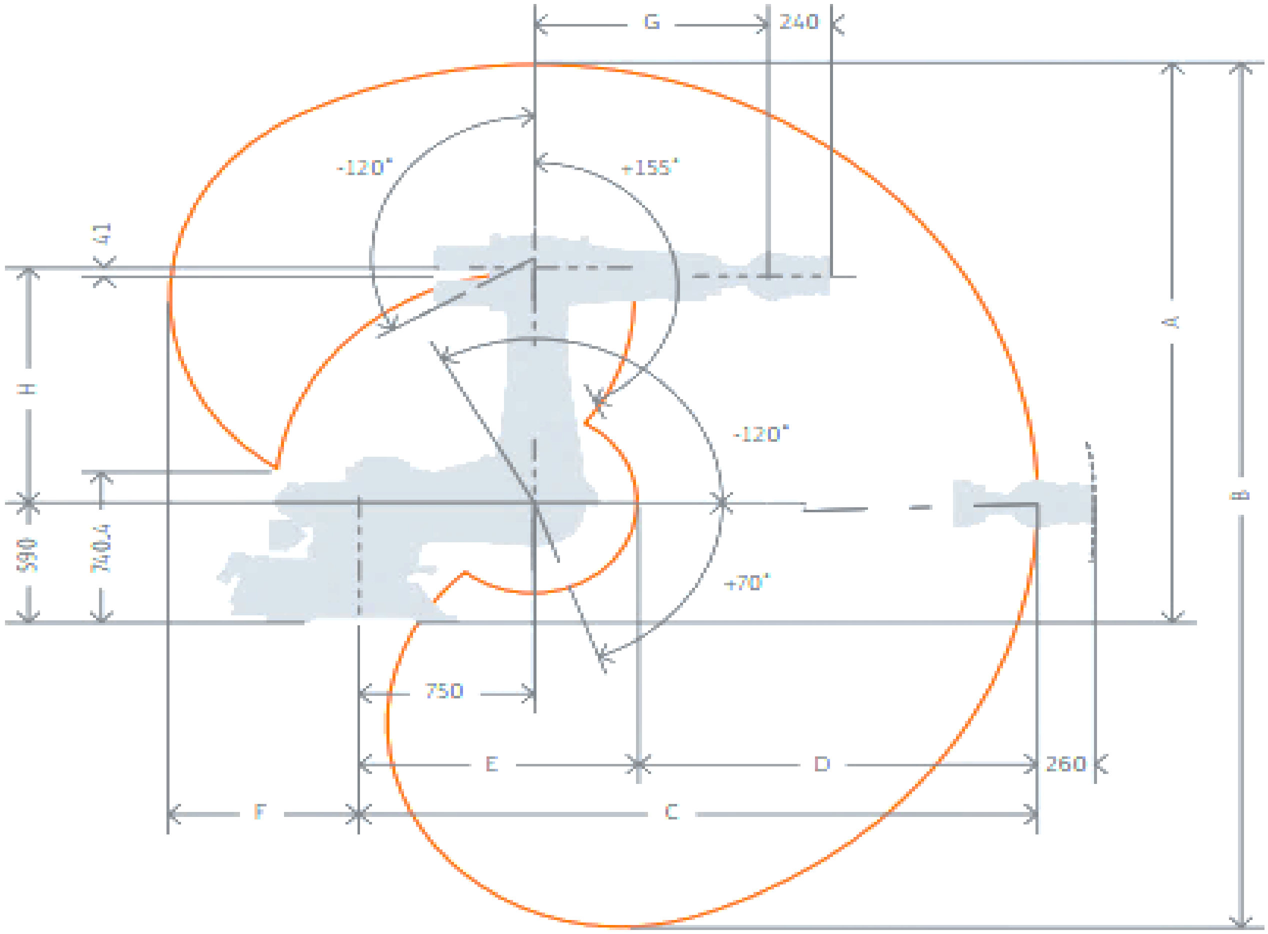
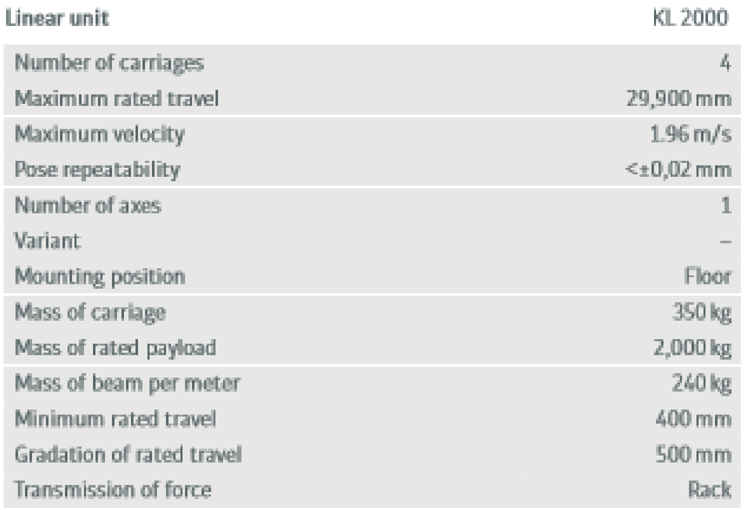


Figure 32: Area of Movement of the Ultra K Robots



Linear unit	KL 2000
Number of carriages	4
Maximum rated travel	29,900 mm
Maximum velocity	1.96 m/s
Pose repeatability	<±0,02 mm
Number of axes	1
Variant	–
Mounting position	Floor
Mass of carriage	350 kg
Mass of rated payload	2,000 kg
Mass of beam per meter	240 kg
Minimum rated travel	400 mm
Gradation of rated travel	500 mm
Transmission of force	Rack

Figure 33: Linear Unit Properties

Adding the linear unit will provide a reach increase into one direction but also reduced the available reach for equipment close to the robot in the perpendicular direction (seen Figure 34). It will have to be considered if the added value of the increase in one direction is worth losing robot reach. This unit adds to the overall robot position repeatability and brings the reliability up to +/- 0.5mm (KUKA Roboter GmbH, 2016).

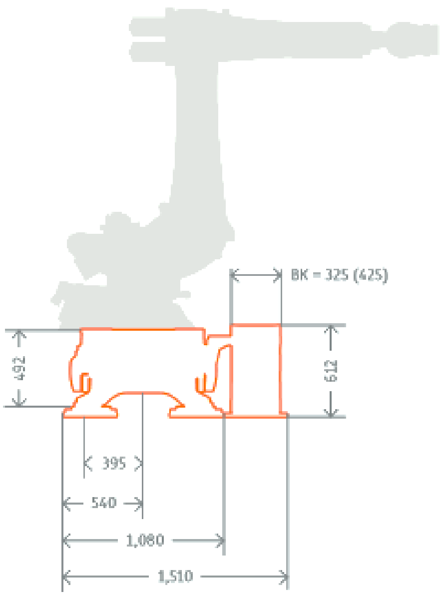


Figure 34: Dimensions of Linear Unit

5.4. PROCESS STEPS

This section elaborates in more detail on the process steps previously identified and describes solution options for each individual step within the automated system. It also points out the automation interconnectivity of each step to one another, starting with the nesting and finishing with the de-bulking equipment.

Refer to Figure 27 at the beginning of this chapter for the action steps provided at the beginning of each step description.

5.4.1. NESTING

The nesting represents flow chart action 1. Usually, automation solutions provide waste reductions through the alteration of the original process. However, since this project avoids performing any alteration on the process, the nesting is the only mean to achieve waste reduction with the integration of the automation.

Plies are currently nested using the software Alphacam Advanced Profiling. It is used for nesting the parts and more importantly to convert the dxf drawings into files that the cutter can read. Each nesting software works with a different algorithm. The second software discussed in this section comes from the provider of the cutting table, Zünd. The comparison between the two helps to show the improvement potential of the automation system.

The nesting is the only source of potential waste material reduction without altering the production process. The advantage of the P&P solution is that the nesting can be formed over the entire length of the roll since the cutter has a conveyor. Currently the plies are cut out of at most 5m in length sections. The longest rolls have up to 250m of material (Table 1).

The Alphacam software was used to create nests of the sample product. The longest sections Alphacam can generate are only 100m long. So, the impact in length on the nest effectiveness can only be analysed upon this length. The comparison of nests seen in Figure 36 to Figure 37 shows the difference in material use between 5m and 100m nests. The red areas provide an indication of the amount of waste caused by the nest. The first two figures compare the nest differences with an increase in roll width. These show that even though there is a significant decrease in section needed (68 sections less) the amount of waste material is not reduced but rather tripled. The cause of this are the larger plies, whose widths do not snugly fit onto the roll width. They can however be tightly fitted to the 300mm wide material. The calculated values of this visual comparison are summarized in Table 28.

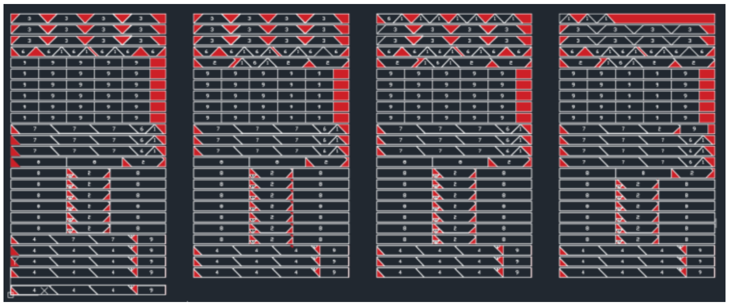


Figure 36: Nest of 5m Sections with 300mm Width

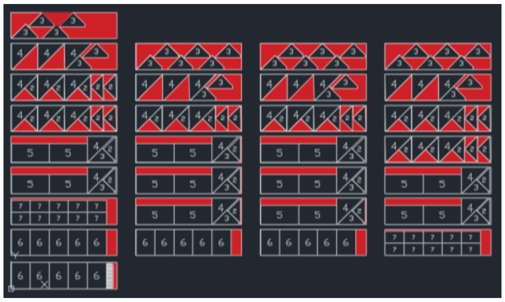


Figure 35: Nest of 5m Sections with 1270mm Width

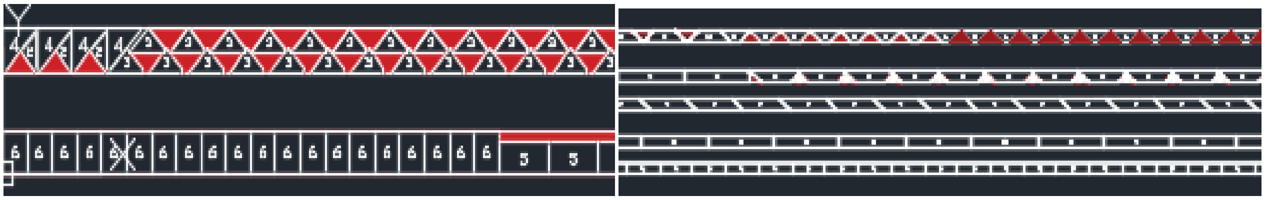


Figure 37: Comparing Sections of the 100m Nest for 300mm and 1270mm Width

The nests are compared to the nest of the larger 100m sections. The most noticeable difference is that the number of material changeover is reduced to 5 for the thin roll. The increased length only reduces the amount the waste percentage by 2.8%. The wider ply only needs 1.5 rolls of material but makes use of 37.6m^2 more than the thin roll. In terms of cost it is a difference of 707 €. This is assuming that both roles have a cost of 18.8€/m^2. This is the price of the thin roll of the same material. Compared to the part production cost it makes up 23% of it. The most expensive prepreg costs 40.3 €/m^2 which would increase this cost difference up to 1515€.

Table 28:Nest Size Comparison

Width of Section (m)	0.3	1.27	0.3	1.27
Length of Section (m)	5	5	100	100
Number of sections	98	30	5	2
Leftover material (m)	3.2	1.5	57.3	21.4
Material used (m^2)	145	189	144	143
Area of plies (m^2)	130	130	130	130
Waste (m^2)	14.9	59.0	14.0	51.6
Waste (%)	10.3	31.3	9.7	28.5

The same nest for the wide roll has been performed on the Zünd nesting software, to be able to analyse the differences between them. It can be concluded that the overall software interface is more user friendly on the Zünd development. However, the nesting on this software is stopping once the maximum number of plies nested on the indicated area is reached. All other plies must be nested in another nesting session, meaning the overall used length has to be estimated. In comparison Alphacam automatically generates a second section equal to the first, onto which it continues to nest. This provides a better overview of the overall situation. As Table 29 indicates from the statistics of the Zünd nesting software, between 782 € to 1677 € of nesting waste can be saved by applying the alternative algorithm. It is a nest waste reduction of nearly 20%. However, it should be kept in mind that this value depends on the shape of the material and its ratio to the final product.

Table 29: Nesting Software Comparison

Nesting software	Zünd	Alphacam
Width of Section (m)	1.27	
Length of Section (m)	100	
Length of material used (m)	104.3	178.6
Efficiency (%)	91.1	71.5
Waste cost (€)	174 - 373	956 - 2051

This concludes that the process movement simulation of the automation system need to determine to optimize for either:

- The number of plies handled by the robot and with it the amount of material roll change overs.
- The amount of waste produced by the cutting of wider material.

The particularity of this sample plate is that the width of 900mm is divisible by 300mm, which gives the 300mm roll a significant advantage. A further investigation could intale to check whether these results are also supported if the plate has width dimensions not evenly divisible by 300mm.

The data gained from this analysis is used as a generic reference value in the automation process predictions in CHAPTER 7.

5.4.2. CUTTING

The cutter represents action 2 on the flow chart. In the Airborne process, the bottleneck of the process is the cutter. The robot can operate with up to 2m/s and the airborne cutter cannot match that speed. The cutter currently installed at Rondal is not suitable of the task. One of the main features required to make it an automated entity is a conveyor. This mean a new cutter will have to be purchased to be integrated into the automation cell. A possible supplier for this cutter, that has been recommended by Airborne, is the Swiss company Zünd. Their equipment is often implemented into larger automation systems in textile industries. The cutter from their selection that bests fits the requirement for this production system is the G3 M-2500 (Figure 38), with extension table.

The cutter consists of 6 main features: a traveling clamp beam, a traveling cutter beam, a conveyor, an extension table, a feeder and a controller. First the cutter is loaded with material by the operator. The cutter clamps the material and move it together with the conveyor belt into position. This happens at a speed of 200 mm/s. This clamp will serve as a place holder for the ply during the picking operation. The conveyor has suction through the belt keeping the material from moving during cutting. A problem observed during the testing at Zünd, is that the clamp is not able to release the material since the resin of the prepreg keeps it in place after having pressed down onto it. A simple solution for this is to cover the clamp with Teflon coating which will prohibit it form sticking.

Once the nesting has been performed on the controller, the cutting process is ready to start. The traveling beam, onto which the drag cutter is mounted, allows cutting operations to be performed at up to 1 m/s. This reduces as corners or curvatures have to be cut. In contrast to the cutter seen at Airborne, the Zünd cutter performs the operation with a standing conveyor, whilst the Airborne machine can cut with a continuously moving belt.

Another observation on the Zünd cutter is that only the material in the cutting region is cut. As such this is to be expected but due to the large size of plies and dependent on how the nest has been calculated, this might result in half cut plies. This half-cut ply will only be cut in the following cut session, which makes the communication between the cutter and the robot important. Only the fully cut plies are to be picked up by the robot. An intermediate conveyor belt movement will have to also be commanded as a controlled movement to provide the robot the opportunity to pick up the previously half cut plies. This also means that the flow of the entire cutting process needs to be paused until those plies have been dealt with.
Another way to resolve this problem is to instruct the robot to pick-up the ply whilst the cutter is still in process of cutting other plies. This means the robot enters the working space of the cutting beam. Such an action will significantly increase the complexity of the robot program since there is a high risk of damaging equipment during collisions of the dynamically moving bodies. The robots and cutters movements would have to be coordinated either by direct connection of the systems or though sensors. To avoid such complexity the extension table has been chosen as part of the cutter.

If this issue is not addressed the conveyor will simply move the entire cutting section to the end of the extension table, causing half of the plies to fall off the table. These plies can then no longer be handled accurately and safely by the robot gripper. A continuously moving conveyor, might slow the cutting speed down but will prevent full cutting pauses to occur.

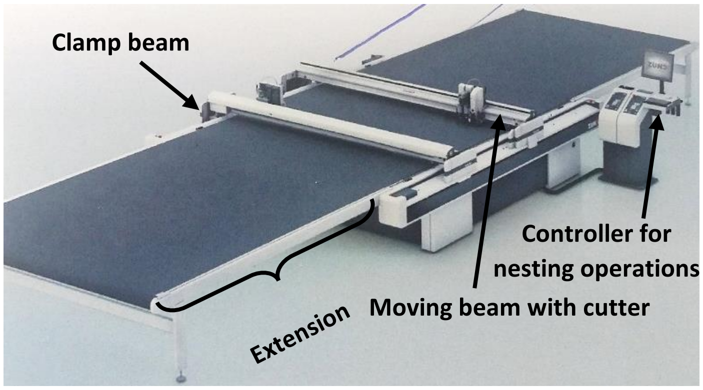


Figure 38: Zünd G3 M-2500 Cutter with Extension

The Zünd cutter is one of the few pieces of equipment that can be considered ‘off-the-shelf’ solutions within the concept. The Zünd assortment has cutting tables of dimensions between 1330mm and 3200mm width and 830mm to 3210mm length. To handle the largest prepreg rolls, the cutter only needs to be 1330mm wide. It does require a length of 2500mm to handle larger plies. The corresponding extension tables can at maximum be of the length of the cutter. So, the entire cutting unit conveyor moves the material over a surface of 1330mm by 5000mm (Zund Benelux BV, 2017).

There are a few plies, mostly for the spreaders, that have a length up to 4m. To keep opportunities, open for these products to be fully automated a redesign of the spreader wall thickness will be required. This allows to half the size of the plies, making them fit onto the cutting table.

As can be seen from the nesting example, the plies for one plate production use more than one roll of material. Hence, it is important to have a feeder system that makes it quick and easy to reload the cutter.

The material rolls have a variety of diameters, since it depends upon the material how tight they can be rolled up. Therefore, the feeder needs to be able to adapt to all the different roll size diameters.

If this process were to run fully self-sufficient in a light-out-factory, this feeder would be required to hold a sufficient stock of material types. This is not needed so the chance overs will be performed by the operator. The nest software can predict the cutting time to 32min 13s. this value will later be used for performance prediction of the entire P&P process.

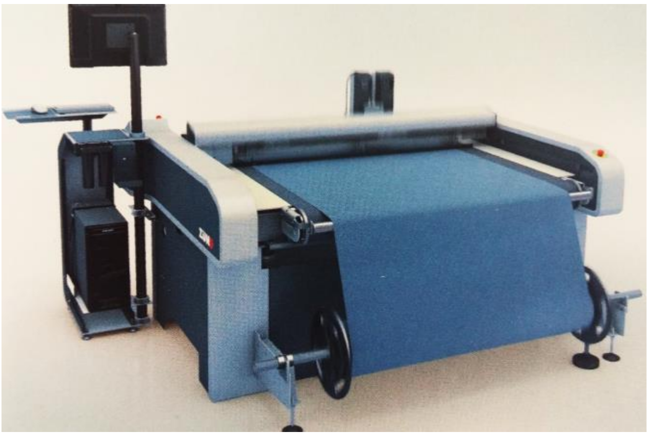


Figure 39: Zünd Cutter Feeding System

5.4.3. IDENTIFICATION

The identification of supplies is action 3 on the flow chart. The identification of the ply involves the recognition of the shape and location. It also needs to know the orientation at which it is picked up and in at which it is placed in the stacking sequence. It is the most important part of the entire automation system. As mentioned in section 5.3.2, for simple processes with small number of different type plies, this can be done through teaching. But for more complex scenarios the robot needs to recognize the plies on its own. This is done though communication of the information in the cutting file.

The cutting file has the origin coordinates of each shape. If this is transferred to the robot it can identify that coordinate system and match it with the one of the end position provided through the input information. The set-up of a generic system performing such tasks has been predicted by experts to be a lengthy process.

5.4.4. PICKING

This represents flow chart step action 4. The picking action is fully reliant on the design of the so-called end effector or gripper. Appendix IV indicates the design of the end effector has a great influence on the successful process handling, since it determined how control is kept on the ply during the peeling process. At the initial implementation stage the main task is to grip and lift the plies. In later stages, it will also be required to pick and lift moulds. This means two different types of end effector for these tasks must be designed.

5.4.4.1. END EFFECTOR FOR PLY HANDLING

The end effector design for the ply handling is itself also split into two main design concerns:

1. Connecting the ply plies to the end effector
2. Mean of lifting the ply

The material properties that are of most importance when gripping prepreg are the tack, the ability of the ply to adhere, and the rigidity (Buckingham & Newell, 1996). Each type of prepreg material has different tack properties based on the environmental condition. It has been shown that not all prepreg undergo an increase in tack as the temperature rises. (Crossley & Warrior, 2012) This fact is of special importance for the protective film removal. There are many different types of gripping tools that serve different purposes most of which directly contact the object that is lifts. When handling prepreg, direct contact can result in resin transfer and contaminate of the material. It can also cause a build-up of resin, which at times results in a gripping failure (Björnsson, Lindbäck, Eklund, & Jonsson, 2015). Each of the gripping methods have their own advantages when handling different materials. the circumstances of their work environment must be analysed in detail to determine the most suitable gripper for a composite P&P system.

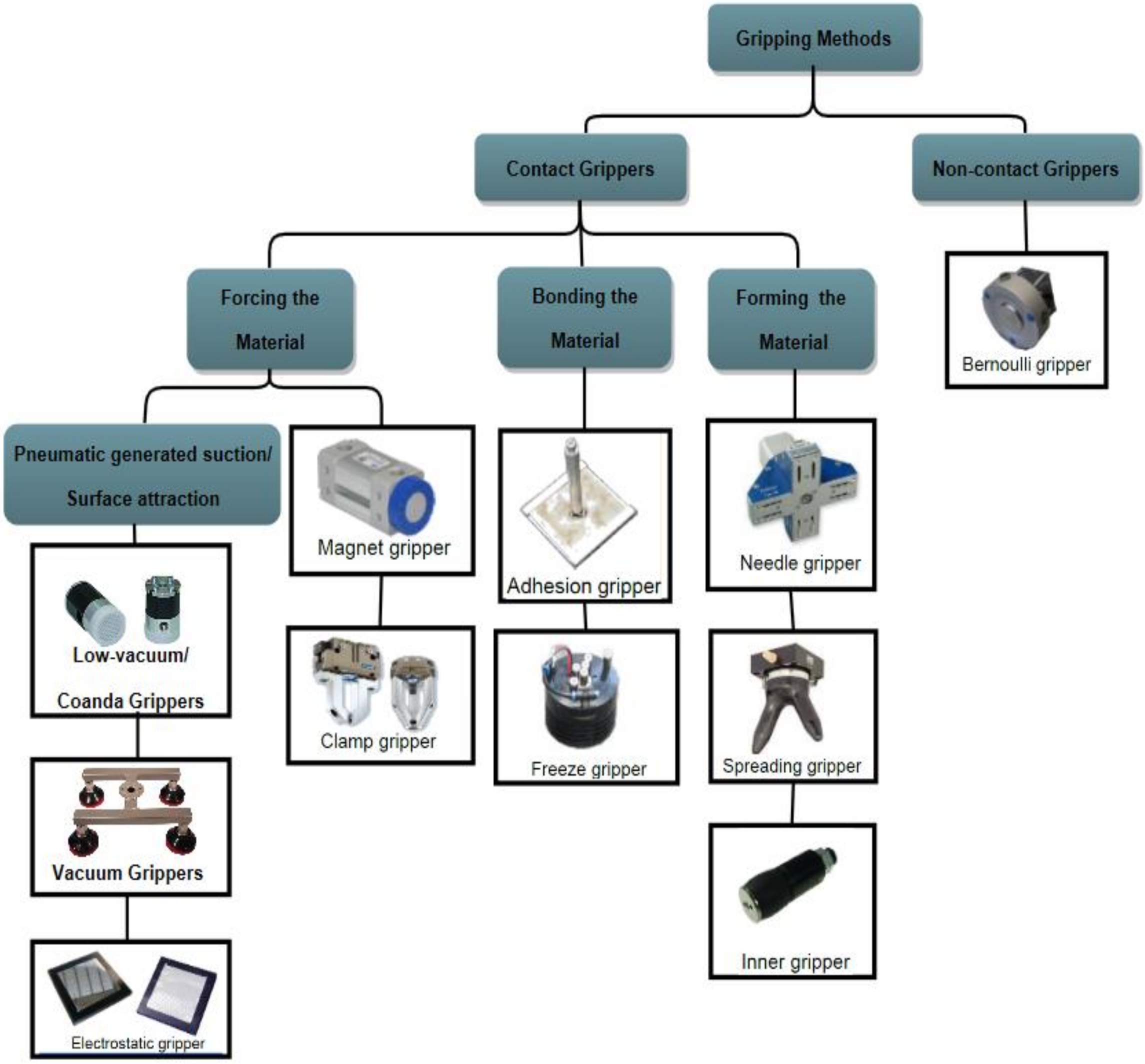


Figure 40: Overview of Gripping Methods

Figure 40 provides an overview of the grippers used in a variety of industries (Brecher, Emonts, Ozolin, & Schares, 2017). *Table 30* up the figure by providing more detailed information about each type. It provides a description of the working and explains the advantages and draw backs of each method. This is based on Brechers et al. (2013) analyses and Lankalapalli et al. (2003) as well as Björnsson et al. (2013) reports.

Table 30: Comparing Gripping Methods

Method	Description	Advantage	Disadvantage
Needle	Straight or curved needles penetrate the textile to keep it in place.	Simple and effective mechanism.	Can causes damage and displacement to the fibres
Clamp	Clamp fingers pick the ply up.	Simple and effective commonly used mechanism.	Risks of ply deformation and contamination through folding of the fabric.
Bernoulli	Creates an airflow over the surface of the ply, results in a negative pressure causing a gripping force of about 0.2N.	Only little or no direct contact, relatively affordable.	Risks of ply deformation through aero elastic effect. It is difficult to maintain the material position during the movement. It does not provide strongest grip.
Vacuum surface/ suction cup	Uses suction to lift the ply up.	Well established technology with a good lifting force and a simple system. Suction cups are very cheap.	Requires constant vacuum intake due to the permeability of prepreg. Can also cause deformation.
Electrostatic	Polarizes the ply inducing a force by applying potentials to gripper electrodes, creating an electric field.	No distortion due to evenly distributed surface attraction and non-intrusive method. It can also be applied to curved surfaces.	High voltage levels required. The effective design of the gripper can be difficult.
Gecko	Using the principle of van der Waals forces induced by a polymer sheet.	Independent of external power sources. Simple release.	Vulnerable to contamination due to direct contact and shear force created on the surface.
Adhesion	A sticky gripping surface is placed on the fabrics surface and lifted.	Easy and ensures a secure bond.	The adhesive surface degrades and has to be replaced resulting in consumption costs. The material release is difficult and risks contamination.
Cryogenic/ Freezing	Freezes moisture that is sprayed onto the surface of the fabric to create a direct bond between the material and the gripper. It is released by heat.	No damage is done to the material, and it is a reliable technology	Requires about 3s to freeze, therefore increases the lifting time. Adds moisture, which can cause later risks to be trapped within the laminate and reduce the material properties.

A point to note about the protective film on the prepreg is that it has low permeability which means that the suction grippers can easily be applied. It makes technology such as the Cryogenic unnecessarily complicated for the desired application (Björnsson, Lindback, & Johansen, 2013). This is probably why every recent R&D research performed on P&P systems has been using low vacuum/Coanda method (Reinhart & Straßer, 2011). This fact is another indicator that this type of gripper is the most appropriate for this application. Both the NLR and Airborne do however developed end effectors that induce a vacuum through compressed air with a coanda grippe. Thereby combining the two pneumatic gripping methods approaches from Figure 40. This approach also had the added advantage to not only grip the plies but also release the plies in a controlled manner with a blow of compressed air clearing the suction cups.

The choice of the right gripper is only one part of the picking operation another part is the lifting of the ply. A decision has to be made on how to adapt the gripping tool to the different size plies. The tool needs to adapt to a vast number of differently shaped plies, but also lift the plies so that they can be deposited in a controlled manner in the desired position. Björnsson et al have researched two ways to handel plies (2015):

1. By using a single robot arm that can reach along the entire ply using a specifically designed tool head. This method keeps most control over the ply, whilst keeping the robot programming simple to a single arm application. This limits the ply size handling to the size of the tool head. The tool heads can be designed in different manners, specific to the shape of plies handled with it, by placing suction cups in different locations.

Figure 42: Single Robot Arm Solution by Björnsson (2013)

Figure 41: Quick Release Gripping Tool by the NLR

2. By using two robot arms both ply ends can be lifted independently. This method solves the issue of size restriction, but can also cause sagging of the plies which can led to problems during stacking. A robot with two arms is also more complicated to program, thereby increasing the preoperational work required. If the solution of two independent robots is applies these require an additional level of coordination between the system equipment. The two arms could however, also work to solve assembly issues or perform ply consolidation.

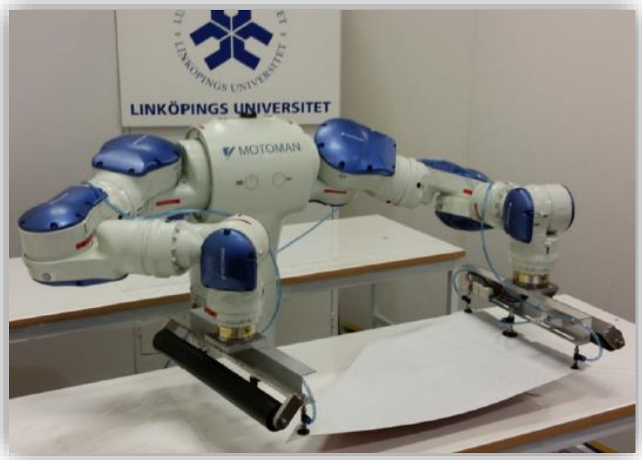


Figure 43: Double Arm Gripping and Consolidation Tool Solution by Björnsson (2013)

5.4.4.2. END EFFECTOR FOR MOULD HANDLING

The robot head will also need to perfom other lifting tasks such as lifting moulds, which requirers a different type of gripper. A quick releace tool head adaptor will come very useful when dealing with the changovers. The NLRs adaptation of this techniek can be seen in the Figure 44 (NLR media, 2015) This also means that tasks such as resin bleeder removal after curing or demoulding can also be done using this approach.

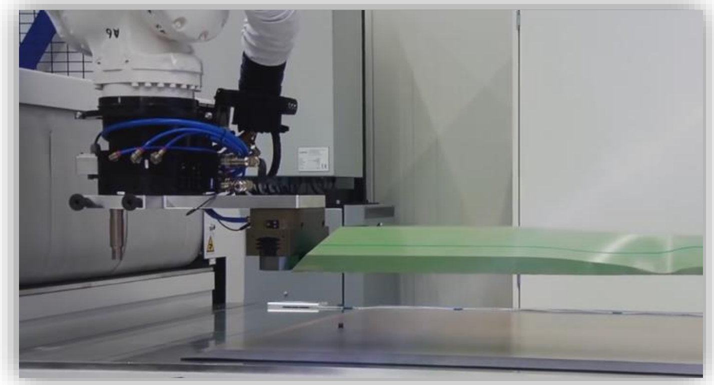


Figure 44: The NLRs Quick Release Tool to Lift Moulds

5.4.4.3. SUGGESTIONS FOR END EFFECTOR DESIGN

Testing showed, as described in Appendix IV, that the spacing, material and size suction cups need to be thoroughly investigated to optimized the end effector. The sketch in Figure 45 illustrates some of the problem areas within the picking action.

Area I is mostly related to the pickling done out of the sorting station before the actual film removal is performed. It is important that the front corner is covered by a suction cup, which allows full control of the movement of the initialization peeling process. More details are given in section 5.4.6.

Area II on the other hand shows that the spacing will have to be adjusted in such a way that sloped plies do not have sides that are complexly without grip. As soon as one suction cup is no longer fully located within the area of the ply it cannot be sued for the picking process without causing disturbances.

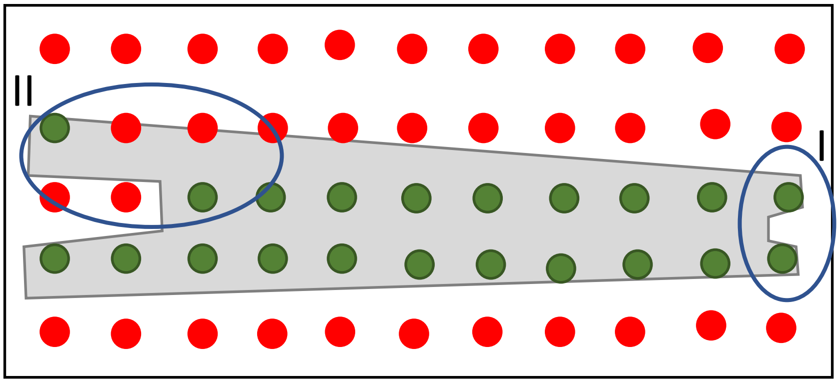


Figure 45: Problematic of Suction Cup Spacing

Airborne and the NLR have developed program interfaces that makes it possible to control the individual suction cups, adapting them to every individual ply. One aspect to note is that neither of their development involved touching the resin within the prepreg with the suction cups. The NLR handles dry fibre whilst

Figure 46: Suction Cup with Stroke

Airborne only handles prepreg that is still covered with protective film. The stroke of the suction cups (Figure 46) will be pushed in during the picking process, no matter if the valve in the suction cup is open or not. The pressure applied upon the surface will most likely result in adhesive forces between the rubber of the suction cup and the resin. Unless these forces are separated before the ply is lifted off the table, one risks to pick up surrounding plies or waste material. This destroys the robots coordinate orientation and would need recalibration of the material on the conveyor. Such factors cause more inaccuracy during release if not addressed from the very start of the development. Airborne's gripper interface needs to be adapted to push a blow of air though all unused suction cups as well as all suction cups when releasing the ply. This it could result in a successful gripper and release action.

The weight of the end effector needs to be matched to the payload of the robot. For a smaller end effector like the one used at Airborne, this is not an issue, however when having to deal with plies of up to 2m length the end effector weight does add up, dependent on the material it is made off. The Airborne end effector, which has not been weight optimized, has a weight of 15kg and is approximately half the size of the end effector needed for Rondals set-up. It is assumed that the maximum weight of the end effector will be approximately 30kg. Based on an observation made during testing at Airborne a good choice of material for the frame of the end effector would be transparent, so that it does not prohibit vision during teaching operations of the robot. Prohibiting visual access to the ply surface reduces the accuracy of the teaching and slows down the process.

The overall size and the detachment of the tool from the wrist joint of the robot are two other factors that influence the design. The vacuum tubing that run along the length of the arm and connect to the end effector might cause restriction to the robot joint movement. The movements of the robot need to be adapted to the connections of the tubing, if this is not done carefully the connections can easily fail. The robot does not feel the resistance so it just snaps connections that don't withstand the motion. Table 31 describe the advantages and limitations of having one standardized gripper or several to better adapt to the plies sizes.

Table 31: End Effector Comparison Single to Multiple

One generalized end effector	Several ply type end effectors
– The large frame size will force any rotary movement to be lifter overhead of the robot. It adds additional challenge to the movement programming.	– An extra step is added to the process which requires the tool head to be changed via a quick release mechanism. Additional space within the robots' reach is required to store the tool that is not in use.
+ Interface design become more complex since the tool needs to switch on the appropriate suction cups on the tool dependent on the plies shape.	+ The quick release mechanism forces to place connection apparatus on the tip of the arm and reduces the diameter tube running along the length of the arm. This can improve the robots freedom of movement.
+ One tool fits all, there are no change over action required to be performed.	+ Provides the opportunity to optimize the spacing and shape of the tool for different ply groups.
– Physics related problems can occur due to the higher weight of the end effector and the added motion limitations.	- More expense in design and construction of the tools, but such a tool only costs approximately 7000€ (based on Airborne experience).
	+ The smaller tools have more freedom in movement at the operating level

No experience has been gained dealing with large end effectors such as they are desired to be used at Rondal. There is a high likelihood of there being other challenges discovered once operating such a tool. Tests and movement simulations will have to be done to fully analysis which of the two approaches is the most convenient. It can be assumed that the several tools option provides a simpler and faster process solution. Such a process is of more interest for the first stage of the automation implementation.

5.4.5. KITTING

The kitting process step represents flow chart actions 5 and 6. The nesting software does not allocate the positions of the plies based on their order within the stacking sequence but based on the ideal use of space of the material roll. This means that kitting involves two main stages: the placing of the plies in temporary storage places and the sorting of the plies in the right stacking sequence to form a kit. An important requirement for this set-up is that there is sufficient space for the final and to place the different types of plies in preliminary storage places.

Airborne has developed a buffer system for this sorting process that minimizes space usage. IP reasons do not allow the exact functioning of the sorting station to be disclosed. However, from discussions with the developers at Airborne it can be said that the buffer provides similar opportunities to a vertical storage carousel or simply a cabinet with an actuator that can open draws to either side access Figure 47.

The advantages of this method are that it gives flexibility to the sorting system and provides sufficient space to work on numerous kits simultaneous. This also means that the planning needs to be set-up to incorporate the ply cutting of numerous different parts. Ideally, this storage system is accessible by both sides. Once to be filled by the robot and on the other, for the operators to remove the plies that are further processed manually. The sorting of the kits has to be done in reverse to ensure the first plies of the stack is accessible for further processing without having to flip over the entire tray to access the first ply.

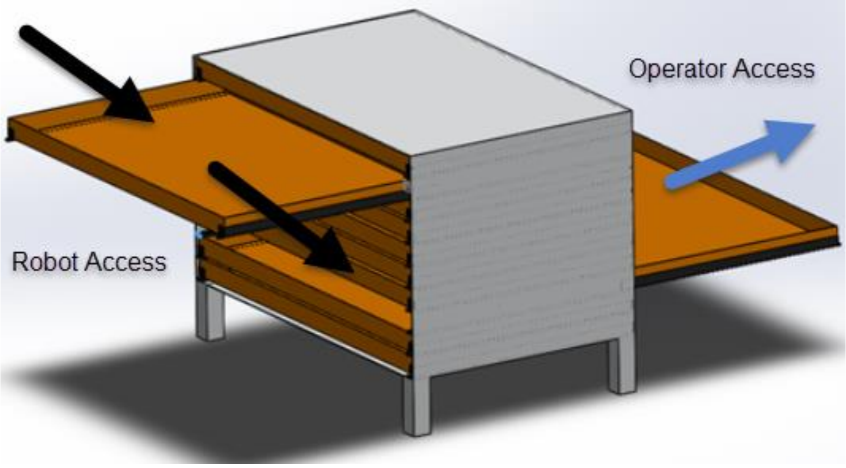


Figure 47: Sorting Station

5.4.6. FILM REMOVAL TOOL

The film removal tool is part of process step 7b in the flow chart. The film removal tool was the only significant piece of equipment in the robot cell that did not have any physical process data available. To be able to fill this 'black hole' in the process understanding it was decided to develop a film removal tool as part of this project, to help understand the complexity behind its development and obtain data for a later process performance prediction.

A considerate amount of this project was dedicated to developing a solution to the problem of protective film removal. The description of the tools design process as well as its capability and development potential are summarized in this section. A detailed development report that goes into specifics about the design and set-up of the tool is found in Appendix I and IV.

The design of the tool has been based on previous research solutions of this tool. The main research has been performed on the removal of packing paper, which is more ridged than the polibacks that are used on the prepreg at Rondal. Even though this stage is of importance for the overall automation of the process, the aerospace industry has not yet developed a solution. Their industry is highly restricted by regulations that specify the handling of the prepreg. The marine industry does not have these restrictions and is thereby free to come up with their own solutions.

5.4.6.1. REQUIREMENTS

The following points have been determined to be requirements of a first stage film removal tool design:

- The tool needs to be a separate, stand-alone unit, which is not controlled through the robot, but rather used by it to help perform the film removal. That way it is independent of the type of robot.
- He tool is required to sense the approach of plies and trigger its own working mechanism.
- The tool needs to be able to achieve the initialization and peeling operation without human input requirements.
- The tool should minimize the contact to the plies to reduce damage and contamination to the prepreg or any other kind of action that can impact the material properties of the final laminate.

In later stages, a more industrially applicable tool will also have meet the following requirements:

- The tool needs to be a design that can handle a large variety of ply sizes, yet be small enough to be able to be placed within the robot cell.
- The tool need to be sturdy enough to handle forces acting upon it at full operational speed
- The tool needs to have a safety system in place that at stops the process if the peel has not been performed successfully.

There are three main stages identified during the peeling of the ply. The first is the initialization stage which includes the start detachment and clamping of the film. The second stage is the continued peeling action in which the entire ply is removed of the film. The process is concluded by an inspection phase that determines the successful completion of the peeling. This final stage has not been implemented into the preliminary concept of the film removal tool.

5.4.6.2. TOOL SET-UP

It has been determined that the initialization is to be achieved by shock cooling the film, to force it apart from the plie’s surface. In search of a sustainable way to sufficiently cool the surface, several cooling approaches have been taken. Both a spot cooler with an integrated vortex tube and a Peltier element have been tested to determine if they can reach a sufficient drop in temperature. Neither of them were successful. It was however determined during material tests that the air blow create by the spot cooler at a less intense cooling setting, halfs the peeling force required. Further, these tests (Appendix V) also made it possible to calculate a rough production of maximum peeling force of 344N for a ply of 1,5m x 2m dimensions.

Another cooling solution was found to be chemical cooling spray (Cold Spray PRF 101, cooling down to -55°C) that was measured to cool the prepreg surface down to -33°C. It causes the film to detache on its own from the surface of the prepreg. It is sprayed only on the surface of the film and evaporates quickly thereby not leaving residue to contaminate the ply in the laminate. This approach is not desirable to be integrated into production since it is reliant on the fluid cans that need to continuously be replaced. This is expensive and labour intensive. The same results have been achieved whilst testing liquid nitrogen. It has been concluded that spraying liquid nitrogen is indeed a solution for the industrial application of the tool. Even though liquid nitrogen itself is not expensive (the US energy Information Administration states it's price per kg converted in Euros to be 0.06€/l (US Department of Energy, 2017)), the storage and the equipment required to stray it need a capital investment that is not reasonable for this project. So, the liquid nitrogen is simulated with a chemical cooling cans for the prototype development.

The initial peeling process is further supported by a suction cup that ensures sufficient separation is created between the two surfaces before it is clamped. The clamp itself is tightened by forcing it through a guiderail as well as activating an electromagnet that pulls it downward. All five actuators (2 servos, an electromagnet and two valves) are controlled over a raspberry pi. The flow chart in Figure 50 describes in more detail the exact working of the film removal tool, with its integrated safely mechanisms in stage two and three to prevent early triggering of the tool. For more detailed information about the design changes undertaken and the electronics work performed on the tool refer to Appendix IV. Figure 48 and Figure 49 provide a general overview of the tool set-up and the interaction with the robot.

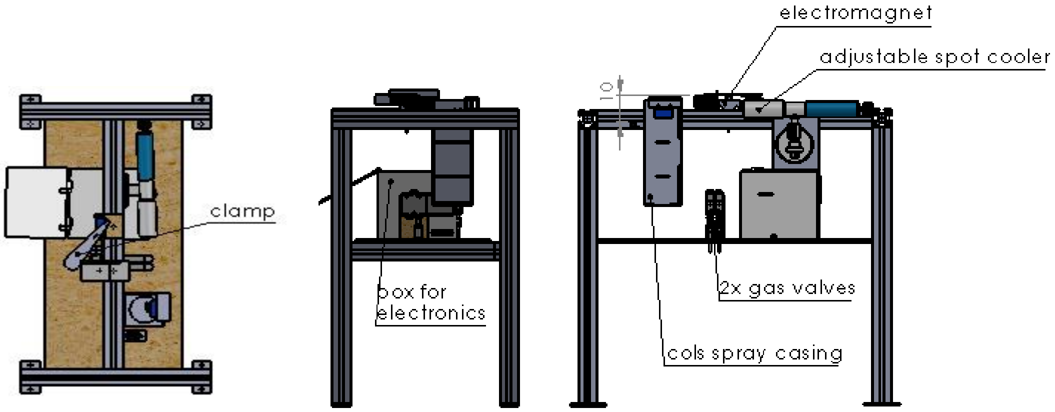


Figure 48: Set-up of the Self Developed Film Removal Tool Prototype

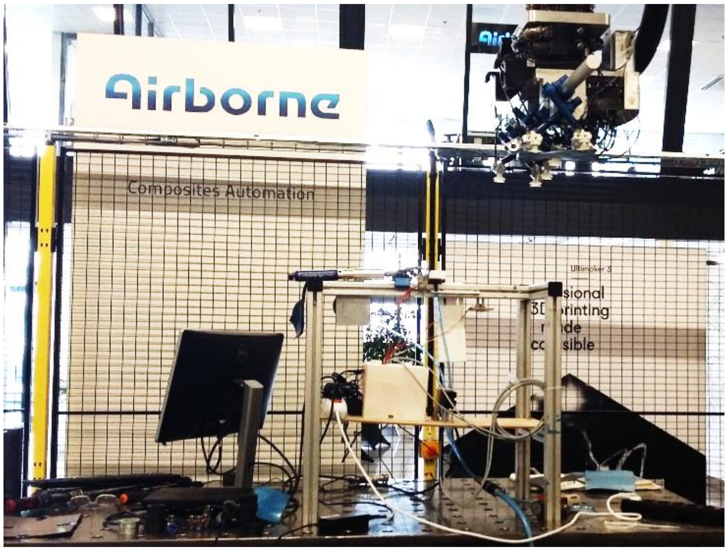


Figure 49: Testing of the Self Developed Film Removal Tool

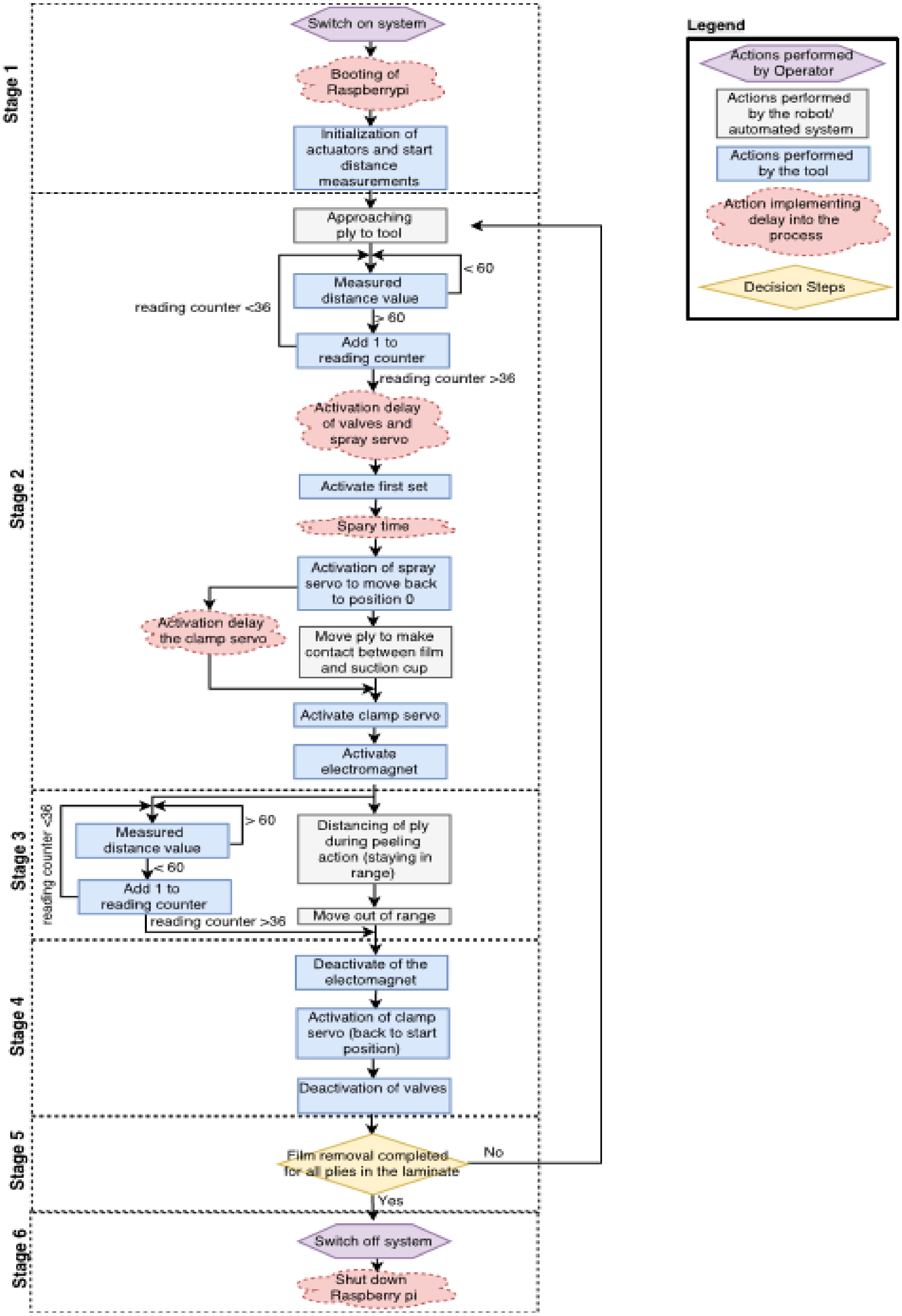


Figure 50: Flow Chart of the Film Removal Tool

5.4.6.3. DEVELOPMENT RESULTS

The individual stages of the tool concept have shown to work separately however, the overall proof of concept was not fully possible to be achieved for the two following reasons:

- The primary reason is that during the test trial, it became clear that a general end effector used during the test trials would not suffice to prove a fully working of the tool. A specially designed end effector for the handled plies need so be built to demonstrate the working tool. Building this is out of the scope of this project.
- Secondly, the clamp requires tinkering and tuning to be able to adjust it to the process and the peeling forces. This is doable but very time consuming. Given that the proof of concept would need an alternative end effector either way it was decided to spend the time on other areas of this project instead and leave recommendations for future improvements.

The testing provided many improvement ideas and research recommendation based on the experience developing the tool (appendix V). These are summarized to include:

- Developing a solution that helps keep better control of the plie tension and spreads the peeling force over the width of the surface. This is especially relevant once dealing with larger plies.
- Developing an inspection process that at pauses the process if the peeling has not been achieved perfectly.
- Developing an algorithm that instructs the robot about the best central peeling motion over the tool, to ensure even complex shapes can successfully be pealed.

5.4.7. FLIPPING TOOL

This represents flow chart action 8a. The film removal step has two different aspects, gripping the ply on the correct side and the film removal itself. The grip problem only concerns the UD material which have protective film on both surfaces. All other woven material is usually cut with the protective film on the bottom side. Hence, an apparatus is required that can help the robot easily flip the ply onto its back side. Such a tool can simply be the same end effector on the robot but mounted vertically on a frame that is hydraulically lowered to a horizontal position.

The flip tool has to have the same properties as the end effector. It is however not required for the tool to know what shape ply is handled nor to control individual suction cups. In contrast to the end effector on the robot this gripper is not in danger of attaching to other plies since only one ply is handled at a time. The robot end effector is not in danger of being sucked onto the flip gripper since it will release pressured air to release the ply. The flip tool needs to however be instructed when the flip needs to occur. It also requires an inspection step before the flip is performed to ensure the entire ply is properly attached to the gripper and no folds are created by flipping. This come especially important since at this stage the ply no longer has protective film and will thereby make it difficult to separate the surfaces if a bend were to occur.

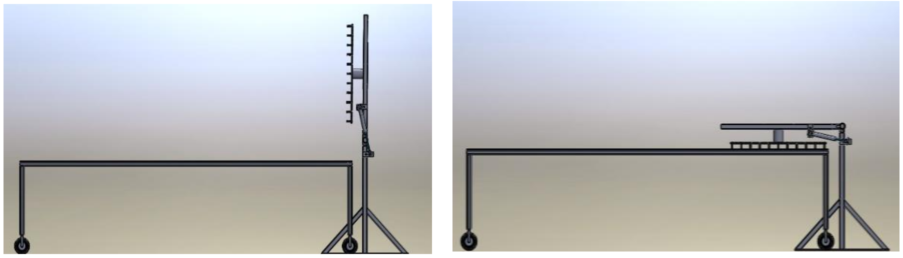


Figure 51: Side View Flipping Tool

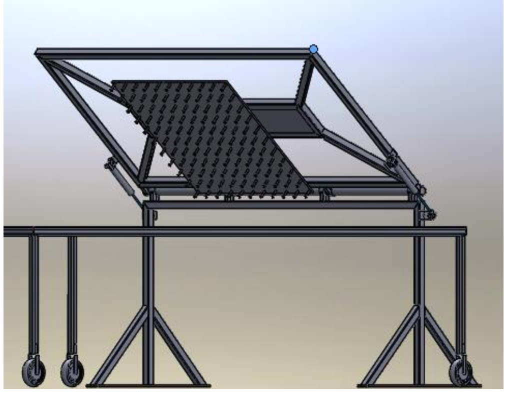


Figure 52: Flipping Tool Set-up

5.4.8. STACKING

The stacking of the plies is a straight forward task if the robot program can successfully identify the shape, size and orientation of the ply it is handling. The robot can determine its movement to a given coordinate given that joint and collision constraints are integrated into its program movement. The main concern regarding the stacking process step is the accuracy of the robot. A tolerance of 0.5 mm is sufficient for the plate production since the actual parts will be waterjet cut out of it. The stacking table itself is a big table with wheels to remove it from the cell for the de-bulk. These tables are already in use at Rondal.

Figure 53: Automated Consolidation Tool

The consolidation step can be considered as part of the overall laminating/stacking step. It is a natural step within the manual layup procedure, however it has not been scientifically proven that consolidation reduces the amount of de-bulking required. It is as such of not much interest for de reduction of lead time in the automated process.

There have been test runs performed on the layup of plat laminates using a roller as shown in Figure 53 (Björnsson, Lindbäck, Eklund, & Jonsson, 2015). The human fine feeling is missing, so the plies can be slightly moved along the surface deforming the weave during consolidation if the pressure is too high. This can further add to the inaccuracy of the laminate.

Once the mould tools are included into the entire process this step can become important to prevent wrinkling within the shapes. It might then require a complex adjustable tooling that can sense the pressure differences at the suction cups when placing the ply into the mould shapes.

5.4.9. DE-BULKING

The de-bulking step is the final action 10 in the cell concept. The main concern about de-bulking is the preparation and set-up of the sealed surface with each de-bulking round. The de-bulking time itself cannot be reduced. The point of automation in this process step is to eliminate the waste material for every individual part debulk and to achieve a possible debulk of several parts simultaneously.

The first solution for this step can not only be used to debulk but also to heat. In later stages, this can be used to automate the production of the products type 1 and 2 that require HDF. It is called a global vacuum press. This process step is however still only mechanized since the closing of the lid and the activation of the vacuum has to be done by an operator.

Figure 54: Hot Drape Forming Press (Global Vacuum Presses, 2017)

The HDF process stacks 3-5 plies at a time on a flat surface as it is done for the plat plates. The flat laminate is placed on top of the mould and draped into shape by the membrane that pushes onto the surface with help of the vacuum induced. This step is repeated until the required laminate thickness is achieved.

The difficulty of the automation of the HDF step lies in the prepreg. The individual prepreg plies create bonds between one another that prevent the pressure membrane to fully shape the laminate into the mould without wrinkling or bridging. Dependent on the resin content, thickness of the ply and the orientation of the fibres these forces can vary. Which means, for one stacking sequence of a laminate the drape might provide good results, whilst if in the same laminate some plies are interchanged the draping conditions might have to be altered to create the same high-quality end-product. This means drape tests for each laminate sequence should be performed (Meyer, Katsirpoulos, & Pantelakis, 2009). Looking at the custom-made production this has to be applied to, it cannot be said for certain that it will work effectively. An example for wrinkling imperfection quality impact due to HDF can be seen in Figure 55.

The drape problems occur mainly in moulds with sharp angles (Meyer, Katsirpoulos, & Pantelakis, 2009). The high and complex shapes of the spreaders and hatches might cause significant problems Yet, even if it is possible to only apply HDP on these products without any further automation their manufacture could become more cost effective.

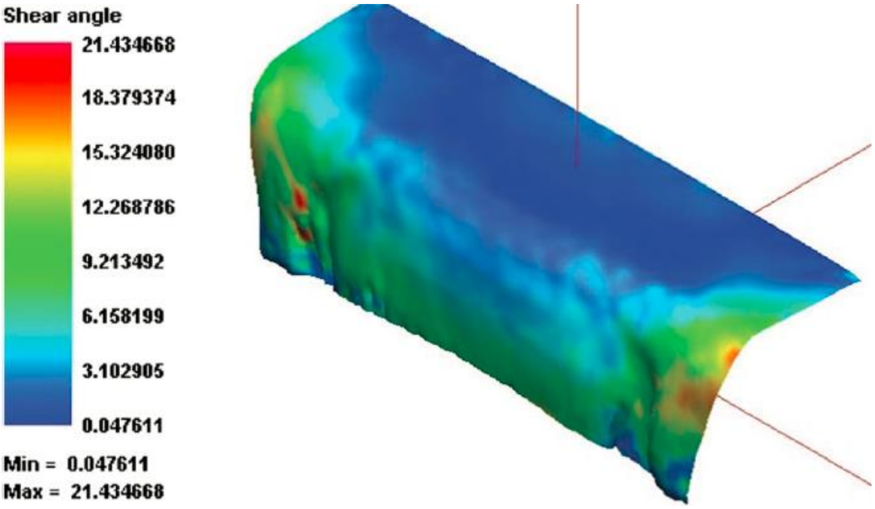


Figure 55:HDF Results of a 90° Angle (Sorrentino & Bellini, 2016)

A simpler way to mechanize de-bulking is by using a frame that is already in use at Rondal. It is a frame that can be clipped on top of a table. This provides the opportunity to debulk multiple part simultaneously and eliminates the need of a vacuum bag for the de-bulking process. Nevertheless, there is a drawback to this approach. Once placed under vacuum for several hours the membrane remembers the shape of the last placed object. This is especially occurring with high moulds. Even though the membrane recuperates after a few hours, after a larger number of uses the membrane will permanently deform. This is not a problem for part of the same mould height. Only parts with a lower height will result in a lower quality de-bulk. Even though every part is of custom-made dimensions, the mould height usually stays constant. Consequently, as long as each product type has its own membrane this de-bulking step can be achieved successfully.

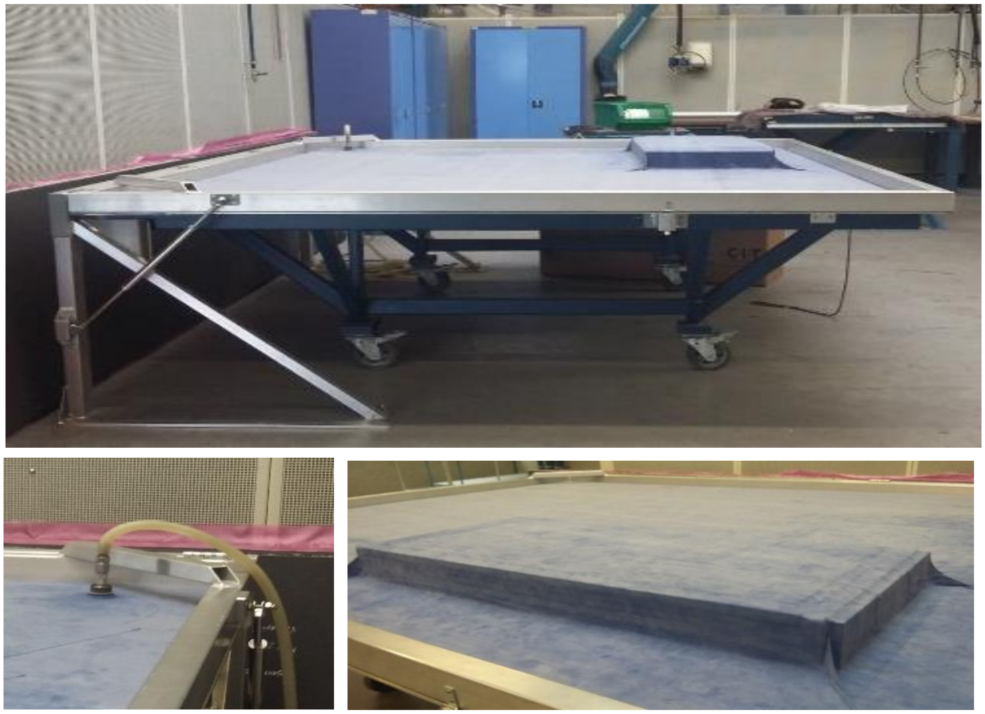


Figure 56: De-bulking Frame

5.4.10. CONCLUSION

Looking at each individual piece of equipment for this automation concept pointed out the challenges that each face but more importantly also showed how they interact with one another. It is now clear that even though each individual component has its own importance for the cell, the entirety of the automation concept will not work if these individual components are not adjusted with regards to one another. The robot requires some form of communication with all moving components. Hence, the development of the different sections are equally important and needs to be well coordinated.

CHAPTER 6 - IMPLEMENTATION

The implementation of an automation system reaches topic areas from optimizing cell layout to communication between equipment entities and calibration of equipment to determine the systems repeatability and accuracy. This implementation analysis mainly focuses on elements that help determining further system requirement and equipment at this starting stage of the automation process development. These are:

- Layout within the robot cell
- Integration into the overall workshop
- Utilizing current equipment
- Provide shared access to equipment for both the autonomous system and the manual work

These points help determine the impact of the robot on the overall factory production flow.

6.1. FACILITY LAYOUT WITHIN THE CELL

As it is stated in the ISO 10218-2:2011 (E) (section 4.2) classification rules, the design of the cell layout 'is a key process in elimination of hazards and reduction of risks.' These are to be achieved by doing the following:

- Establishing of clear physical limits through drawing that provide dimensional overview of the facilities and the equipment.
- Identifying workspaces, access and clearances. These include space for the robot, equipment access as well as traffic routes for operator aisles and indications in which the flow of material is moving outside the safeguarding perimeter.
- Easy access to support services that include electricity, compressed/vacuum lines or even possibly to the liquid nitrogen supply and other control systems.
- Tripping hazards within these access areas due to cable or tubing leading to equipment are to be reduced or dealt with accordingly, by covering them or leading them along a safe path that does not prohibit movement.
- Any manual intervention is ideally supposed to be performed from outside the safeguarded space.
- The ergonomics of the set-up also needs to provide full visibility of operations at all times.
- The cell set-up needs to allow the interface between the robot and the equipment to 'be suitable for the work being done and permit, where necessary, teaching, setting, maintenance, programme verification and troubleshooting operations to be carried out safely'.

Apart from the layout design meeting the classification rules for risk reduction, its main objectives for the manufacturing process are to achieve efficient utilization of space and labour. Considering different options of the layout also addresses the operator's interaction with the system and makes it possible to not only find bottlenecks but also eliminate or relocate them to minimize the impact of the overall system. Overall all these aspects add towards minimizing the investment cost and maximizing the efficiency of the system. (Slack, Chambers, & Johnston, 2007)

Different manufacturing approaches require different types of layout. For instance, a product layout is mainly used in high volume manufacturing environments whilst process layouts are more appropriate for the customized production the Rondal production. A fixed position layout is already used at the yard since a large ship is difficult to move, so the resources need to be brought towards it. At the centre of the automation system is the robot thereby making it a cellular layout. Equipment is grouped for the robot to be able to access it. Within this robot cell an additional cellular layout approach can be applied since there are different processes accomplished by its use. To determine such a layout a fundamental step has to be clear: every transport carriers only one type of part at a time. Based on that and assignment problem approach is taken to see if there are blocks of equipment that need to be put together within the robot cell.

The following values and letters have been assigned to the equipment and products types. To ensure the cell is also capable to adapt to future developments the mould product process is also included which involves the HDP equipment. Every equipment that is used during the production of a product is identified with an 'X' within the matrix (Table 32). In an iteration, the rows and columns of the matrix are interchanged with one another to group all 'X' in blocks. These indicate which equipment needs to be located close to one another.

Equipment

1- Cutter (includes nesting and feeding)
2- Sorting station
3- Film removal tool
4- Flip tool
5- Stacking table
6- Hot drape forming

Products

A- Flat plates
B- Mould products
C- Products for kitting

Table 32: Assignment Problem for Cell Components

Products	Equipment					
	1	2	3	4	5	6
A	X	X	X	X	X	X
B	X	X	X	X		X
C	X	X				
Iteration	1	2	3	4	6	5
A	X	X	X	X	X	X
B	X	X	X	X	X	
C	X	X				

It can be seen, that stacking and hot drape forming equipment have been switched in position. But once the HDF is in place the stacking table might no longer be needed, dependent on the set-up of the new process. For this set-up the assignment problem analysis is simple since the processes are equal, execpt that some product do not follow the full process. The cutter and the sorting station need to be grouped and the film removal tool, the flip tool and stacking table need to be grouped.

With this in mind a morphological study has been performed in which the different layup options for each equipment have been considered. Table 33 shows these different layout options, whilst Table 34 indicates their the advantages and draw back.

Table 33: Morphological Study of Cell Layout Options

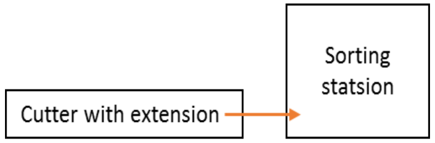
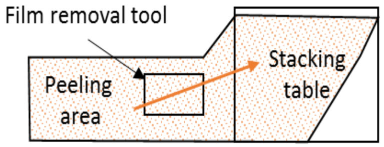
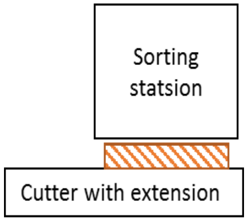
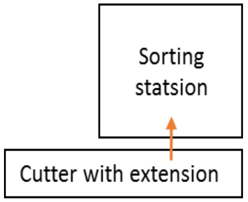
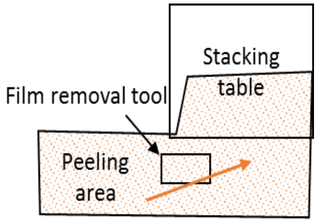
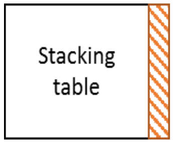
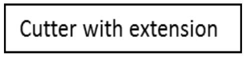
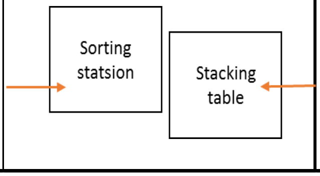
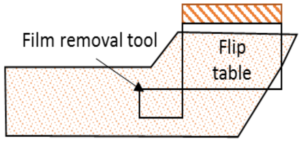
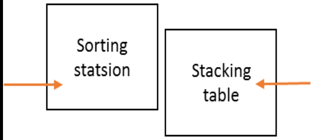
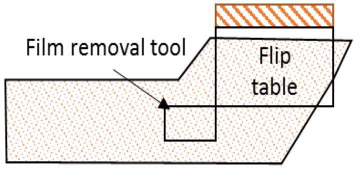
Set-up	**Equipment**				
	Cutter	**Sorting station**	**Film removal tool**	**Stacking table**	**Flip tool**
Option 1					
Option 2					
Option 3					

Table 34: Comparing Layout Options of Morphological Study

Set-up	**Equipment**				
	Cutter	**Sorting station**	**Film removal tool**	**Stacking table**	**Flip tool**
Requirement	Feeder needs to be accessible outside of the fence	Part of the sorting station needs to be accessible to operators.	Sufficient space needs to be available in front or behind the tool.	Needs to be able to be easily moved out of cell	Requires a flat surface of the size of the largest ply to deposit the ply
Layout 1					
Pro	Allows the sorting process to be done with space for maneuvering.		The peeled ply is nearly at its stacking location by the time it is finished peeling. The robot movement within the cell is minimized.		Makes use of the available space. The conveyor is used for multiple purposes.
Cons	Increases the space requirement within the robot reach.		Collision danger with the stacking table.		Collision risk with the robot passing over the tool to place plies in the sorting station. The flip tool needs to be 1.3m over the height of the convey. This is not going to fit fully into the width reach of the robot.
Layout 2					
Pro	Makes use if the depth of the robot range and keeps larger areas free for maneuvering.		Makes use if the depth of the robot range and creates space next to the table for other equipment.		Makes use of excising table space.
Cons	Rotation of ply will be done above the conveyor. This is not going to fit fully into the robot reach. It requires a floor space robot reach of at 1.95m. The sorting cabinet also restrict the visibility onto the parts which is against the ISO regulations.		This will not fit with a robot range less than 3.1m. Collision danger with the stacking table during the peeling action.		Spacing on the table need to be well arranged since the stacked laminate cannot lay underneath the flipped ply.
Layout 3					
Pro	Placing the cutter independent form, the equipment in the cell, makes it possible to optimize the locations with regards to all other equipment.	Brings the access area for the operator's closer together.	Brings the full peeling set-up closer together. Both tools can be designed to be on the same level, so that there is no collision danger during the peeling	Brings the access area for the operator's closer together.	Brings the full peeling set-up closer together. Both tools can be designed to be on the same level, reducing collision danger.
Con	The path of the flow is interrupted since the following process step is not necessarily next.	Completely disrupts the flow of the plies. Restricted in location choices.	Uses extra space within the robot reach. Dependent on the sensor design of the film removal tool this could cause the tool to trigger during the flipping of the ply.	Completely disrupts the flow of the plies. Restricted in location choices.	It adds an entirely new piece of equipment, as well as uses extra space within the robot reach. Dependent the design of the film removal tool this could cause the tool to trigger during the flipping of the ply.

From the morphological chart three layout have been determined. these are clarified in Table 35.

Table 35: Layout Possibilities for the Robot Cell

Layout	Cutter	Sorting Station	Film removal tool	Stacking table	Flip tool
1	Option 1	Option 1	Option 1	Option 1	Option 2
2	Option 2	Option 2	Option 1	Option 1	Option 2
3	Option 3	Option 3	Option 2	Option 2 and 3	Option 2

The three layouts are illustrated in Figures 58 to Figure 60. The objects in these layouts are either annotated or explained by the legend in Figure 57. The layouts have been developed based on the reach an footprint of the KR QUANTEC KR150 R3700 model (3.7m reach). This reach is longer than most other models. If a different payload is decided upon it can have a significant impact on the layout choice, since it might reduce the reach of the robot.

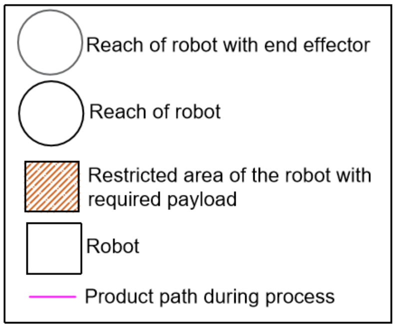


Figure 57: Legend of the Layout Sketches

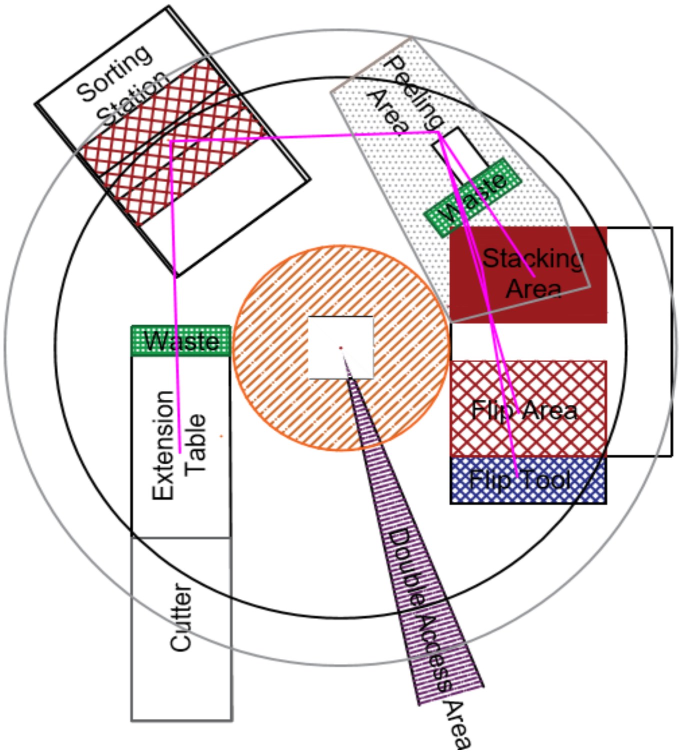


Figure 58: Layout 1

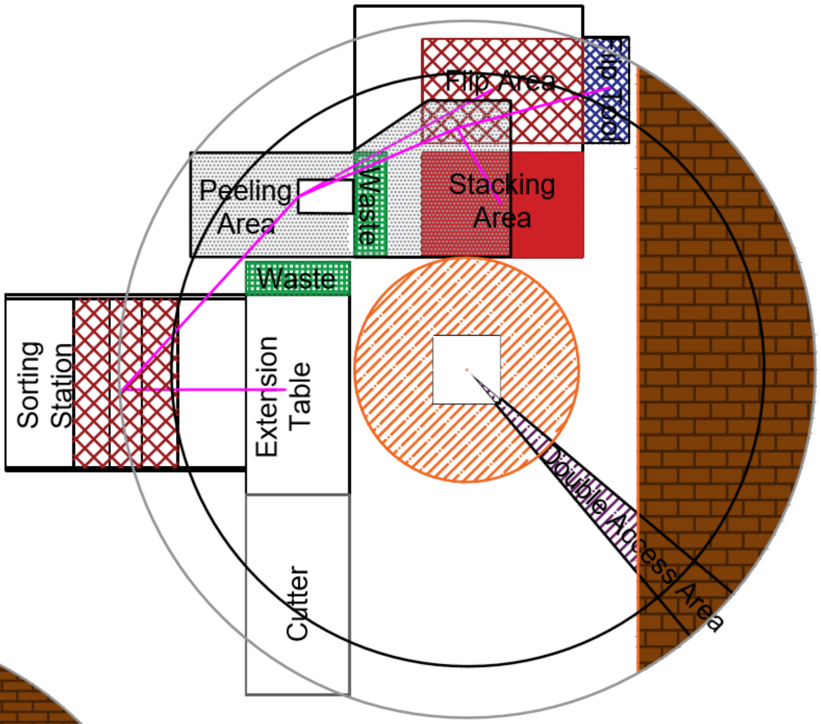


Figure 59: Layout 2

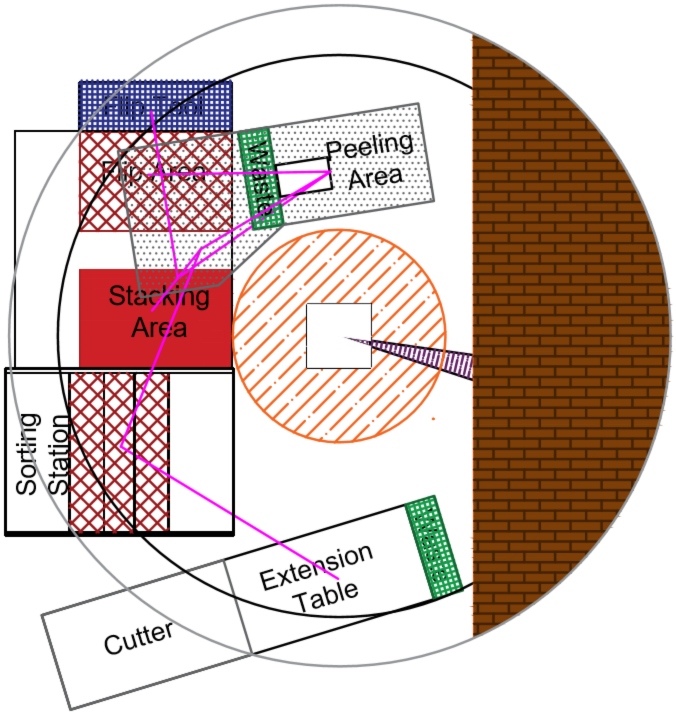


Figure 60: Layout 3

The layout sketches all show that the stacking table seems too big, in contrast to the handled plies. The table is indeed big, but this size is required to fit the existing de-bulking frame at Rondal. This shows that current equipment is being integrated into the layout. It is therefore not a problem if the table is not fully in reach of the robot and the end effector.

A similar, problem can be observed with the flip tool. Only a design suggestion has been developed for this tool. The dimensions of the tool itself are not relevant as long as, the vertical front face is within reach of the robot end effector. That position is where the robot deposits the ply for it to be flipped over. The mechanism that causes the tool to move does not have to be in reach of the robot.

The process path lengths (indicated in pink) for one UD ply, are given from the centre of the ply. These have been measured and compared to one another to determine which layout requires the most robot movement. The steps of the sorting process itself is not included since that depends on the nest. Table 36 provides the comparison in lengths. Layout 2 minimizes the path length. This layout favours the block gathering result of the assignment result. Nevertheless, the sorting station is not fully in the reach of the end effector. Which means the plies can potentially not be placed properly in the sorting station, thereby ruling it out for the final choice. Additionally, the conveyor in located in front of it forces the sorting station, so the station will likely have to be designed larger than otherwise necessary, else the robot might not be able to access the bottom draws. This layout observation also does not meet the ISO regulations; the operators view onto the conveyor is prohibited due to the sorting station.

Table 36: Layout Path Lengths Summary

Layout	Length of Process Steps (mm)					
	A-B	B-C	C-D	D-C	C-E	SUM
1	4264	3473	4840	3981	2338	18896
2	2031	3257	4119	2771	3248	15426
3	3348	4795	3914	2400	2032	16489

A-B: Cutter extension table to sorting station
B-C: Sorting station to the peeling area
C-D: Peeling area to the flipping tool
D-C: Flipping tool to peeling area
C-E: Peeling area to stacking area

Layout one makes full use of the space surrounding the robot. This means that a large amount of floor space is required. All other layouts provide the opportunity that the robot is backed by a wall. This layout also reduces the collision danger since it increases more manoeuvring space for the robot and its end effector, especially in front of the sorting station.

Layout three is only 1 m longer than the second layout in terms of path length, yet manages to incorporate all equipment within the reach of the end effector. It also manages to gather all the operators access points to one side of the layout. The work flow direction in this layout is however interrupted which means this could influence the cycle time. The robot will need to decelerate and stop more to change orientations. Additionally, this option uses up nearly all the available space within the robot reach, so potential expansion of the process will be restricted.

It was concluded that none of these options provide the ideal set-up. Therefore, a final option has been created in which the robot is placed on a linear track unit of 5 m. It gives the robot the ability to move in a further axis. This provides the opportunity to set-up the equipment next to each other, keeping the distance covered small in comparison to layout one. Simultaneously, it provides the opportunity to potentially integrate tool change over area and a hot drape forming table. The final layout sketch is provided in Figure 61.

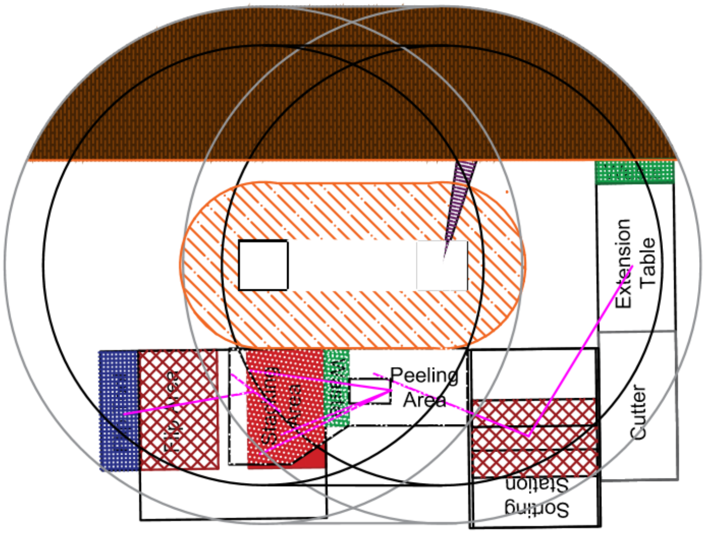


Figure 61: Final Layout

Table 37: Final Layout Path Length

Layout	Length of Process Steps (mm)					
	A-B	B-C	C-D	D-C	C-E	SUM
Final	3375	2434	4538	4493	1897	16737

The illustration Figure 61 in shows specifics about the cell layout that are aimed to meet the ISO regulation. The sketch also shows sufficient access for an operator aisle. The shaded area surrounding the robot only represents the area the robot cannot access due to its joint limitations. However, this does not mean the operator cannot access this area when the robot is in safe mode. The footprint of the robot is only the white centre of the shaded area. The layout provides sufficient space for an additional station to changeover tools if the need arises one the gripper has been designed.

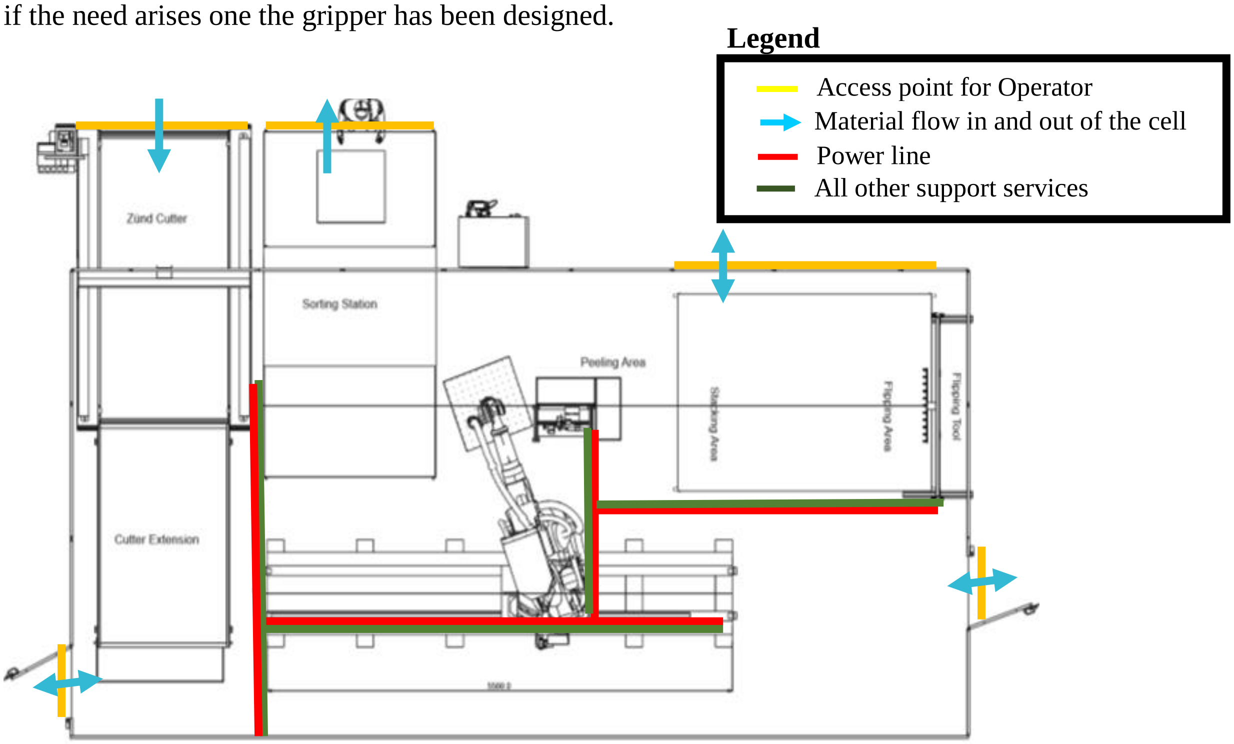


Figure 62: Access and Supply Points to the Final Layout

A better overview of the clearances around the individual equipment is obtained through the drawing in Figure 62. It shows the linear track unit requires a length of 5.5m to be able to access all equipment. Also, further layout details are elaborated upon with concertation of the regulations. All the operator access points are indicated together with the flow direction of the material at these locations. Potential access points to the power line and the support services are also identified in the drawing.

Having this layout fixed also provides a specific value for floorspace requirement within the Rondal production. The fence is surrounding and area of nearly 83m^2 with a width of 6.8m and a length of 12m. ISO 10128 also states that open access area in the fence as they are present for the stacking table, the cutter and the sorting station measures should be taken to prevent harm. This must either have integrated sensors that detect access passing though these barriers and stopping the robot's operation or prevent access by physical barriers such as it is done for the cutter and the sorting station. The cess point to the stacking table needs more space to ensure access to the table, so for this either sensors should be integrated or a fence door that can be lifted when needed. Figure 63 is a 3D visual representation of the robot cell taken from the work flow and movement simulation.

Figure 63: 3D Layout of the P&P Cell

6.2. ROBOT CELL LAYOUT WITHIN THE CURRENT PRODUCTION

The integration of the cell within the entire shop floor respects the size of the area but also other structural and environmental condition factors. This section discusses some of these factors, that most affects the decision making of the location.

The first criterion that makes up the location choice is naturally the size. It needs to fit area wise, but also with sufficient headroom for the robot not to knock against the ceiling. Ideally, there should be sufficient head space for the robot to rotate moulds or larger plies overhead. The robot specifications indicate movement a reach upwards of 3,5 m in height, another 0.62 m need to be added for the linear track unit as a base. A minimum clearance 4,2 m ought to be available at the cells location. The ISO 10218-2:2011 add a rule regarding the clearance space at the exits of the cell, where the clearance should not be less than 500 mm when the door is open.

The next criterion is that the floor needs to be structurally sound enough to carry the load of the robot and the surrounding equipment. The robot itself weights 1215kg and is expected to be the heaviest equipment within the cell. The criterion is trivial in view of the fact that the facilities have been designed for shipbuilding which is implying a much larger mass than the entirety of the cell weights together.

The cell needs to be located with access to the main lines for power and support services for vacuum and compressed air, that run alone the entire workshop. The service access that might cause an issue is to the liquid nitrogen for the film removal tool. Nitrogen tanks are usually located outdoors for security reasons and due to their large sizes. It is also important that the refill vehicle has easy access to the tank. The problem of the liquid nitrogen is that the tanks should not be located far away from the location of use since it is difficult to effectively move the liquid nitrogen through piping.

Two factors also influencing the process effectiveness are ventilation and room temperature regulation. There is large amount of electronics integrated into the cell. Dust or even worse fibres of carbon fibres, flying through the air, and getting into the electronics can cause short circuits. This is mainly a problem when dealing with dry fibres, but prepreg fibres does still conduct. To reduce this risk the air surrounding the cell should be well ventilated ensuring clean air blows into all electronics. It would also be ideal to control the environmental conditions surrounding the cell. Experimental testing with Zünd cutters has shown that the ideal cutting temperatures for prepreg lies between 20°C- 25°C. Above that temperature the stickiness might prevent effective cutting. The film removal process is also impacted by this factor hence it would be of great use if the temperature can be regulated in the summer with an air conditioning unit. In the open workshop area, this is not possible. The energy cost to do so for such a wide-open space would far outrun the benefits. However, if the cell can be placed in an area that is apart from the main work space it would be a beneficial set-up. Air conditioning a smaller room becomes indeed feasible.

The easy accessibility of the de-bulking frames to both the manual laminating work and the cell operator is another feature that decides upon the location of the cell in the production. This means the distance from the manual workbench to the debulking frame should be as short as possible, since heavy mould will have to be moved towards it. On the other hand, the access to it should be wide open to manoeuvre the bulky stacking frame towards it from the cell. Ideally, the implementation of this new technology should not disrupt the rest of the production process. So, a location should be chosen that only requires the movement of light equipment.

Figure 64 provides the floorplan of all locations the automation system could be installed in. It is possible to install the cell at one of the recently acquired locations of the yard, but that would mean the set-up is not be part of the main composite manufacturing processes. This therefore eliminates this choice, for the purpose of this project. The facilities that are allocated to the actual ship building of Royal Huisman are also not considered as feasible options.

1. Mast assembly
2. Mast assembly metal workshops
3. Hatches assembly
4. Small parts lamination area
5. Boom laminating area
6. Automated ply cutting
7. Composite post cure processing
8. Furniture assembly
9. Metal workshops
10. Doors assembly hall
11. Carpentry
12. Offices
13. Mast Laminating hall

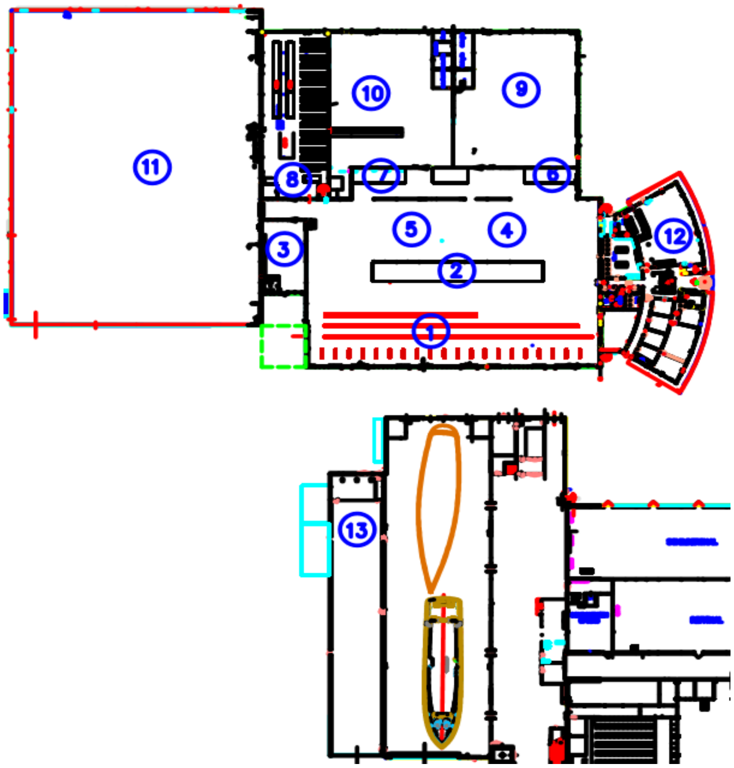


Figure 64: Floor Plan of the Rondal and Royal Huisman Facilities

When systematically going through the different location, to see if they meet the criteria, it is quickly possible to reduce the options from 13 down to 4. Descriptions of the reasoning are now made.

1. Mast assembly
   The full length of the mast assembly area is needed to be able to adjust to different masts sizes. Sometimes this length of the hall has to be extended to fit the longer masts. This extension is indicated by the dotted green box in Figure 64.So, no space can be spared to place the cell at that location.

2. Mast assembly metal workshops
   These workshops are well set-up in tandem with the assembly area. It would require significant reshuffling to reallocate these workshops in different location so that they are as accessible to the assembly hall. They are also located in the middle of the open space which makes ventilation extremely difficult.

3. Hatches assembly
   It is a separate room, so that ventilation and even temperature control is possible. Concerning the dimension it is also sufficiently large to accommodate the cell. Additionally, it is at close proximity to outside making it possible to even install a nitrogen tank nearby. It does however have the disadvantage that the stacking table has to be rolled out through the doors to be able to reach the de-bulking frames. The frames do not fit into the room together with the robot cell. This area is thereby suitable for the installation of the automation cell.

4. Small parts lamination area
   The equipment there is light weight and easy to rearrange. It also means that both the automation and the manual composite work is performed right next to each other. Thereby, making it possible

for the operator to perform manual laminating work whilst the automation system is running. Placing the cell in the middle of the room also improves visibility of the robot's actions from all slides. However, this is part of the main workspace which means no control over the environmental temperature is possible. It is also not located nearby the outer-door access. Moreover, it has quick access to the autoclave as well as cranes running overhead. This area is thereby suitable for the installation of the automation cell.

5. Boom laminating area
   This area has the same quality as the small part production area. The only difference is that it is located even further way from an outdoor source.

6. Automated ply cutting
   The cutter in this place is no longer required once the full cell is implemented, hence this would simply mean a switch of equipment in this location. It is located close to the manual composite work and the outdoor, which makes it one of the most ideal choices for the set-up location. Alike all the other areas in the main workshop area, it also does not make it possible to control the environmental conditions.

7. Composite post cure processing
   The equipment in this location is still required for manual work, unlike its counterpart in the automated ply cutting area. Moreover, it is not located near an outdoor source.

8. Furniture assembly
   This location has a low ceiling due to a second-floor storage area, therefore not providing sufficient headroom for the cell.

9. Metal workshops
   Even though this is also a separate room, with access to outside; it has heavy-duty metal work machinery that would be difficult to relocate. This location however would allow the debulking frames to be right next to the cell.

10. Doors assembly hall
    This location would probably appropriate with regards to a separate room, dimensions and outdoor access. But, it is located far from the manual composite work making it difficult to debulk the products together.

11. Carpentry
    This area is too big and well established. The implementation would disrupt too much. Additionally, it is not in close vicinity to the manual composite laminating work.

12. Offices
    These are not part of the manufacturing facilities and are hence ruled out.

13. Mast laminating hall
    This is a specifically designed area for the manufacturing of the mast. This area is not wide enough to fit the entire cell. It also turns into a giant oven when needed to cure the mast. The automation system should not be exposed to such heat.

To take a closer look at the four remaining options, each of the area requirements are sketched out onto the floorplan in different colours together with the path taken to bring the stacking table to the de-bulking frames (see Figure 65).

The least interruption in the work flow is achieved the closer the automation system is located to the debulking frame. A way to potentially achieve this and still have the opportunity to have control over the environmental conditions of the cell is to locate the cell into the current hatch assembly room and swap the boom laminating area and the small parts laminating area. That way the manual products for debulking are closer to the frames. This does also mean that the operator cannot see the cell in operation since it is in a different room. If the system is set up with good safety systems this should not be a problem. It would however, be useful to have a device that can communicate to the operator when a safety feature has kicked in. That way he knows when to check the cell. Given these adjustments the hatch assembly room is the best location for the automation system for a good combination with the manual work flow to be achieved.

Figure 65: Placement Option in the Workshop

6.3. INSTRUCTION TO WORKERS

One final major necessity that determines the effectiveness of the automation system is its frequency of use. For the P&P system to actually deliver its full potential it needs to be used as much as possible. One way to ensure that is done even for plies that otherwise would be cut by hand, is to create quick access files of standard dimensions that can quickly be called upon for manual workers. By proving a simple but clear introduction to the all workforce that could potentially have the need for the automation system it can be ensured that a possible use barrier is overcome. Such information can be communicated via a handbook that provides a check lists for before, during and after use situations in addition to the ‘should be’ state of each piece of equipment within the cell.

It is also important that a clear procedure is set-up in which most of the plies required within a timeframe of for instance two weeks are cut in as few automations runs as possible. This does require the project planning to be foreseen and all kits to be labelled properly so that they can be identified for their proper usage.

CHAPTER 7 - COMPARING MANUAL AND AUTOMATED PROCESS

7.1. SIMULATION

A simulation is an important tool to be able to predict the work flow and restrictive movements within the cell. It is a way to obtain some realistic values about the concept process to be able to make direct comparisons to the existing process. The three-dimensional visualization also helps to notice unforeseen issues within the layout, as well as to convey more clearly the specific intentions behind the automation concept development.

7.1.1. SET-UP

All data obtained are based on simulation done in the software Visual Components, except for, the cutting data, that has been determined by a run through of the Zünd cutting and nesting program. The reason for which visual components has been chosen for the simulation is that it is very similar to software's such as KUKASim that robot manufacturer uses to simulate their products before and during their development stages. It is possible to create movement and process time simulations obtaining quick results using their integrated robot equipment library, in which many different types of robots are available, ready for use.

As it turned out through the simulation attempt, this generic equipment could only be partially applied to this concept simulation. Most equipment only copes with single product manufacture for mass production scenarios, which makes the simulation of the custom-made production difficult to simulate. Even though design ideals and functionalities of each piece of equipment have been determined in the previous chapters, it is another level of detail to integrate them into the system of the simulation with their full logic. This was not achieved within the timeframe of this project. Nevertheless, the simulation of the robot movements within the cell still provided important insights and timing data that is later used in the comparison of the manual and automated process.

The first set-up particularity of this process time simulation is that, it was not possible to fully create the cutting process since visual components does not have the capability, like other simulation softwares such as for instance PlantSim, to identify geometries from an imported cutting file. Instead, only two different ply shapes are dealt with in this simulation to imitate the different types of layers of the sample product. These shapes are either square or triangular. The simulation is only going to be performed on one block of plies. The information obtained through that approach will already provide sufficient information to make rough predictions. It is assumed that the plies come in in the order indicated in Table 38.

Table 38: Ply Order for Simulation

Order	Shape	Orientation	Layer Number
1	Square	0	1
2	Triangular	45	2a
3	Triangular	45	2d
4	Triangular	45	2b
5	Square	90	3
6	Triangular	45	2c
7	Triangular	- 45	4c
8	Triangular	- 45	4a
9	Triangular	- 45	4b
10	Triangular	- 45	4d

Although all equipment; namely the sorting station, the film removal tool and the flipping tool have been added into the cell, these do not operate with working logic and interactions behind them. They are mainly there as path markers that help orientate the robot's movements within the cell whilst handling the plies. From these movements, valuable information has been observed. Figure 66 shows the set-up of the simulation. Minor differences to the set-up in Figure 63 can be observed. These are specific to facilitate the simulation given its software limitations.

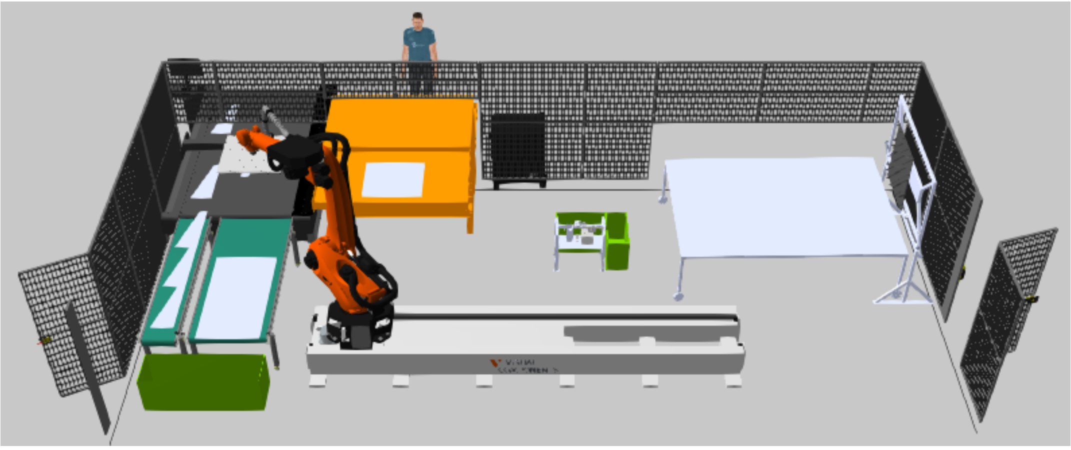


Figure 66: Set-up of the Simulation

7.1.2. OBSERVATIONS

An aim of performing this simulation was to determine location of the bottleneck within the process. As it has been identified before, this is expected to be at the cutter. The belt speed of the Airborne conveyor cutter is known to be 75mm/s. As it can be seen from Figure 67 the simulation shows that the feeder operating at this given path speed quickly overwhelms the robot. It shows that the bottleneck is not located with the cutter when dealing with large plies, but rather in the picking ability of the robot. However, the validity of the cutting simulation is uncertain due to the set-up restriction previously described. It will have to be determined, whether this bottleneck still lies with the same equipment when using the Zünde cutting method. Unlike the airborne cutter, the Zünd cutter first cuts the plies and then moves them along at a speed of 200mm/s into their picking locations. Identifying this bottleneck is a vital part to determine the success and full impact of the process concept.

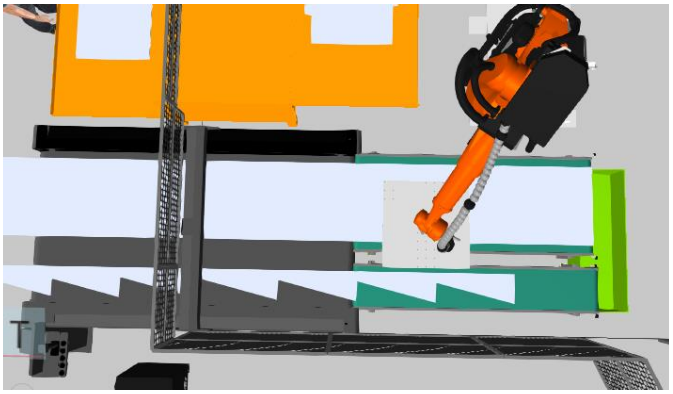


Figure 67: Determining the Bottleneck

The Zünd nesting software was not only able to provide the efficiency of the nest as described in section 5.4.1 but was also able to predict the overall cutting time for the sample product. This was calculated to take 32min 13s. This does not include the belt movement of the finished cut section to the extension table.

The takt time provided by the Airborne of 6s per ply has been confirmed by the simulation. As seen in Table 39 the handling of the plies that could directly be stacked onto the kit is on average 4s whilst the plies that need to be moved from a buffer to the stack have an average handling time of about 2s. Is was also seen that the same timespan as the picking action needs to be taken into consideration for the robot to move back into position and get ready to handle the next ply.

Table 39: Timing of the Picking of Individual Plies

Pick rectengular	Pick triangle	Place on Buffer	Pick from Buffer	Back movement
4.4s	2.7s	2.2s	2.7s	3.9s
4.6s	2.7s	1.8s	2.0s	3.1s
3.3s	5.2s	1.9s	2.2s	3.6s
4.0s	5.6s	2.1s	2.1s	4.8s
X	5.4s	X	X	5.0s
X	5.3s	X	X	3.8s
X	3.9s	X	X	4.7s
X	4.4s	X	X	4.1s
X	4.3s	X	X	3.9s
X	2.6s	X	X	3.4s
4.1s	**4.2s**	**2.0s**	**2.2s**	**4.0s**

Another observation made during the simulation is that robot is most of the time not moving at its maximum speed of 2m/s. Even though it is set to be moving at that speed, the distance travelled to reach its next point of action is not far enough away to allow the acceleration to reach maximum velocity. This seems to especially be the case when the linear unit track is involved in the movement. Another point to be noted is that some re-orientations of the plies are needed to be performed rotating around the longer way. This is due to the joint limitations of the robot. The path optimization is a factor that needs to be addressed for the final concept. It has most probably not fully been exploited during this simulation.

Another time entity recorded during the simulation on which later calculations are based is the time for the laminating process of the woven and the UD material. The delay time estimations for the simulations have been taken from the observed characteristics of the film removal tool prototype development. The following time delays have been integrated into the path for the laminating process of the flat plate block:

- 2s spraying of coolant

- 1s clamping film into place
- 2s waiting for the flipping tool to perform its action

The two laminating times, including these time delays are 28 s for the laminating of a UD ply and 16s for the laminating of a woven ply.

7.2. LABOUR TIME AND COST

Calculating the labour time and cost for both the manual and the automation process is based on assumptions. This section explains the reasoning behind these assumptions and compares the results of both processes to determine the effectiveness of the new concept.

7.2.1. SET-UP OF CALCULATION

First, assumptions for the manual process and later, the ones for the automation system are clarified.

7.2.1.1. MANUAL

A large amount of the time estimation and assumptions for the calculations are based on observations made on the shop floor whilst working on the spreader manufacture. All individual steps of the process have been recorded and timed in detail. Similar, but less time elaborate information has also been recorded while observing part of a plate manufacture.

The timings observed from the spreader process conclude that only 54% of the laminating time is spent adding new layers to the stack. The rest of the hours that are added to lamination within Rondals hour log, are tasks such as cutting off the flange, lifting or alignment of the mould with the laser projector and many other tasks. In view of the fact that flat plates do not require the plies to be cut into shape the same way mould products do, a laminating time percentage of 60% is taken instead of the 54% deducted from the recoded data. The layup rate of the flat plate is based on the average logged value in the Rondal system for the top and side plate of 90h (view Appendix II). A de-bulking preparation of 1.1 min/ply and a kitting rate of 1.6 min/ply is used. This value has also been calculated from the spreader timings. As a reminder, the ply value of 462 plies does not represent the number of layers, but rather the number of plies that need to be laid up. Several of these next to each other make up one layer. As Table 40 summarizes, the layup rate for flat plates is taken as 12.2 plies/h which is more than twice as fast as for the spreaders. Laminating rates are highly dependent upon the size of the plies handled, but for the purpose of these estimations this rate will suffice.

Table 40: Determining Laminating Rate

Spreader				
Number of plies (including local reinforcements)	75	plies		
Laminating time	12.5	h		
Laminating rate	6.0	plies/h		
laminating time % of overall production	54%	hours		
Average mast top and side plate			**Assuming 50% laminating**	
Labour hours for top and side	90	h	90	h
Overall plies	93	Plies	93	Plies
Number of plies for top and side	462	plies	462	plies
De-bulking prep (1.1 min/ply)	8.5	h	8.5	h
De-bulking ever 5 plies for 1h	18.7	h	18.7	h
Laminating time	62.9	h	37.7	h
Laminating rate	7.3	plies/h	12.2	plies/h

Having these values makes it then possible to calculate the internal manual labour cost. An additional factor adds to the lead time and labour cost of the plates. This is the external cost for the water jet cutting. It is a value that is dependent upon the geometry and parameter of the product, however the cutting costs are calculated upon an hourly rate of 125 €/h. From previous invoices of the water jet cutter service company Aluboot, a rate of 10.16 min/m has been determined that is applied to the plate circumference. This value is added to the internal cost, to form an overall overview of the plate manufacturing cost. A sample calculation for the mast plates is given in Table 41. The same has been performed for the boom plates. The cost of this subtask is small, a lot of the clause are lost or gained when rounding the end value. The more impacting factor is the addition of lead time due to the delivery to and from the cutting service company. This can take up to 20 days. This prediction assumes that all the plates are being sent to Aluboot with the same delivery, so only a maximum of 20 extra days are added. It is however likely, dependent on the planning of the manufacturing parts, that the plates are sent in with different deliveries which would increase the lead time of the parts significantly.

Table 41: External Cost of Mast Plate Manufacture

Mast	Cost	Delivery Time
Top Plate	€ 260	10-20 days
Side Plates	€ 280	
Gooseneck Baseplate	€ 110	
Vang Baseplate		
Mandrel Swivel Baseplate	€ 100	
Forestay Lug Plate	€ 190	
--> Web Plate	€ 90	
Cunningham Cylinder Plate	€ 70	
Total (rounded)	**€ 1,100**	**max 20 days**

Another factor taken into consideration in the cost estimation, is the waste reduction that was identified with a change of the nesting software. The nest only represents a single product in a vast range, so any results that are to be obtained from calculation must be considered with great caution. It is very likely that these results can vary significantly, especially when considering differently shaped products than just flat plates. These results provide at least a rough idea of what magnitude results one is looking into.

The products that are being analysed, have not been nested, so it is not possible to predict how many meters of material roll will be using for the nest. A percentage efficiency of the nest compared to the overall section material as it is given in Table 28, is not a useful parameter to have. The needed comparison has to be drawn within the used material for the overall part. This is the percentage calculated in Table 42.

Table 42: Percentage of Used Material in Plate

Nest software	**Alpha cam nest**				**Zund nest**
Material nest sample	wide (100m)	thin (100m)	thin (5m)	thin (5m)	wide (100m)
Waste material from roll (m^2)	52.8	13.9	14.9	58.5	9.3
Material needed for overall part (m^2)	129.6	129.6	129.6	129.6	129.6
Percentage of used material in plate	41%	11%	11%	45%	7%

7.2.1.1. AUTOMATED

The described data on the nesting of the plies in also used for the prediction of the automation system. The main data used in the automation prediction are based on the Zünd cutting simulation and the previously discussed simulation in Visual Components. Table 43 summarizes the data obtained though this simulation and concludes that an average cutting time of 9.25 s per ply is to be used for the prediction calculation.

Table 43: Zünd Nesting Software Simulation

Parameters	Values	Unites
Cutting time for sample nest	1933	s
Number of plies in nest	209	plies
Number of sections in nest	40	sections
Cutting time per section	48.33	s
Average time per ply	9.25	s
Conveyor movement	227.3	mm/s
Plies per section	2.09	plies/ m

The value obtained through the simulations all come together to form the automation process time estimations Table 44. The cutting does not only consist of the cutting of the ply but also the movement of the conveyor. These extra times are considered within the start conveyor, start cut, conveyor travel time and final pick-up. The conveyor travel time is based on a material roll length of 100m. The sum of 492 s is added to all processes as a constant. The cutting time of 9.25s is faster than the estimated picking and sorting time of 10s. So, the pick and sort time is the dominate value for the process and is the one multiplied by the number of plies of the products.

Table 44: Automation Process Time Estimations

#	Process step	Time	Unit
1	**Cutter**		
1.1	Start conveyor	22	s
1.2	Start cut	9.25	s
1.3	Conveyor travel time	429	s
1.4	Final Pick-up	31.35	s
1.5	Cutting time (dependent on ply)	9.25	s
Cutting process without plies		492	s
2	**Pick & Sort**		
2.1	Place on sorting station	4	s
2.2	Sort onto stack	2	s
2.3	Move back to next ply	4	s
Overall Pick & Sort		10	s
3.1	Peeling and stacking (woven)	16	s
3.2	Peeling, flipping and stacking (UD)	28	s
Kitting (without plies)		**492**	**s/part**
Kitting of plies		**9.25**	**s/ply**
Laminating time woven		**16**	**s**
Laminating time UD		**28**	**s**

7.2.1. RESULTS

Using the set-up assumptions, it is now possible to estimate the process time. This is done in detail for the sample plate as well as for the overall plate production and in general terms for all other products for which data is available. These results are then the foundation of the return of investment calculation.

The results of the detailed calculations of the sample plate are indicated in Table 45. It can be seen that the automation has significant impacts on the cost and lead time reduction as well as, also on the waste material.

This single plate has a product cost reduction of about 30€% making up to 2500€ savings. Nesting the wrong plies on a material roll that is not well suited for the shapes can increase the waste material and with it make due of half of the cost saving achieved through the automation process. This emphasises the importance of the nesting software for the effectiveness of the entire concept application. What's more, the lead time is reduced by 1/3 and the labour hours on the product by about 70%.

Table 45: Detailed Time and Cost Prediction of Sample Plate

Categories	**Manual**	**P&P Wide Ply with Zünd Nest**	**P&P Wide Ply with Alphacam Nest**	**P&P Thin Roll with Alphacam Nest**
Layers	82	82	82	82
Plies	462	222		462
Kitting (h)*	12	0.9		1.6
Laminating (h)**	30	1.7		3.6
De-bulking prep (h)***	8	1.3		1.3
De-bulking time (h)	15			
Total (h)	66	19		21
Cure and cooling time (h)	24-48			
Labour cost without debulk	€ 2,454.56	€ 151.37		€ 298.30
Labour cost with debulk	€ 3,815.82	€ 1,093.87		€ 1,240.80
Material cost of laminated plies******	€ 3,146.66			
Waste material cost due to the nest	€ 361.37	€ 225.38	€ 1,282.17	€ 338.20
Waste material due to cut out	€ 1,038.40			
Total waste material	€ 1,399.76	€ 1,263.78	€ 2,320.56	€ 1,376.59
Total material cost	€ 3,508.02	€ 3,372.04	€ 4,428.82	€ 3,484.85
Lead Time	5.4	3.4		3.6
Overall cost	**€ 7,193.42**	**€ 4,696.85**	**€ 5,753.63**	**€ 4,956.60**
Cost saving	**-**	**€ 2,496.57**	**€ 1,439.79**	**€ 2,236.82**
Waste cost saving	**-**	**€ 135.98**	**€ - 920.80**	**€ 23.17**
% Waste	**-**	**- 10%**	**+ 66%**	**2%**
% Cost saving	**-**	**35%**	**20%**	**31%**
% Labour reduction	**-**	**71%**		**68%**
% Lead time saving	**-**	**37%**		**33%**

*** Manual is based on 1.6min/ply (half of the kitting rate of a spreader)**
Automation based on kitting prediction of Woven and UD

**** Manual based on layup rate of 12.2 plies/h**
Automation based on lamination prediction of Woven and UD

***** Manual based on de-bulking prep rate of 1.1min/ply**
Automation based on 5min per debulk

****** Based on area comparison between laminated plate and final part**

The same method of calculation has been applied on the entire plat manufacturer for the mast and boom. They have not been calculated to the same degree of accuracy, since the data caries a higher amount of uncertainty with it. Differences in overall cost savings that can be identified when comparing the data in Table 46 and Table 47, are due to rounding errors. It shows that a margin of error of about 10% should be considered for these results alone

Table 46 provides the general summary of the calculated estimations. Table 48 on the other hand directly points out the improvements of the automation system for the production. It compares the kitting, laminating and de-bulking prep time savings percentage as well as quantifies a value for cost saving of the entire mast and boom production. The lead time for the mast products are reduced by 5 working days which is percentage wise a lot less than the 50% labour hour reduction. This is due to the de-bulking and waterjet cutting time that are not influenced by the implementation of the automation system. The return of investment calculations will be based on the cost saving of 7,700 € for the mast and 4,200 € for the boom.

Table 46:Summary of Mast and Boom Plate Production Comparison

Product		Plate Production Comparison																
		Layers	Plies	Kitting (h)	Laminating (h)	Debulking prep (h)	Debulking time (h)	Total (h)	Cure and cooling time (h)	Labour cost without debulk	Labour cost with debulk	Material cost of laminated plies****	Waste material cost due to the nest	Waste material due to cut out	Total waste material	Total material cost	Overall cost	Lead time (days) *
Mast	Manual	460	1100	28	88	20	106	242	24-48	€ 6,650.00	€ 14,000.00	€ 5,100.00	€ 600.00	€ 2,000.00	€ 2,500.00	€ 5,700.00	€ 20,600.00	50
	P&P Wide Ply Zünd Nest	460	632	4	5	9	106	124		€ 500.00	€ 7,100.00	€ 5,100.00	€ 400.00	€ 1,900.00	€ 2,300.00	€ 5,500.00	€ 12,900.00	45
	P&P Wide Ply Aplpgacam Nest	460	632	4	5	9	106	124		€ 500.00	€ 7,100.00	€ 5,100.00	€ 2,100.00	€ 1,900.00	€ 4,000.00	€ 7,200.00	€ 15,200.00	45
	P&P Thin Roll	460	1100	6	10	9	106	131		€ 900.00	€ 7,600.00	€ 5,100.00	€ 550.00	€ 1,900.00	€ 2,500.00	€ 5,700.00	€ 14,200.00	45
Boom	Manual	140	700	20	60	5	40	125		€ 3,500.00	€ 6,700.00	€ 2,600.00	€ 300.00	€ 100.00	€ 400.00	€ 2,900.00	€ 11,700.00	35
	P&P Wide Ply Zümd Nest	140	339.5664	2	3	3	40	48		€ 300.00	€ 2,600.00	€ 2,600.00	€ 200.00	€ 1,000.00	€ 1,100.00	€ 2,800.00	€ 7,500.00	33

Table 47:Quantitative Time and Cost Saving Results

Product		% time saving			Cost saving due to labout	% cost saving due to waste reduction	Cost saving due to waste reduction	Overall Cost savings	
		Kitting	Laminating	Debulking prep				Adding cost savings	Comparing final figure
Mast	P&P Wide Ply Zünd Nest	86%	94%	54%	€ 6,900.00	33%	€ 200.00	€ 7,100.00	€ 7,700.00
	P&P Wide Ply Alphacam Nest	86%	94%	54%	€ 6,900.00	-250%	€ -1,500.00	€ 5,400.00	€ 5,400.00
	P&P Thin Roll Alphacam Nest	79%	89%	54%	€ 6,400.00	8%	€ 50.00	€ 6,450.00	€ 6,400.00
Boom	P&P Wide Ply Zümd Nest	90%	95%	40%	€ 4,100.00	33%	€ 100.00	€ 4,200.00	€ 4,200.00

The total production hours calculated in these estimations are significantly lower for some products compared to the hours logged in the Rondal system (Appendix II). Whilst the sum of the hours for the mast top and side plate match those recoded in the Rondal system, the sum for the gooseneck, vang, mandrel swivel and forestay lug plate deviate by 65 working hours. Those high labour times have not been used for this estimation because a large proportion of these cannot be accounted for. The values used in the calculations are can be reasoned with. If these logged values are to be used as basis for the calculations, cost savings of as high as 46%, equal to a value of 11 000€, could be achieved. In the ROI this might prove to be of importance. This fact emphasises the importance of performing a more in-depth process analysis to understand where the additional hours are coming from, before any automation system is further considered for the Rondal production.

In view of the fact that the plate production hours only represent about 2.5% of both the mast and boom manufacturing hours. It also holds a great potential of a lot more cost saving if it is applied onto a larger scale, including other products. To demonstrate some of that potential, further estimations have been calculated to determine the impact of only the pick & sorting process of the concept. It can be applied on products of the inner and outer mast laminate, part of a type 5 product, or even simply on the spreader production (type 2).

The inner and outer mast laminates of +/-45° an 90° add up to approximately 3100 plies per mast, depended on the length of the mast. Even though not the full automation concept can be applying on this product, the kitting part alone already has an impact on such a relatively high-volume process. Aspects such as a change-over of rolls by the operator becomes important since this will most likely be performed more than 10 times. Additionally, the manual kitting rate of high volume ply products for the outer mast laminate are expected to be faster than previously assumed for more complex shapes and different fibre orientations. A rate of 0.5 min/ply is estimated and used in the calculation method to come up with the following results.

Table 48: Cost Savings due to Automated Kitting of the Mast Shaft Laminate

	Labour time (h)	Labour cost savings	% Labour time saving
Manual	24	-	-
Automated	8	€ 1,100	66%

The manual labour hours for mast kitting make up at most 1% of the overall time labour cost, which means that the automated kitting only has an impact of less than 1% of the overall mast production. The last product for which data is available and that has sufficient impact on the production is the spreaders. An alteration done to the calculation to make them more accurate is that less time for de-bulking is considered. Many of the plies are patches that only need de-bulking after every 10th layer instead of every 5th. Indications into the waste of this production process is not available, so that cannot be included into the calculations.

The time estimation for this process only for the spreader shell manufacture. The backing plate lamination and all other post composite manufacture work is not included. The results show a lead time reduction of one working week can be seen as well as a labour cost reduction of 2,000€ spread over the 5 sets of spreaders. Even though this cost analysis has only been performed with regards to the kitting plies, the spreader production has more cost saving potential if the hot drape forming equipment is considered part of the concept in later stages.

Table 49: Labour Time and Cost Calculations for the Spreader Manufacture

Spreaders	Layers	Kitting (h)	Debulking prep (h)	Debulking (h)	Total (h)	cure and cooling time (h)	Labour cost for Kitting	Labour cost with Debulk	Lead time for shell work (days)
Manual	750	40	142	56	238	12-16	€ 2,320.00	€ 13,799.19	32
Robot		5			203		€ 270.16	€ 11,749.35	27

The manufacture of other larger products like the boom laminate do not apply to the automation system. The plies are simply too big and taken off the roll directly into the mould. Cutting the plies into smaller pieces would just result in additional work. There are still numerous other products such as hatches and other mould products that have not been analysed. These will have an impact on the final ROI but are simply not possible to the same level of detail.

7.3. FINANCIAL OVERVIEW

This section aims to provide a rough overview of the investment and operational cost for the automation system to be able to determine the economic feasibility of an investment.

7.3.1. CAPEX

Capital expenditure (Capex) is the most significant investment cost for this automation system. It is also difficult to predict due to its lack of development. Some of the known cost values are described in this section. All information provided is based on interviews with sales personal. None of these values have been presented in an official quote to Rondal.

7.3.1.1. CUTTER

The investment cost for the Zünd cutter is a given for an ‘off-the shelf’ product. It is simply a combination of various options of the Zünd product pallet. The cutter costs 160 000 € with an additional 1 500 € for a drag knife.

7.3.1.2. ROBOT

The robot system development company Gibas was given the specifications of robot reach to be 3m with a payload capability of 150kg. Base on their estimation the robot equipment, is to cost up to 275,000€. Conflicting this information is the value obtained directly from the robot manufacturers. These manufacturer source indicate that equipment the cost of the robot to be between 60,000 € to 80,000 €. Together with additional necessary equipment this cost adds up to 115,000 €. Which is less than half of the value estimated by Gibas.

KUKA indicates that a linear tack unit cost between 14,000€ to 18,000€ for a robot of a reach of a 3m and a payload of up to 200kg. Every additional meter will cost 1,500€ to 2,000€. A brief overview comparing the Fanuc and KUKA robot costs is given in Table 50.

Table 50:Comparing Investment Cost for Robot Equipment

FANUC			KUKA		
Largest Robot	€	66,000	Ultra series Robot	€	80,000
PLC Connector	€	2,500	Fencing*	€	9,000
Dual trace system	€	1,560	Linear Unit	€	18,000
Track	€	14,000	Extra meter for tack (4m)	€	8,000
Sum	**€**	**84,060**	**Sum**	**€**	**115,000**

*** (Bélanger-Barrette , 2016)**

The actual system development and implementation are however expected to be a lot more expensive than the equipment itself.

7.3.1.3. OTHER EQUIPMENT

The only other investment cost that is possible to be added to this current sum is an estimation of the material cost of the gripper, that comes from the known material cost for the Airborne gripper. This has a cost of 7,000€ for a size gripper that is about half the size the Rondal needs. Additionally, that same gripper will also be needed within the set-up of the flipping tool. Additional 14,000€ can be added to the sum. Thus far, with a large part of the equipment and development cost missing, this adds up to 290,500€ investment.

A way to ensure that the development cost stays low is to partner with a company like Airborne that is currently themselves working on the solution to this automation problem. A company such as Gibas has more experience in developing a system that collaborates with the Zünd cutter and will probably be able to solve communication issues between these two main entities faster. Yet, the main challenges of the automation system are lying in the gripper, the sorting station and the film removal tool. Gibas would have to start from scratch on these topics, whilst Airborne has solution developed for the gripper, partially developed for the sorting station and has composite experience that will come to fruition in the further development of the film removal tool. It is therefore more reasonable to invest time and money into providing Airborne with the Zünd cutter communication than to let Gibas develop the entire system.

7.3.2. OPEX

The operational expenditure of such an automation system usually includes material cost, running cost of the equipment, maintenance, repair cost, labour cost of the operator and insurance cost.

The material cost is difficult to predict. The estimations section 7.2 do provide some idea on the material cost for part of the production over a ten-year duration. However, those calculations use an hourly labour rate of 58€. This is not the actual salary of the worker, but the amount the client is charged for the work which means it does not cover actual operator cost.

The running cost of the equipment are negligible. A KUKA robot with 6 servomotors (payload 300kg) will not require more than 300W per motor. At peak performance KUKA predict the power consumption to therefor not surpass 2kW/h.

A calculation of reliability is only possible to be determined based on the robot performance. The robots are designed to operate in industrial facilities that require an uptime of 99.8%, so the robot does meet those standards. The P&P automation systems reliability is mainly dependent on most other contributing factors, such as the robot program and sensors for instance. It is not possible to calculate the reliability of the system, since it has not yet been developed and has not undergone any trial testing. Therefore, no component failure rate can be determined. The manufacturers of the cutter as well as the robot, the high value components, do however provide a two-year warrantee on their products in addition to offering a service maintenance contract.

Zünd has two service contracts that are most commonly used these are[4]:

- 24/7 coverage for 12,000€/year
  This is mainly aimed at manufacturing plants with a high-volume and throughput where the downtime of the operation can result in significant cost.

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- Preventative maintenance once a year together with the newest software update for the cutter. The cost for this service package is 2,340 €/year.
  This second option is more suited to the needs of Rondals' production.

A maintenance contract value from KUKA[5] has been taken as an example for this operational expenditure prediction. Their service contract is dependent upon the geographical location of the company and the robot configuration. It varies between 1,000 € and 2,000 € per year. KUKA does assure that their robots are made to last 20 years problem-free under normal usage and proper maintenance.

Over a period of 10 years the OPEX cost thereby adds up to 43,400€. This is rounded up to 50,000€ to take into for small part repair.

7.3.3. RISK REDUCTION

Usually, two positive side effects of automation are the waste and risk reduction and thereby play a large role in automation analysis. However, due to the state of development of this concept both these features can only be roughly estimated. The impact of the waste reduction has already been taken into consideration in the process earlier this chapter. This section tries to also provide an estimate on the accident risk reduction and the improvement of the health-related working conditions.

The implementation of the automation system reduces the risk of labour injury that cause sick days. It eliminates parts of the manual work on the most repetitive tasks. In the past 10 years 4-5% of working days have been identified sickness related absence days. These are not all related to working conditions induced sick days. Approximately, 30% of this overall percentage is assumed to be cause by the working conditions. To quantify this value calculations have been made assuming 228 working days per year with 14 workers at an hourly rate of 58€.

$$((2280 \text{ days} * 14 \text{ workers} * 464 \text{ €/day}) * 0.05) * 0.03 = 22{,}216 \text{ € over 10 years}$$

This means that Rondal spends approximately 2,200 € on working condition injury related costs every year. The automation system will not eliminate all this cost. Not the entire production is automated when integrating the system, but it can be assuming that 50% of these sick days can be reduced. This means that the maximum financial impact with regards to risk reduction is 1,100 € per year.

It is unknown to what extent new type of work accidents that are robot -human related, are created due to the handling of the new technology. As previously mentioned the ISO regulations limit the operating speed of the robots at close proximities with humans. Thereby, minimizing the accident potential.

7.3.4. ROI

A complete return of investment (ROI) calculation would include a market study to predict occupancy of the composite production for the upcoming years. For this project, the prediction is simply based on the sales overview of the past 5 years, in which the mast, boom and rudder production really started booming Over 5 years, 13 masts and booms have been manufactured and sold. This same value is used as prediction for the ROI. Out of these 13, two are already assured for 2018.

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Usually, ROI calculations are done with a five-year prediction. But, due to the uncertainty of the superyacht business and looking at the volume of production it is more reasonable to do the ROI calculations for this P&P system over a period of 10 years. This is also the timeframe that other investments, such as the current cutting table at Rondal is aimed to balance out. These calculations thereby estimating to produce 26 masts and booms over the ten-year period.

The results from the comparison calculations are summarized in Table 51.

Table 51: ROI Prediction

Products	5 year		10 year	
Mast Plates	€	100,100	€	200,200
Boom Plates	€	54,600	€	109,200
Spreaders	€	26,000	€	52,000
Mast shaft	€	14,300	€	28,600
Improvement of working condition	€	5,500	€	11,000
Risk reduction	€	5,500	€	1200
Total cost saving	**€**	**200,500**	**€**	**401,000**
For 5 year period 13 masts and booms are estimated				

The Capex and Opex add up to a value of 340 500€ which is 71,500€ short of the profit estimations. This leaves barely any budget leeway for the entirety of the development and implementation work that is most likely probably just as costly as the equipment.

At this stage, it has to be acknowledged that about half of the parts that can be partly and fully automated are included in this ROI prediction. Only looking at the number of products from Table 19, these make up at least 46% of the production. Seeing that from the spreader analysis 88% of kitting cost savings were achieved, it is possible to add another 50,000€ to the overall profit estimations. This makes up for the parts that have not been integrated into the calculations.

Only looking at the products that can partially be manufacture using the P&P concept thereby discarding 11% of the products from product type 4; 56% of those products do still have potential to get fully automated if the hot drape forming stage proves to be successful. However, even with that addition, the economic outlook of this automation system does not look promising.

This concludes that from an economical viewpoint, the investment into an automation system for the current occupancy of the Rondal production is not viable to provide any profit within 10 years of the investment. One way to possibly gain more potential out of the custom-made processes is to further standardize individual steps of the process. This standardization could be achieved, by restricting the custom product designs in such a way that they can all be produced by the same size plies. Another option could be to standardize the production of the frequently produced parts to ensure its structural soundness of the products no matter what design. The custom adjustments that would need to be made are then based on an aesthetic construction that can be thinner and thus less labour time intensive. Either way, if an automated process is desired to be introduced for its other advantages, as well as its unique selling point (USP), the custom-made products will be forced to reduce their agility towards the customers choices.

CHAPTER 8 - CONCLUSIONS

The results of the study lead to the conclusion that, while the P&P concept is the most appropriate for the current production, it is not economically feasible to create a return on investment within ten years. It further answers the research question posed in section 1.1 on the implementation of the process by proposing to eliminate the manual kitting process for all products. Instead a robot can perform a more advanced-level of work preparation. This provides the finished stacked kits for the manual laminating of mould products. The concept fully automates the flat plate production with exception for the de-bulking step. The de-bulking is to be mechanized and combined with the manual process. No process changes need to be implement for this automation system to suit the current composite production. Furthermore, in order to fully implement this automation into the production, Rondal need to ensure the P&P cell has access to supply sources, meets all safety conditions and is used at maximum production volume capacity fitting the workshop flow.

The process analysis confirms that all products fall under process families following common production patterns, answering the first supplementary question in section 1.1. The common patterns are: cutting and nesting, kitting, laminating, de-bulking and the curing process. Further, the analysis showed that the material cost amount to max 30% of the production cost. The general composite manufacture sums-up to 45% of the entire labour time of the mast and boom production. This equals to 10% to 16% of the overall mast and boom cost.
The purity level of the laminate needs to meet a specific standard, assessed through a laser shearography test. Another quality standard is that many products require regional reinforcement altering the laminate thicknesses along their length. Yet, these identified quality requirements are demanding less accuracy and handling limitations compared to aerospace industry, for which the automation systems have traditionally been designed.

The second supplementary topic compared the different automation option. It concludes that most systems are designed for a high-volume manufacture but are restricted to simple moulds and shapes. Half of the investigated automation options are not able to cope with the varying local thicknesses required for Rondal products. Only the P&P automation alternative is readily suitable, without the need to redesign the manufacturing approach. Once it has come out of the development phase it will only require minimal amount of programming for the operator. Even though, most other automation processes produce less amounts of scrap material in comparison to the P&P option, the final choice fell onto the most adaptable solution that is easiest to implement with the current process settings.
The task of assembly and finishing automation will most likely only be possible with a collaborative robot to deal with all the unique adaptation. Even though the P&P concept does not have a collaborative robot, the interchangeable tools of the P&P solutions still make future development into the assembly automation possible.

The P&P robot system does not allow any of the system development to be bought ‘off the shelf’ yet. Within the P&P concept there are several pieces of equipment, namely the cutting table the robot, the stacking table and at later stages even the hot drape forming press that can be bought from a combination of product ranges. Hence, they do have the ‘off-the shelf’ status. To answer the supplementary question of the second topic on that regards, it is possible to find partial ‘off the shelf’ automated solutions for the custom-made automation environment. These however, do have to be connected to one another which is a custom adaptation to the process requirements.

The biggest milestones to surpass, to be able to bring this automation system closer to implementation are:

1. The development of a communication interface that can bring human input to the cutter robot, in term of the orientations of plies with regards to either object.
2. The continuation of the development of the film removal tool and inspection systems for it
3. The design of a well dimensioned gripper that is optimized for the various shapes Rondal handles
4. The successful program development of a sorting station to provide the kitting.

The P&P concept in this project has been designed in such a way to make use of on-site pre-existing equipment. This is done thorough the stacking table and the de-bulking frame, that currently are in test trial at Rondal. Another critical aspect for the implementation of this automation system is that the quality control systems at the picking stage, the peeling stage and flipping stage are set-up properly to inform the operator of problems.

In terms of Rondal’s goals for the automation system, the present study concludes that a reduction of lead time by a week, as well as a cost reduction due to labour saving of 50% are achieved. The employees are also performing fewer repetitive tasks and instead plays a supervision role. The quality of the product itself improves with the automation since the robot accuracy lies at about 0.5mm, reducing the risk of stacking mishaps during the program, as long as the information feed into it is as provided by engineering. The investigation also showed that if Rondal were still to invest into automation system the business case brings Rondal ahead of the competition creating a USP since the full process has not been developed yet.

CHAPTER 9 - RECOMMENDATIONS

The ROI calculations are only based on the prediction of a part of the Rondal production. If other products are added to the production though the standardized hatches that Rondal intends to start to build on stock the financial situation could alter. It is the integration of standardizations such as these that will make the automation profitable. Not the entirety of the part need to be standardized it already helps to restrict the designers by limiting the process steps and thereby keeping agility for the custom-made product.

The development of the P&P concept is very much dependent on the interactions between the different equipment. The development of all entities within the cell should be performed simultaneously to ensure the cell as a whole will operate effectively. It is only matter of time before aerospace research and development companies can provide a Pick & Sort system that could be adapted for this automation and with it open the opportunity to start the full development of this entire cell. At that point, the investment potential can also be re-evaluated.

In the meantime, another gap in the concept is required to be bridged. This is the automation of the protective film removal. Due to the aerospace material restriction, many of the composite research centre do not put their focus on the development of a film removal tool. Since the marine industry is not affected by these same regulations it is recommended for Rondal to fill this roll and develop such a protective film removal tool to close the gap that prevents a full automation system to be applies. Developing this in house or in close collaboration with a partner, ensures that the particularities such as the poliback films that Rondal uses can indeed be removed by the developed tool. Such a tool can potentially also be designed as a handheld tool that can be used in support of the manual process as well.

Based on the experience gained in this project it is also possible to provide some technical recommendations concerning the individual equipment of the automation cell. The prototype development of the film removal tool revealed several further research area potentials. These are regarding the clamp system for the ply, the control over the tension of the peeling ply and an inspection system that can determine if the task has been completed successfully. The development of this tool also made clear the importance of the right gripper design. Focus should be placed in the distribution of the suction cup and their ability to adapt to the various ply sizes. A partnership with Airborne in all these research fields will help to adjust their development to this systems requirement.

An area of research into which this project would have liked to dive in further, is an investigation of large ply handling. This is an investigation that needs to be performed to optimize the robot movement with large plies as well as the determination of the gripper effectiveness within the process.

If the P&P concept is to be realized a full simulation of the process with logic behind the equipment is absolutely necessary. Only a full process simulation will be able to reliably predict the effectiveness of the automation cell. Such simulations are a common service offered by the robot manufacturers.

Even though the Hot Drape Forming process is considered a future development step for the P&P concept, it is recommended to do perform testing with the spreader and hatch mould using the NLR equipment. If these moulds prove to be viable for the HDP process, this equipment can already improve the manual process significantly without having to invest in an entire P&P automation system.

The introduction if the automation system opens the opportunity for new composite production potential, that will not require labour hours, simultaneously it creates a USP. If this potential is desired to be integrated then it is recommended to first establish a clear and detailed ERP system log from which a much more detailed production time analysis can be made. Only if the tasks with high time consumption can all be identified then an effective application of automation can be predicted. The problem with such an analysis is the timespan needed could potentially take years to obtain sufficiently data due to the long time-interval between the start and finish of a final product. Additionally, the implementation of the P&P concept limits the impacts of the automated production to approximately 5% of the overall production process and less than 1% of the production cost. If any more major influences are aimed to be realized, then a redesign of the production process is necessary. In that case the P&P concept might no longer be the most suitable automation system available. This concept was only chosen under the assumption that the process is to stay as it currently is.

Finally, an investment into any automation system could provide new business opportunities for Rondal to expand towards a new clientele. This also allows the automation equipment to be used to its full potential. With this in mind, it is definitely a worthwhile investment.

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APPENDIX I- SCIENTIFIC PAPER

Development of Automated Protective Film Removal Tool for an Application in the Marine Composite Production

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Abstract:

A Rondal BV funded project is investigating the automation opportunities for a custom-made composite part production. As part of a pick and place robot cell concept for this application an automated film removal tool is developed. This article describes the current advances in this topic, as well as the design process behind the development. Results of material tests are analyzed and used as a basis for approximate full production volume implementation requirement. A prototype solution for the automated film removal is proposed that uses shock cooling as a mean to initially detach the protective film from the prepreg. The challenges and the reasoning behind the tool are explained. Finally, problems observed during trial testing are summarized and recommendations for further research on material tests, the robot gripping tool and the tools clamp system, are provided.

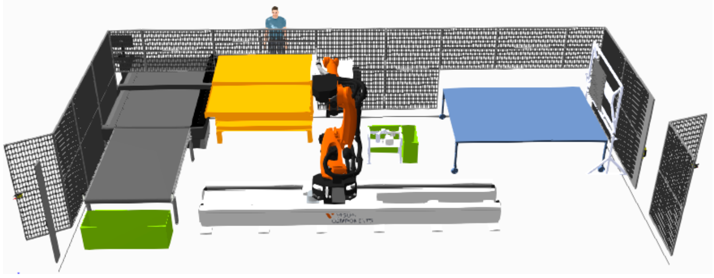
Keywords: automated manufacture**,** automated protective film removal, prepreg, tack, shock cooling

INTRODUCTION

With the increased development of automated composite manufacturing systems in the aerospace industry, the superyacht equipment manufacturer Rondal BV decided to investigate the feasibility of such technology for their own manufacture. The investigation has shown that one of the major piece of equipment currently lacking in the development of the pick and place (P&P) automated system (1) [1,2], is a tool with the capabilities to autonomously remove the protective plastic films from the prepreg surface. Such a tool allows the ply kitting process to be connected to the stacking process of the laminate. This paper describes the approach and challenges of the development of a protective film removal tool for a P&P automation system [3].

Even though there has been previous research performed on this topic, it has mainly been focused on the more rigid backing paper removal. These developments have also further been influenced by the restrictions placed upon the prepreg handling of the aerospace industry.

The application for this tool differs to previous design by focusing on the removal of thin plastic protective films, which are a less rigid that the backing paper and thereby more difficult to separate from the prepreg surface. Additionally, shock cooling is used as a means to aid the detachment between the film and the prepreg.



1 Pick and place robot cell for fully automated prepreg laminating production, including a film removal tool

PRIOR DEVELOPMENTS

The issue of protective layer removal has been identified by numerous sources with regards to automation of prepreg manufacture. Testing, especially applied to the Automated Tape Laying (ATL) technology, has been performed by Crossley et al. [4]. It discusses the impact of heat and peeling rates on the adhesion of the backing papers of the prepreg stripes laid up on the mould surface. Johannson and Sundqvist have dedicated research to the backing paper removal from prepreg plies using specially developed robot tool heads that move over the surface of the plies [5]. In 2014, Björnson continued that research, developing a tool that is independent of the robot arm and can be integrated into a pick and place robot cell [6]. Even the Delft Hochschool in collaboration with Airborne composites tried to remove the protective film only using a suction cup on a robot arm to imitation of a human peeling movement. [7] None of these solutions have however made it into the prepreg pick and place cell developments of the industry.

DESIGN REQUIREMENTS

Certain design requirements need to be met for the tool to be able to properly interact with all other elements of the cell. Firstly, the tool needs to be a separate, stand-alone unit, which is not controlled through the robot, but rather used by it to help achieve the peeling task. That way it is independent of the type of robot the final automation process uses and does not need to be interconnected.

Consequently, it will also require sensing the approach of plies and trigger its own working mechanism.

It also needs to be able to achieve the initialization detachment of the film and peeling operation without human input requirements.

Furthermore, it should minimize the contact to the plies to reduce damage, contamination to the prepreg or any other kind of action that can impact the material properties of the final laminate.

In later stages, the final tool should also be able to handle a large verity of ply sizes. Yet, the set-up needs to be small enough to be placed within the robot cell. The tool also needs to be sturdy enough to handle forces acting upon it, at full operational speed of the robot.

Finally, to fully implement the tool into the automated production process it needs to have a safely system in place that inspects the quality of the peel. This safety should at stops the process until the right quality of peel has been achieved though the input of an operator. Ideally, the robot should be able to resolve partial peels on its own.

FILM REMOVAL PROCESS

Björnsson [8] describes thee stages to the film removal process. These are the initiation stage, the continued peeling stage and the quality check stage.

The initiation stage very much dependent upon the kind of prepreg and the type of protective material used. A solution for one type of prepreg might not necessarily be feasible for another due to the difference in tack and adaptation to the environmental conditions. Numerous different approaches to achieve the initial detachments have been tested [5,6] including air injection between the layers though a needle. The most commonly used solution is through mechanical bending of the ply to cause a detachment between the layers. Another method to cause the detachment of the two surfaces is to reduction the tack by cooling of the surfaces.

The continued peeling stage needs to provide sufficient friction so that the protective layer does not slip out of grip nor tear during the peeling process.

The inspection system, ensures the required high-quality laminate is achieve. It verifies that no protective film ends up in the laminate. Inspection though imaging is commonly addressed inspection method in other industries. An alternative inspection method that has been suggested by Björnsson (2013) [6] involves the weighing of the peeled material to analyse if all material is present. Since there are existing solutions for this inspection this stage will not be addressed within in this development.

Dependent on which type of prepreg is handled the film removal process might also require the flipping of the ply over. For instance, the Rondal production uses partially woven prepreg which only has protective film on one side of the mat, but mostly Rondal uses unidirectional mats. These have protective film on both sides of the prepreg to help with the transverse rigidity of the ply during handling. This thereby adds a process step and an apparatus to the overall film removal step in the automated cell.

MATERIAL TESTING

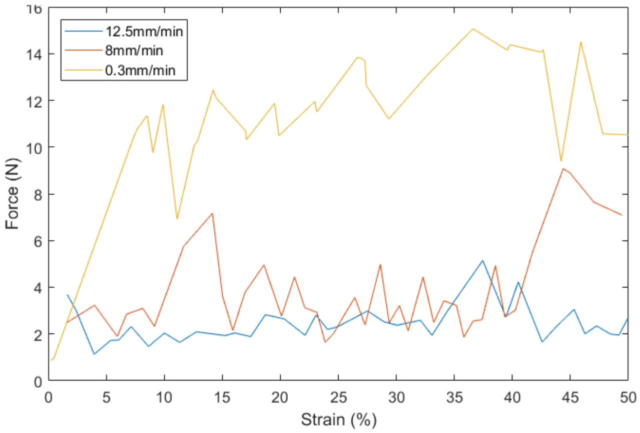
The prototype design is based on data obtained through material tests. The results make it possible to estimate the adhesion force on larger size plies that the tool will needs to handle. The adhesion test on the prepreg has not been performed on the standard Bell adhesion peel test equipment [4] but rather on a set-up that imitates the peeling action of the final tool. The film is initially detached from the surface and then is fixed into a clamp that is attached to tensile test equipment. (2)

2 Set-up of the material test

The test samples chosen are based on being able to analyse the effects of an increase in width, peeling speed, prepreg surface temperature, fibre type and the addition of an external air blow to reduce the adhesion forces.

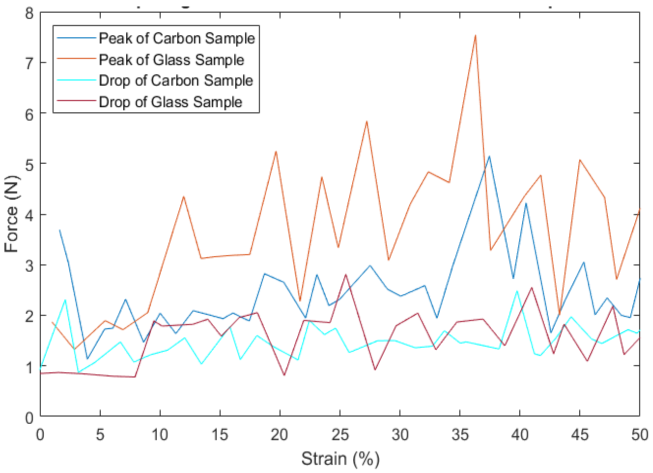
The results obtained through the testing showed a large amount of fluctuations. These are most likely due to the elasticity of the protective film as well as the adhesive release behaviour. To be able to properly analyse the results all data has been run though a filter which only leave the peaks and throughs of the originally recoded data. Another observation made throughout the test, that will have to be considered for the design of the tool, is the slipping of the film out of the clamp. This ruined some of the data sets. It also occurred that the film tore which falsified the data and did not let the full detachment to be achieved. This last observation is not uncommon and will have to be identified by the inspection system of the tool.

The analysis on the alteration of peeling rates supported the findings Crossley [4] has observed with ATL prepreg on a robot head. The low detachment rates allow the resin to gather at the peeling front. This not only causes a higher force to be required for the peeling but also leave resin residue upon the peeled surface. Once a threshold peeling rate is attained this gathering no longer occurs. This can be seen in the much smaller adhesive forces when comparing the 0.3 mm/min test results at 8 mm/min and 12.5 mm/min. These rates do not represent the rates at which the robot is capable to peel the film. Robots can move at speeds up to 2m/s which cannot be imitated by this tensile test device. Another way for testing the material at such high peeling speeds will have to be thought off to gain data on such analysis.



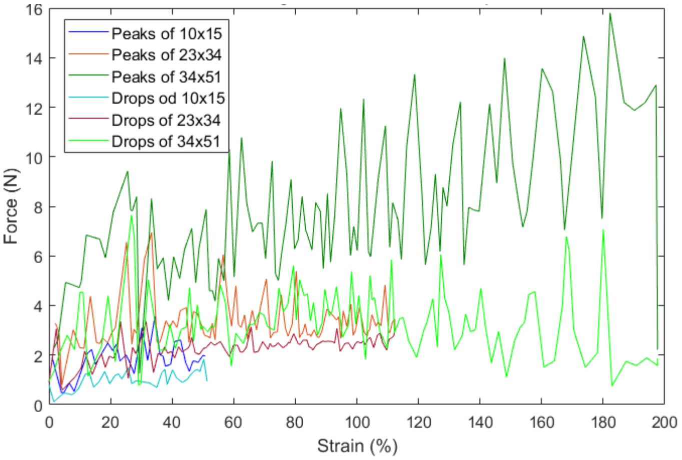
3 Impact of alterations on peeling rates

The second comparative test, analysed the difference between carbon and glass prepreg. Both material are woven fabrics but do have different areal weights. Although both materials are made with the same resin the carbon fabric has resin contend of 42% whilst the glass fabric only has 35% resin. In view of these facts and that carbon fibres usually forms stronger bonds with epoxy resin, it is expected that the carbon fabric has a stronger adhesive bond to the protective film. Yet, the results of the test show the opposite. The glass samples partially require twice the force to detach the film from the prepreg surface than the carbon material. It could be the difference in areal weight or the way impregnation was performed, that causes the resin of the glass mat to keep the resin more on the surface of the material. Another reason could even be the difference in fibre orientation. Further material testing is required to determine the exact cause of these discrepancies. However, the results do provide a guidance value of 0.04 N/mm width of the glass fibre material, upon which later estimation can be made.



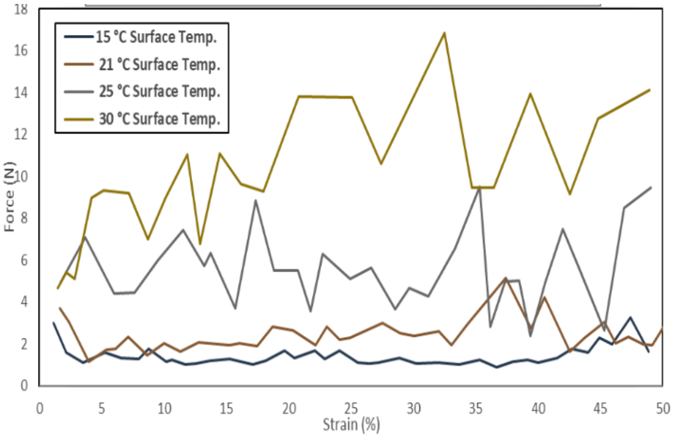
4 Comparing adhesion tests of carbon and glass prepreg

The material properties that are of high relevance to the tool design are the size and temperature impact on the adhesion force. To obtain comparable size results it has been ensured that the length to width ratio of all samples are equal. The results of these tests (5) demonstrate that with every 50% increase of the ply size the maximum forces at least doubles. It can also be seen, especially with the lager plies, that there is an increase in force as the film lengthens. Less control can be exhorted over the film which no longer provides sufficient tension in the film. The data processing showed that the variety of sizes all had close force per mm values. These average to 0.05 N/mm. These results do suggest that the relationship between the size and the adhesive force is probably linear.



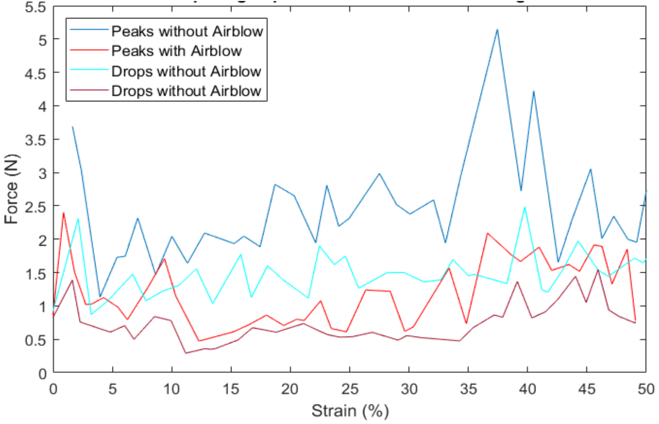
5 Adhesive force variation due to an increase in ply

The temperature test showed to have a much more impact on the overall forces. Whilst at the lowest temperature only maximum 3 N are required, at 30°C up to 17 N are necessary to remove the protective film. It can be observed on the graph (6) that the 4°C difference between 21°C and 24°C do cause the biggest increase in forces requirements. The average force per mm at 30°C has been calculated to be 0.18 N/mm, which is the closes result to the 0.2 N/mm Crossley obtained with his material. [7]



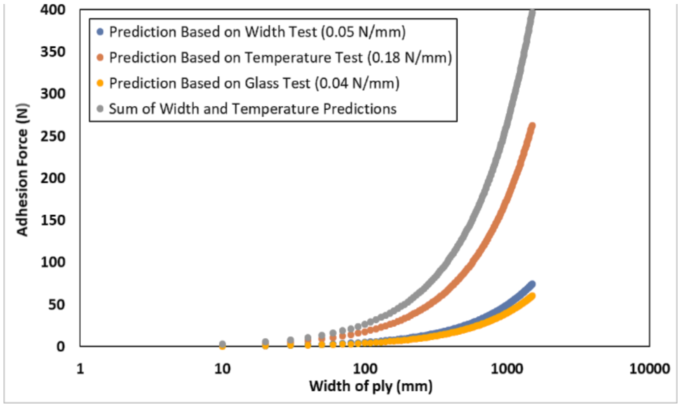
6 Comparing adhesion forces with changing surface temperature

An additional mean of supporting the peeling process was thought to be the addition of a cold air blow onto the connection face between the two surfaces. A spot cooler with an included vortex tube has been used to blow cold air from a pressure source of 6 bar. A reduction in adhesive force is visible (7), but it is uncertain to what extend this reduction can be sustained on a larger scale ply peel.



7 Comparing the impact of air blow on adhesive force reduction

Each material test type provided a different force per mm width values. If these are now combined and extrapolated to a width of 1.3m, which is the maximum with of a material roll, a force prediction for a large ply can be obtained. This prediction assumes that the protective film of a 1,3m glass fabric ply is removed at a surface temperature of 30°C. It is not fully accurate to add these different values to one another since some of the forces would be in parts included multiple times. Yet, it provides sufficient accuracy for a prototype design to me made. This peeling force required 344 N.

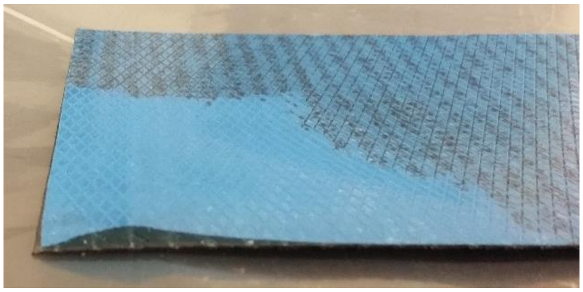


8 Overall peeling force predictions for the film removal tool design

TOOL DEVELOPMENT

A large focus in the tool development was placed on finding a sustainable way to achieve the initialization by cooling. Preliminary test with a chemical coolant spray, that is usually used for electronics failure detection, showed that a high temperature drop causes the protective film to shrink and detach from the prepreg surface on its own. This is an ideal situation for the initialization of the peeling process to occur. This state was tried to be achieved using both a spot cooler. It is a vertex tube that uses compressed air to create a hot and a cold air stream. Testing revealed that even though this equipment is indeed able to create an extremely cold air stream, the volume flow rate at that temperature is so low that it did not manage to achieve the desired temperature drop at the surface of the prepreg. The second option involved a Peltier element. Unfortunately, even this second alternative was proven to be successful, since the surfaces were not able to be insulated sufficiently to prevent a heat transfer from the environment. As concluded earlier, the spot cooler can however be used to help the peeling when it is adjusted to a higher air pressure setting.

The next cooling solution tested is liquid nitrogen. It was found to be a good alternative solution for the chemical coolant. The nitrogen manages to cool the surface down to -122°C. An important observation made at those temperatures is that the protective film does not become brittle. This means the peeling process can still be performed at such low temperature, given that the materials used for the initialization can withstand such temperatures. Also, the prepreg surface warmed back up to its original temperature within half a minute of applying the liquid nitrogen. At that point, it is possible to laminate the ply again. Unfortunately, for the prototype development, the liquid nitrogen option, is not feasible since it requires a storage tank and spraying apparatus that have a high investment cost. Therefore, for the proof of concept the tool set-up continuing to use the chemical spray as liquid nitrogen imitation.



9 Detachment of film due to shock cooling

An issue concerting shock cooling is that it might create a moisture build up within the prepreg. Additionally, coolant spray chemicals or even the liquid nitrogen could potentially leave chemical residue on the prepreg, even if the coolant is only sprayed onto film. The effects of these on the final laminate must be investigated through further material tests. It is most probable that these effects are so minimal that for a marine the effects can be neglected for the laminate quality.

The coolant test also provided information regarding the clamping. The detachment between the prepreg surface and the film is small. Approximately 4 mm for a carbon prepreg fabric. Based on that fact it has been decided to create a clamp that approaches horizontally, slicing in between the two layers and that is clamped down with help of an electromagnet.

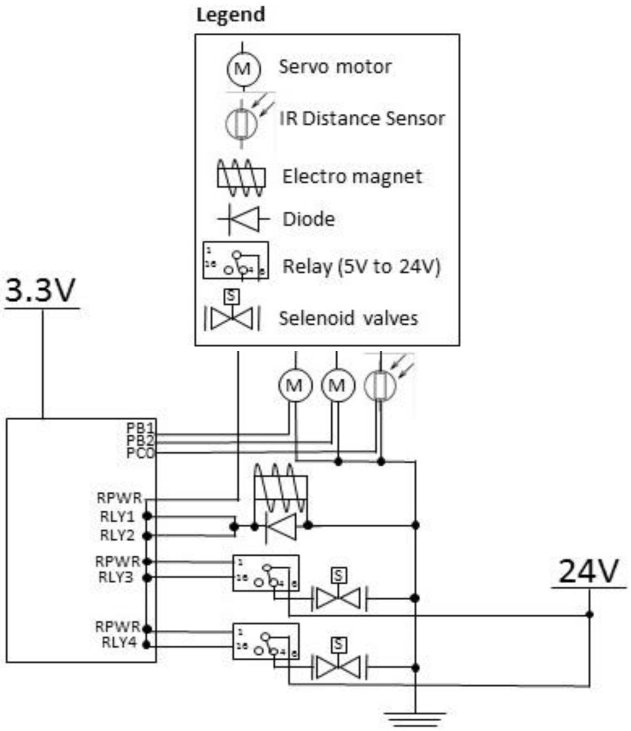
As it was observed during the material tests, the film is likely to slip out of the clamp. To prevent that, a suction cup is added to the bottom surface onto which the film is pressed, through which, at the right time in the process, a vacuum is flowing keeps the film in place. Additionally, a rubber surface is glued onto the bottom side of the clamp plate to create further resistance for the film.

TOOL SET-UP

The previously described development all lead to the prototype tool system set-up. It includes the interaction between:

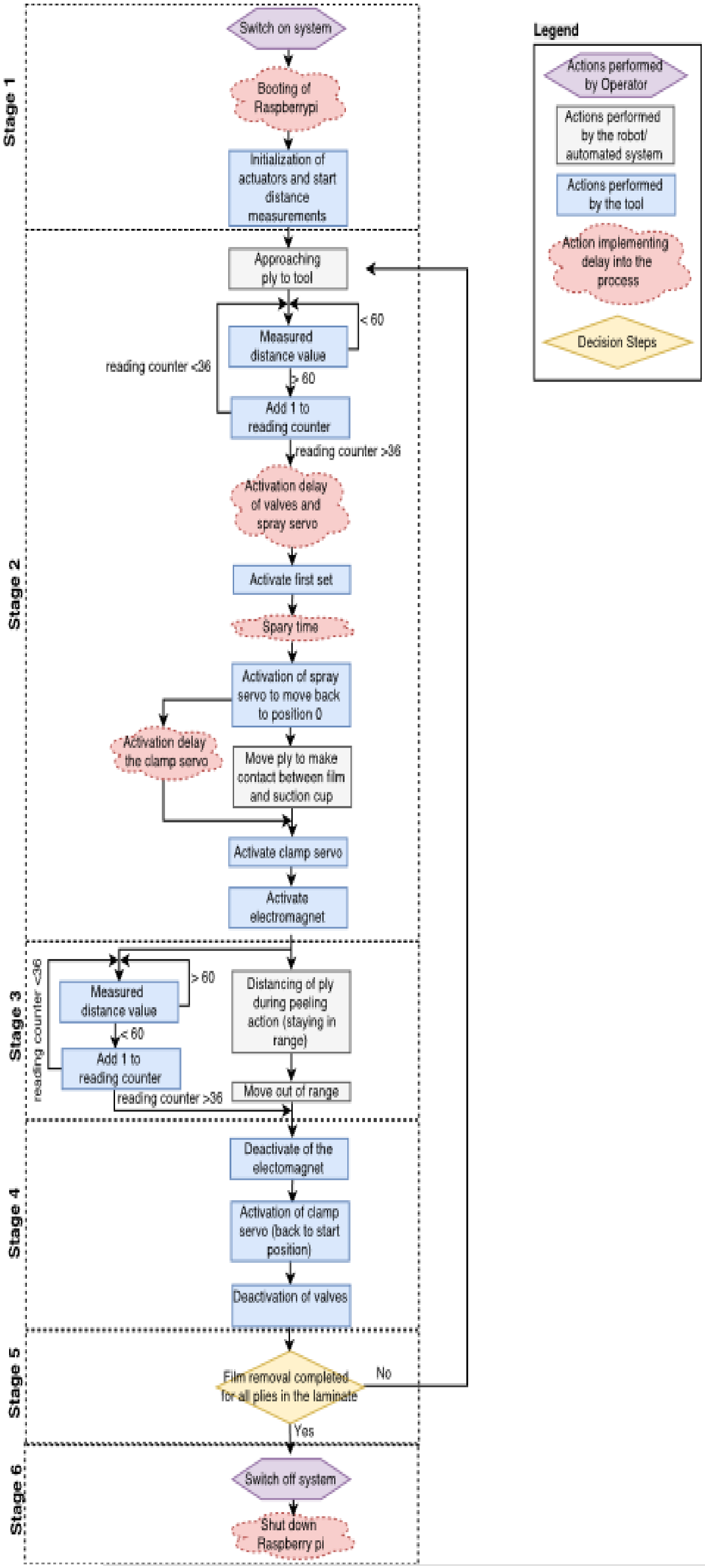
- ➢ An infrared sensor, to detect the approach of the ply
- ➢ A servo motor, to activate the spraying
- ➢ A valve, to activate the vacuum on the suction cup
- ➢ A second valve, to activate the compressed air for the spot cooler
- ➢ A second servo motor, to initiate the clamp opening and closure
- ➢ An electromagnet, to keep the clamp in place during peeling

The electronics is controlled via a raspberry pi connected to a gertboard [9]. The wiring of each of these actuators to one another is represented in the schematics (10). It can be seen that different actuators are also running of different voltages; hence several separate power sources are required.



10 Wiring of the actuators of the tool

The flow charts add onto this by explaining at which point of the process the individual actuators jump into action. Stage 1 and 6 represent the booting and shut down time of the tool before and after use. The code of the film removal tool needs to be called upon correctly otherwise the file risks to corrupted. Stage 2 is the initialization of the film, with an integrated safety to prevent a trigger from IR sensor miss reading. Stage 3 is the continuous peeling stage.

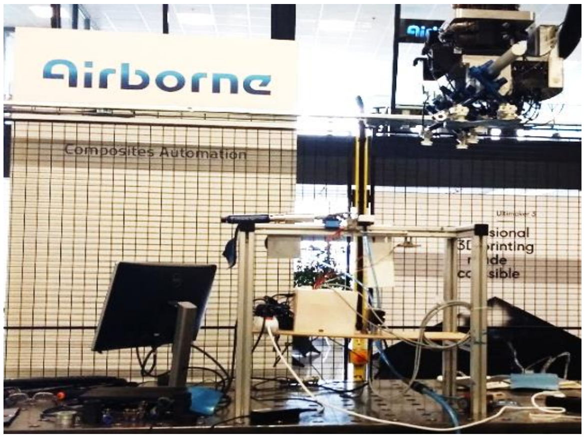


11 Flow chart of the film removal tool working process

DISCUSSION

The film removal tool has been tuned and tested using the Airborne Automation Composite Robot facilities. The prototype testing made two development point abundantly clear. Firstly, the ability of the peel to be performed successfully is fully dependent on the appropriate design of the end effector (gripper). Unless the gripper, is designed for the specific ply, it will not be able to sustain sufficient strength during the peeling process to keep hold of the ply. It has also been noted throughout the testing that small diameter suction cups with a large stoke can adapt much better to ply movements. They have a better grip during ply handling.

The second development point is concerning the clamp. It has been observed that the clamp is not always able to fully keep the film fixed in place. The rubber surfaces together with the pressure created by the electromagnet is simply do not suffice. Moreover, when the clamp manages to keep hold of the film it usually tears due to the high stress concentration surrounding the film at the edges of the clamp. A mechanism need to be added that not only helps spread the pressure of the peel over a wider area but also keeps the peeling tension constant throughout the entire peeling process. This will make the peel more controlled and will prevent high stress areas that could result in tears.



12 Tool tuning and testing with Robot interaction

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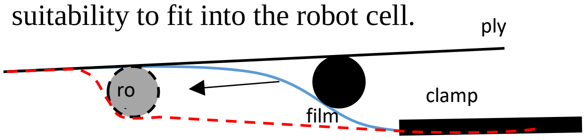
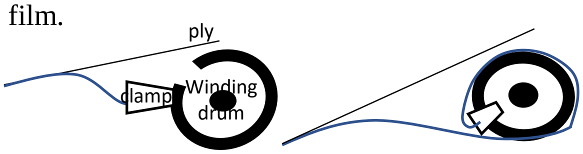
Two concept mechanism that could help keep control during peeling have been thought of. The film can either be kept under tension by placing an object it in the path of the peeling or by ensuring a constant distance is kept between the peel interface and the tool.

The first is achieved by inserting a rod along the width of the ply (13), once the initialization is complete. It forces the film downward as it moves along the length of the surface. The advantage of this is that it eliminates the need of the robot movement along a path over the tool. It however, also means that a tool the size will need to be increased to size of the largest ply. This limits its suitability to fit into the robot cell.



13 Tension mechanism solution 1

The second mechanism option, keeps the distance between the tool and the peel interface constant. It reduces the length of the peeled film throughout the peeling process. This is done by winding the film onto a drum. The original initiation is still performed by a clamp, that then slots into a winding drum. The advantage of this option is that the distance reduction improves the control over the peeling and with it increases the peeling force spread over the entire length of the film. Thereby, no stress concentrations risk to tear the film.



14 Tension mechanism solution 2

An important part of this peeling process is not integrated in the tool but rather the robot control system. The robot needs to move the ply so that all areas can be peeled. This is most likely to be possible when moving along the centreline of the ply shape. As the ply shapes become larger and more complex with the industrial application of this tool, an algorithm will need to be established that can calculate the robot path based on the known the shape of the ply.

CONCLUSIONS

The development of the automated film removal tool showed that it largely based on the material properties of the prepreg. Handling the thin plastic can result in tearing which brings a high importance to the necessity of an inspection system following the main film removal process.

The main difference in application of this tool compared to previously developed tools is that is uses shock cooling to cause the initial detachment of the film from the prepreg surface. A further method to help reduce the tack between the surfaces is to point an air blow between the interfaces. Any development of this tool will require a large amount of adjustment dependent on the prepreg material used. The two most significant aspects that need to be dealt with before such a tool can be implemented in an actual industrial environment is; improved control over the ply when dealing with large plies and the inspection step to ensure the quality of the laminate.

Even though the full proof of concept could not be realized due to a lack of appropriate end effector on the robot arm, this solution shows a great promise once the still problematic topics have been resolved. A successful finished development of such an automated film removal tool will bridge the automated process gap in the pick and place robot cell for composite part production.

RECOMMENDATIONS

Recommended areas of research concerning the material science aspects, are definitely required to determine the effect of shock cooling on the quality of the final composite product. Furthermore, material test could also be performed to investigate the impact of the fibre orientation upon the adhesive forces between the surfaces. A more in-depth analysis should also be performed on finding concrete answers to the cause of the glass prepreg having larger adhesive forces to the protective film. A final kind of adhesive test that ought to be performed before the implementation of this tool is to observe peeling behaviours at high peeling rates at which the robot can be operating, to determine if that changes parts of the overall process.

Concerning the peeling process, it is recommended to place further resources on the development of a tension mechanism as well the development of an appropriate gripper. Without it no full proof of concept will be able to be obtained.

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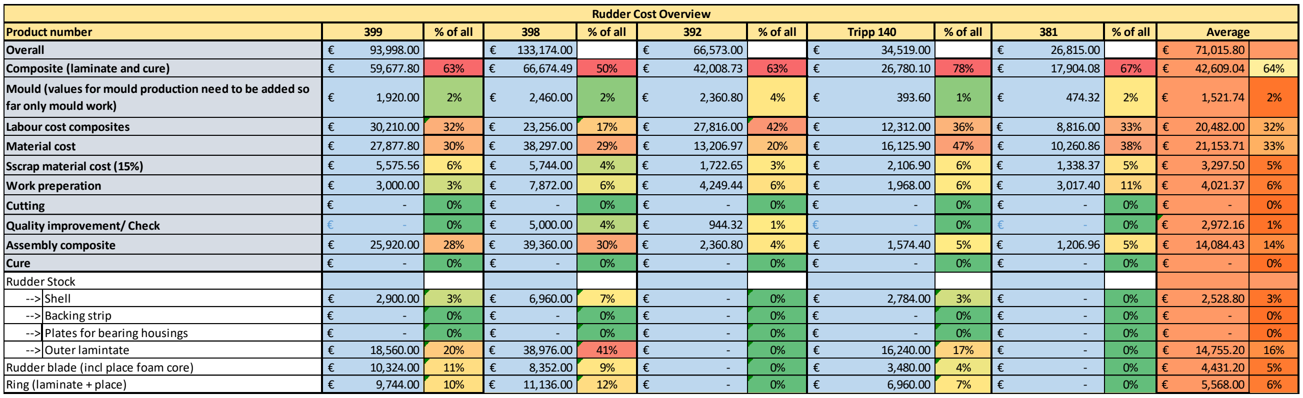
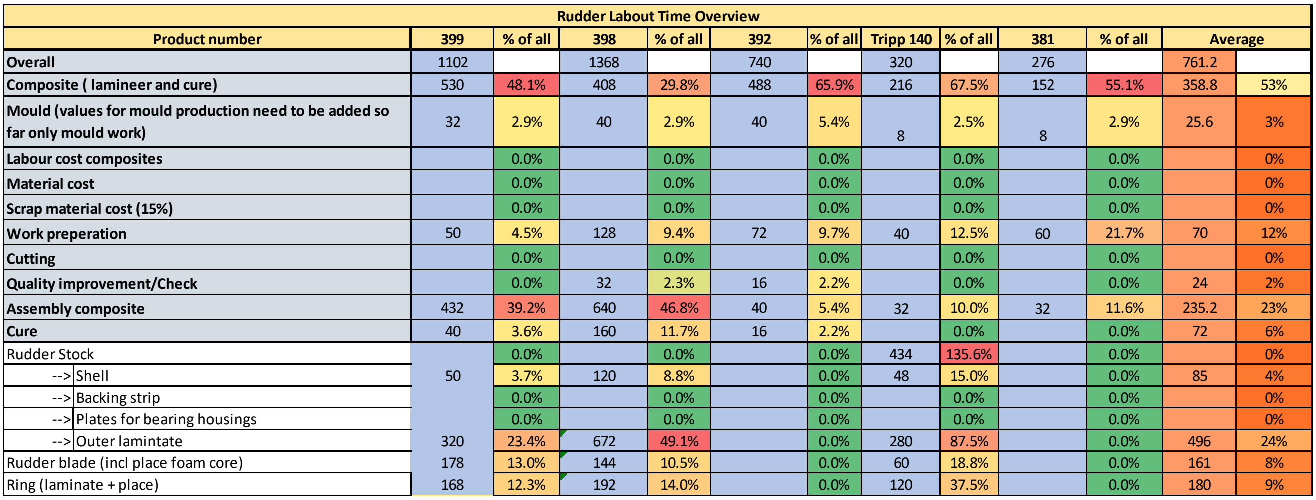
APPENDIX II- SUMMARY OF ALL CONSIDERED PARTS

Table - II-1: Rudder Cost Overview from Log



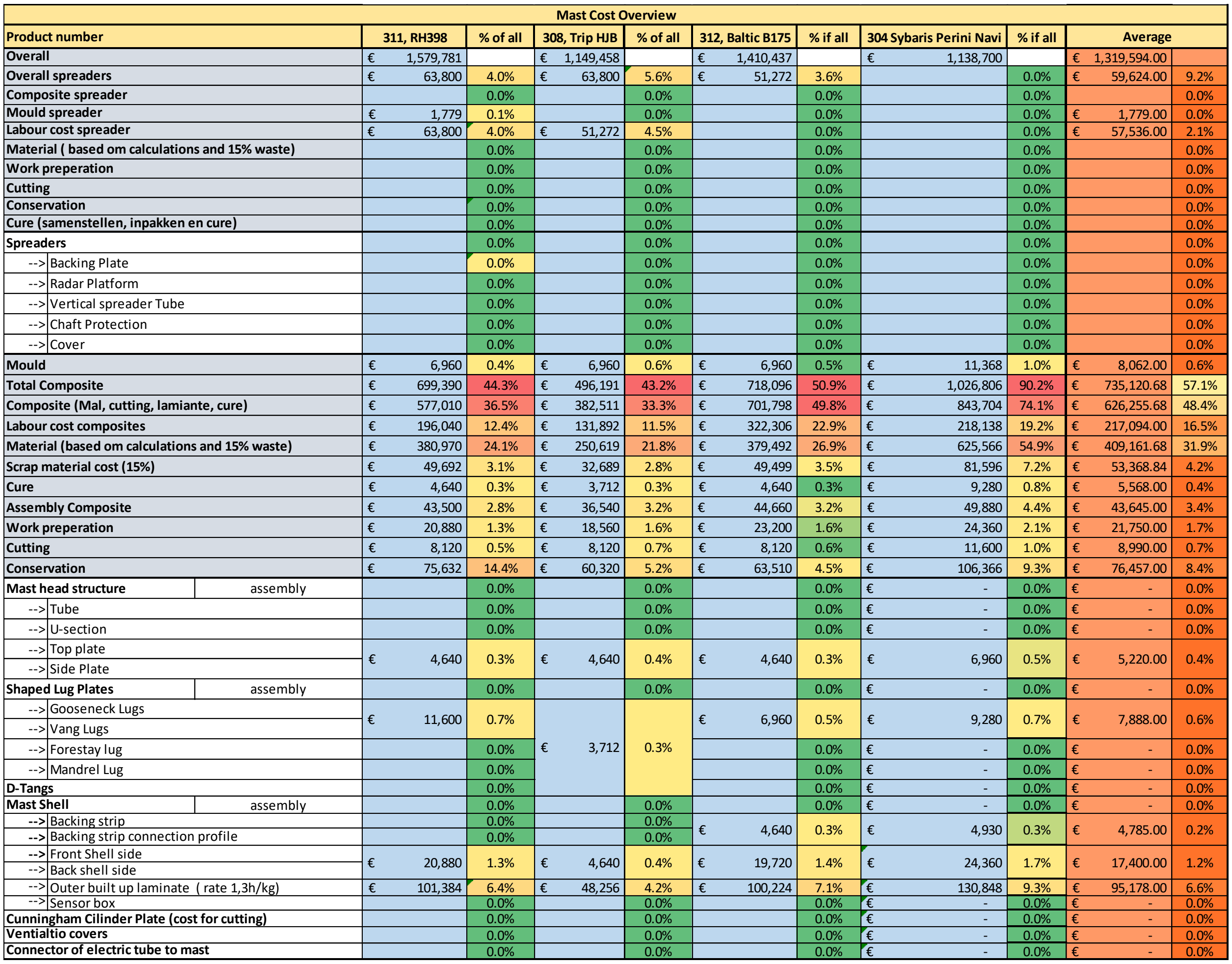
Rudder Cost Overview												
Product number	**399**	**% of all**	**398**	**% of all**	**392**	**% of all**	**Tripp 140**	**% of all**	**381**	**% of all**	**Average**	
Overall	€ 93,998.00		€ 133,174.00		€ 66,573.00		€ 34,519.00		€ 26,815.00		€ 71,015.80	
Composite (laminate and cure)	€ 59,677.80	63%	€ 66,674.49	50%	€ 42,008.73	63%	€ 26,780.10	78%	€ 17,904.08	67%	€ 42,609.04	64%
Mould (values for mould production need to be added so far only mould work)	€ 1,920.00	2%	€ 2,460.00	2%	€ 2,360.80	4%	€ 393.60	1%	€ 474.32	2%	€ 1,521.74	2%
Labour cost composites	€ 30,210.00	32%	€ 23,256.00	17%	€ 27,816.00	42%	€ 12,312.00	36%	€ 8,816.00	33%	€ 20,482.00	32%
Material cost	€ 27,877.80	30%	€ 38,297.00	29%	€ 13,206.97	20%	€ 16,125.90	47%	€ 10,260.86	38%	€ 21,153.71	33%
Sscrap material cost (15%)	€ 5,575.56	6%	€ 5,744.00	4%	€ 1,722.65	3%	€ 2,106.90	6%	€ 1,338.37	5%	€ 3,297.50	5%
Work preperation	€ 3,000.00	3%	€ 7,872.00	6%	€ 4,249.44	6%	€ 1,968.00	6%	€ 3,017.40	11%	€ 4,021.37	6%
Cutting	€ -	0%	€ -	0%	€ -	0%	€ -	0%	€ -	0%	€ -	0%
Quality improvement/ Check	€ -	0%	€ 5,000.00	4%	€ 944.32	1%	€ -	0%	€ -	0%	€ 2,972.16	1%
Assembly composite	€ 25,920.00	28%	€ 39,360.00	30%	€ 2,360.80	4%	€ 1,574.40	5%	€ 1,206.96	5%	€ 14,084.43	14%
Cure	€ -	0%	€ -	0%	€ -	0%	€ -	0%	€ -	0%	€ -	0%
Rudder Stock												
--> Shell	€ 2,900.00	3%	€ 6,960.00	7%	€ -	0%	€ 2,784.00	3%	€ -	0%	€ 2,528.80	3%
--> Backing strip	€ -	0%	€ -	0%	€ -	0%	€ -	0%	€ -	0%	€ -	0%
--> Plates for bearing housings	€ -	0%	€ -	0%	€ -	0%	€ -	0%	€ -	0%	€ -	0%
--> Outer lamintate	€ 18,560.00	20%	€ 38,976.00	41%	€ -	0%	€ 16,240.00	17%	€ -	0%	€ 14,755.20	16%
Rudder blade (incl place foam core)	€ 10,324.00	11%	€ 8,352.00	9%	€ -	0%	€ 3,480.00	4%	€ -	0%	€ 4,431.20	5%
Ring (laminate + place)	€ 9,744.00	10%	€ 11,136.00	12%	€ -	0%	€ 6,960.00	7%	€ -	0%	€ 5,568.00	6%

Table - II-2: Rudder Labour Time Overview from Log



Rudder Labout Time Overview												
Product number	**399**	**% of all**	**398**	**% of all**	**392**	**% of all**	**Tripp 140**	**% of all**	**381**	**% of all**	**Average**	
Overall	1102		1368		740		320		276		761.2	
Composite (lamineer and cure)	530	48.1%	408	29.8%	488	65.9%	216	67.5%	152	55.1%	358.8	53%
Mould (values for mould production need to be added so far only mould work)	32	2.9%	40	2.9%	40	5.4%	8	2.5%	8	2.9%	25.6	3%
Labour cost composites		0.0%		0.0%		0.0%		0.0%		0.0%		0%
Material cost		0.0%		0.0%		0.0%		0.0%		0.0%		0%
Scrap material cost (15%)		0.0%		0.0%		0.0%		0.0%		0.0%		0%
Work preperation	50	4.5%	128	9.4%	72	9.7%	40	12.5%	60	21.7%	70	12%
Cutting		0.0%		0.0%		0.0%		0.0%		0.0%		0%
Quality improvement/Check		0.0%	32	2.3%	16	2.2%		0.0%		0.0%	24	2%
Assembly composite	432	39.2%	640	46.8%	40	5.4%	32	10.0%	32	11.6%	235.2	23%
Cure	40	3.6%	160	11.7%	16	2.2%		0.0%		0.0%	72	6%
Rudder Stock	50	0.0%		0.0%		0.0%	434	135.6%		0.0%		0%
--> Shell		3.7%	120	8.8%		0.0%	48	15.0%		0.0%	85	4%
--> Backing strip		0.0%		0.0%		0.0%		0.0%		0.0%		0%
--> Plates for bearing housings		0.0%		0.0%		0.0%		0.0%		0.0%		0%
--> Outer lamintate	320	23.4%	672	49.1%		0.0%	280	87.5%		0.0%	496	24%
Rudder blade (incl place foam core)	178	13.0%	144	10.5%		0.0%	60	18.8%		0.0%	161	8%
Ring (laminate + place)	168	12.3%	192	14.0%		0.0%	120	37.5%		0.0%	180	9%

Table - II-3: Mast Cost Overview from Log

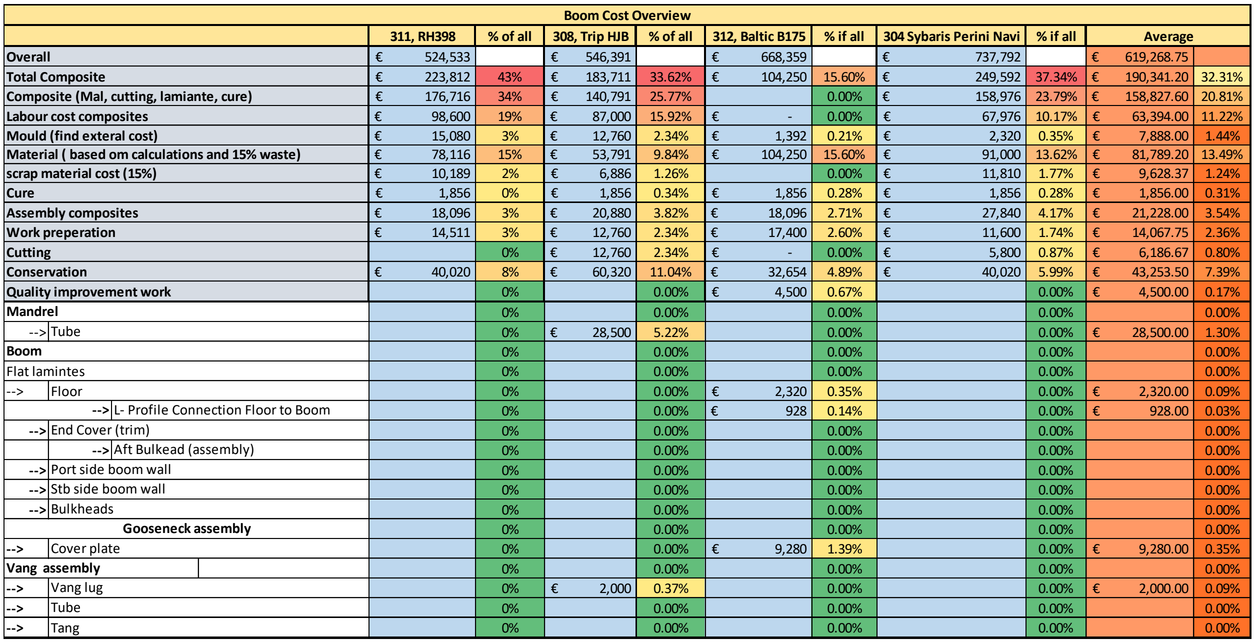


Mast Cost Overview											
Product number		**311, RH398**	**% of all**	**308, Trip HJB**	**% of all**	**312, Baltic B175**	**% if all**	**304 Sybaris Perini Navi**	**% if all**	**Average**	
Overall		€ 1,579,781		€ 1,149,458		€ 1,410,437		€ 1,138,700		€ 1,319,594.00	
Overall spreaders		€ 63,800	4.0%	€ 63,800	5.6%	€ 51,272	3.6%		0.0%	€ 59,624.00	9.2%
Composite spreader			0.0%		0.0%		0.0%		0.0%		0.0%
Mould spreader		€ 1,779	0.1%		0.0%		0.0%		0.0%	€ 1,779.00	0.0%
Labour cost spreader		€ 63,800	4.0%	€ 51,272	4.5%		0.0%		0.0%	€ 57,536.00	2.1%
Material (based om calculations and 15% waste)			0.0%		0.0%		0.0%		0.0%		0.0%
Work preperation			0.0%		0.0%		0.0%		0.0%		0.0%
Cutting			0.0%		0.0%		0.0%		0.0%		0.0%
Conservation			0.0%		0.0%		0.0%		0.0%		0.0%
Cure (samenstellen, inpakken en cure)			0.0%		0.0%		0.0%		0.0%		0.0%
Spreaders			0.0%		0.0%		0.0%		0.0%		0.0%
--> Backing Plate			0.0%		0.0%		0.0%		0.0%		0.0%
--> Radar Platform			0.0%		0.0%		0.0%		0.0%		0.0%
--> Vertical spreader Tube			0.0%		0.0%		0.0%		0.0%		0.0%
--> Chaft Protection			0.0%		0.0%		0.0%		0.0%		0.0%
--> Cover			0.0%		0.0%		0.0%		0.0%		0.0%
Mould		€ 6,960	0.4%	€ 6,960	0.6%	€ 6,960	0.5%	€ 11,368	1.0%	€ 8,062.00	0.6%
Total Composite		€ 699,390	44.3%	€ 496,191	43.2%	€ 718,096	50.9%	€ 1,026,806	90.2%	€ 735,120.68	57.1%
Composite (Mal, cutting, lamiante, cure)		€ 577,010	36.5%	€ 382,511	33.3%	€ 701,798	49.8%	€ 843,704	74.1%	€ 626,255.68	48.4%
Labour cost composites		€ 196,040	12.4%	€ 131,892	11.5%	€ 322,306	22.9%	€ 218,138	19.2%	€ 217,094.00	16.5%
Material (based om calculations and 15% waste)		€ 380,970	24.1%	€ 250,619	21.8%	€ 379,492	26.9%	€ 625,566	54.9%	€ 409,161.68	31.9%
Scrap material cost (15%)		€ 49,692	3.1%	€ 32,689	2.8%	€ 49,499	3.5%	€ 81,596	7.2%	€ 53,368.84	4.2%
Cure		€ 4,640	0.3%	€ 3,712	0.3%	€ 4,640	0.3%	€ 9,280	0.8%	€ 5,568.00	0.4%
Assembly Composite		€ 43,500	2.8%	€ 36,540	3.2%	€ 44,660	3.2%	€ 49,880	4.4%	€ 43,645.00	3.4%
Work preperation		€ 20,880	1.3%	€ 18,560	1.6%	€ 23,200	1.6%	€ 24,360	2.1%	€ 21,750.00	1.7%
Cutting		€ 8,120	0.5%	€ 8,120	0.7%	€ 8,120	0.6%	€ 11,600	1.0%	€ 8,990.00	0.7%
Conservation		€ 75,632	14.4%	€ 60,320	5.2%	€ 63,510	4.5%	€ 106,366	9.3%	€ 76,457.00	8.4%
Mast head structure	assembly		0.0%		0.0%		0.0%	€ -	0.0%	€ -	0.0%
--> Tube			0.0%		0.0%		0.0%	€ -	0.0%	€ -	0.0%
--> U-section			0.0%		0.0%		0.0%	€ -	0.0%	€ -	0.0%
--> Top plate		€ 4,640	0.3%	€ 4,640	0.4%	€ 4,640	0.3%	€ 6,960	0.5%	€ 5,220.00	0.4%
--> Side Plate											
Shaped Lug Plates	assembly		0.0%		0.0%		0.0%	€ -	0.0%	€ -	0.0%
--> Gooseneck Lugs		€ 11,600	0.7%	€ 3,712	0.3%	€ 6,960	0.5%	€ 9,280	0.7%	€ 7,888.00	0.6%
--> Vang Lugs											
--> Forestay lug			0.0%				0.0%	€ -	0.0%	€ -	0.0%
--> Mandrel Lug			0.0%				0.0%	€ -	0.0%	€ -	0.0%
D-Tangs			0.0%				0.0%	€ -	0.0%	€ -	0.0%
Mast Shell	assembly		0.0%		0.0%		0.0%	€ -	0.0%	€ -	0.0%
--> Backing strip			0.0%		0.0%	€ 4,640	0.3%	€ 4,930	0.3%	€ 4,785.00	0.2%
--> Backing strip connection profile			0.0%		0.0%						
--> Front Shell side		€ 20,880	1.3%	€ 4,640	0.4%	€ 19,720	1.4%	€ 24,360	1.7%	€ 17,400.00	1.2%
--> Back shell side											
--> Outer built up laminate (rate 1,3h/kg)		€ 101,384	6.4%	€ 48,256	4.2%	€ 100,224	7.1%	€ 130,848	9.3%	€ 95,178.00	6.6%
--> Sensor box			0.0%		0.0%		0.0%	€ -	0.0%	€ -	0.0%
Cunningham Cilinder Plate (cost for cutting)			0.0%		0.0%		0.0%	€ -	0.0%	€ -	0.0%
Ventialtio covers			0.0%		0.0%		0.0%	€ -	0.0%	€ -	0.0%
Connector of electric tube to mast			0.0%		0.0%		0.0%	€ -	0.0%	€ -	0.0%

Table - II-4: Last Labour Time Overview from Log

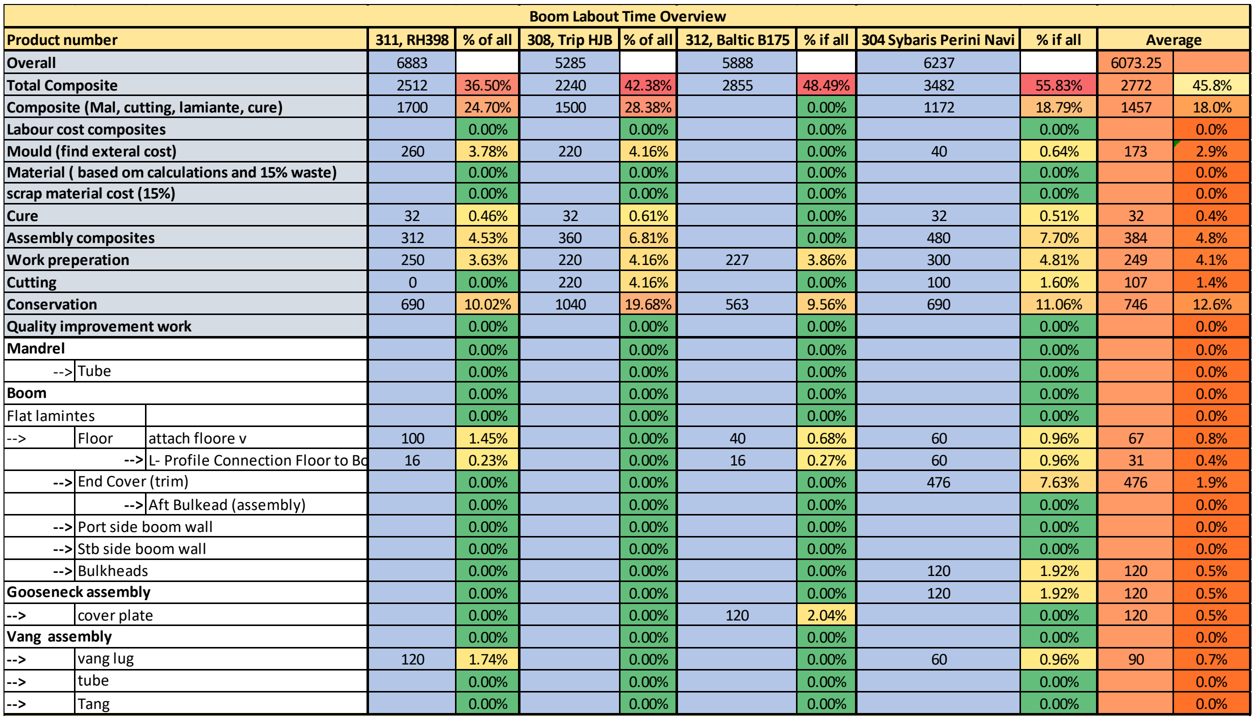
Mast Labout Time Overview										
Product number	**311, RH398**	**% of all**	**308, Trip HJB**	**% of all**	**312, Baltic B175**	**% if all**	**304 Sybaris Perini Navi**	**% if all**	**Average**	
Overall	13408		10102		11156		15960		12657	
Overall spreaders	1100	8.2%	884	8.8%	1000	9.0%	1000	6.3%	996	6%
Composite spreader		0.0%		0.0%	415	3.7%		0.0%	415	1%
Mould spreader		0.0%	43	0.4%	30	0.3%		0.0%	37	0%
Labour cost spreader		0.0%		0.0%		0.0%		0.0%		0%
Material (based om calculations and 15% waste)		0.0%		0.0%		0.0%		0.0%		0%
Work preperation		0.0%		0.0%	33	0.3%		0.0%	33	0%
Cutting		0.0%		0.0%	112	1.0%	200	1.3%	156	0%
Conservation		0.0%	1040	10.3%		0.0%		0.0%	1040	2%
Cure (samenstellen, inpakken en cure)		0.0%		0.0%	160	1.4%		0.0%	160	0%
Spreaders		0.0%		10.3%		0.0%		0.0%		3.4%
--> Backing Plate	80	0.6%		0.0%	318.97	2.9%	60	0.4%	153	1.0%
--> Radar Platform		0.0%		0.0%	98.5	0.9%		0.0%	99	0.2%
--> Vertical spreader Tube		0.0%		0.0%		0.0%		0.0%		0.0%
--> Chaft Protection		0.0%		0.0%		0.0%		0.0%		0.0%
--> Cover		0.0%		0.0%		0.0%		0.0%		0.0%
Mould	120	0.9%	120	1.2%	120	1.1%	196	1.2%	139	1.1%
Total Composite	6331	47.2%	4234	41.9%	5557	49.8%	7405	46.4%	5882	46.3%
Composite (Mal, cutting, lamiante, cure)	3380	25.2%	2274	22.5%	3660	32.8%	3761	23.6%	3269	26.0%
Labour cost composites		0.0%		0.0%		0.0%		0.0%		0.0%
Material (based om calculations and 15% waste)		0.0%		0.0%		0.0%		0.0%		0.0%
Scrap material cost (15%)		0.0%		0.0%		0.0%		0.0%		0.0%
Cure	80	0.6%	64	0.6%	80	0.7%	160	1.0%	96	0.7%
Assembly Composite	750	5.6%	630	6.2%	770	6.9%	860	5.4%	753	6.0%
Work preperation	308	2.3%	320	3.2%	276	2.5%	420	2.6%	331	2.6%
Cutting	140	1.0%	140	1.4%	140	1.3%	200	1.3%	155	1.2%
Conservation	1304	9.7%	1040	10.3%	1095	9.8%	1477	9.3%	1229	9.8%
Mast head structure		0.0%		0.0%		0.0%		0.0%		0.0%
--> Tube		0.0%		0.0%		0.0%		0.0%		0.0%
--> U-section		0.0%		0.0%		0.0%		0.0%		0.0%
--> Top plate	80	0.6%	80	0.8%	80	0.7%	120	1.1%	90	0.8%
--> Side Plate										
Shaped Lug Plates		0.0%	64	0.6%		0.0%		0.0%	64	0.2%
--> Gooseneck Lugs	200	1.5%			120	1.1%	160	1.4%	160	1.3%
--> Vang Lugs										
--> Forestay lug		0.0%				0.0%		0.0%		0.0%
--> Mandrel Lug		0.0%				0.0%		0.0%		0.0%
D-Tangs		0.0%		0.0%		0.0%		0.0%		0.0%
Mast Shell		0.0%		0.0%		0.0%		0.0%		0.0%
--> Backing strip	100	0.7%	80	0.8%	80	0.7%	85	0.8%	86	0.8%
--> Backing strip connection profile										
--> Front Shell side	360	2.7%	280	2.8%	340	3.0%	420	3.8%	350	3.1%
--> Back shell side										
--> Outer built up laminate (rate 1,3h/kg)	1748	13.0%	832	8.2%	1728	15.5%	2256	20.2%	1641	14.2%
--> Sensor box		0.0%		0.0%		0.0%		0.0%		0.0%
Cunningham Cilinder Plate (cost for cutting)		0.0%		0.0%		0.0%		0.0%		0.0%
Ventialtio covers		0.0%		0.0%		0.0%		0.0%		0.0%
Connector of electric tube to mast		0.0%		0.0%		0.0%		0.0%		0.0%

Table - II-5: Boom Cost Overview from Log



Boom Cost Overview										
	311, RH398	% of all	308, Trip HJB	% of all	312, Baltic B175	% if all	304 Sybaris Perini Navi	% if all	Average	
Overall	€ 524,533		€ 546,391		€ 668,359		€ 737,792		€ 619,268.75	
Total Composite	€ 223,812	43%	€ 183,711	33.62%	€ 104,250	15.60%	€ 249,592	37.34%	€ 190,341.20	32.31%
Composite (Mal, cutting, lamiante, cure)	€ 176,716	34%	€ 140,791	25.77%		0.00%	€ 158,976	23.79%	€ 158,827.60	20.81%
Labour cost composites	€ 98,600	19%	€ 87,000	15.92%	€ -	0.00%	€ 67,976	10.17%	€ 63,394.00	11.22%
Mould (find exteral cost)	€ 15,080	3%	€ 12,760	2.34%	€ 1,392	0.21%	€ 2,320	0.35%	€ 7,888.00	1.44%
Material (based om calculations and 15% waste)	€ 78,116	15%	€ 53,791	9.84%	€ 104,250	15.60%	€ 91,000	13.62%	€ 81,789.20	13.49%
scrap material cost (15%)	€ 10,189	2%	€ 6,886	1.26%		0.00%	€ 11,810	1.77%	€ 9,628.37	1.24%
Cure	€ 1,856	0%	€ 1,856	0.34%	€ 1,856	0.28%	€ 1,856	0.28%	€ 1,856.00	0.31%
Assembly composites	€ 18,096	3%	€ 20,880	3.82%	€ 18,096	2.71%	€ 27,840	4.17%	€ 21,228.00	3.54%
Work preperation	€ 14,511	3%	€ 12,760	2.34%	€ 17,400	2.60%	€ 11,600	1.74%	€ 14,067.75	2.36%
Cutting		0%	€ 12,760	2.34%	€ -	0.00%	€ 5,800	0.87%	€ 6,186.67	0.80%
Conservation	€ 40,020	8%	€ 60,320	11.04%	€ 32,654	4.89%	€ 40,020	5.99%	€ 43,253.50	7.39%
Quality improvement work		0%		0.00%	€ 4,500	0.67%		0.00%	€ 4,500.00	0.17%
Mandrel		0%		0.00%		0.00%		0.00%		0.00%
--> Tube		0%	€ 28,500	5.22%		0.00%		0.00%	€ 28,500.00	1.30%
Boom		0%		0.00%		0.00%		0.00%		0.00%
Flat lamintes		0%		0.00%		0.00%		0.00%		0.00%
--> Floor		0%		0.00%	€ 2,320	0.35%		0.00%	€ 2,320.00	0.09%
--> L- Profile Connection Floor to Boom		0%		0.00%	€ 928	0.14%		0.00%	€ 928.00	0.03%
--> End Cover (trim)		0%		0.00%		0.00%		0.00%		0.00%
--> Aft Bulkead (assembly)		0%		0.00%		0.00%		0.00%		0.00%
--> Port side boom wall		0%		0.00%		0.00%		0.00%		0.00%
--> Stb side boom wall		0%		0.00%		0.00%		0.00%		0.00%
--> Bulkheads		0%		0.00%		0.00%		0.00%		0.00%
Gooseneck assembly		0%		0.00%		0.00%		0.00%		0.00%
--> Cover plate		0%		0.00%	€ 9,280	1.39%		0.00%	€ 9,280.00	0.35%
Vang assembly		0%		0.00%		0.00%		0.00%		0.00%
--> Vang lug		0%	€ 2,000	0.37%		0.00%		0.00%	€ 2,000.00	0.09%
--> Tube		0%		0.00%		0.00%		0.00%		0.00%
--> Tang		0%		0.00%		0.00%		0.00%		0.00%

Table - II-6: Boom Labour Time Overview from Log



Boom Labout Time Overview										
Product number	311, RH398	% of all	308, Trip HJB	% of all	312, Baltic B175	% if all	304 Sybaris Perini Navi	% if all	Average	
Overall	6883		5285		5888		6237		6073.25	
Total Composite	2512	36.50%	2240	42.38%	2855	48.49%	3482	55.83%	2772	45.8%
Composite (Mal, cutting, lamiante, cure)	1700	24.70%	1500	28.38%		0.00%	1172	18.79%	1457	18.0%
Labour cost composites		0.00%		0.00%		0.00%		0.00%		0.0%
Mould (find exteral cost)	260	3.78%	220	4.16%		0.00%	40	0.64%	173	2.9%
Material (based om calculations and 15% waste)		0.00%		0.00%		0.00%		0.00%		0.0%
scrap material cost (15%)		0.00%		0.00%		0.00%		0.00%		0.0%
Cure	32	0.46%	32	0.61%		0.00%	32	0.51%	32	0.4%
Assembly composites	312	4.53%	360	6.81%		0.00%	480	7.70%	384	4.8%
Work preperation	250	3.63%	220	4.16%	227	3.86%	300	4.81%	249	4.1%
Cutting	0	0.00%	220	4.16%		0.00%	100	1.60%	107	1.4%
Conservation	690	10.02%	1040	19.68%	563	9.56%	690	11.06%	746	12.6%
Quality improvement work		0.00%		0.00%		0.00%		0.00%		0.0%
Mandrel		0.00%		0.00%		0.00%		0.00%		0.0%
--> Tube		0.00%		0.00%		0.00%		0.00%		0.0%
Boom		0.00%		0.00%		0.00%		0.00%		0.0%
Flat lamintes		0.00%		0.00%		0.00%		0.00%		0.0%
--> Floor attach floore v	100	1.45%		0.00%	40	0.68%	60	0.96%	67	0.8%
--> L- Profile Connection Floor to Bo	16	0.23%		0.00%	16	0.27%	60	0.96%	31	0.4%
--> End Cover (trim)		0.00%		0.00%		0.00%	476	7.63%	476	1.9%
--> Aft Bulkead (assembly)		0.00%		0.00%		0.00%		0.00%		0.0%
--> Port side boom wall		0.00%		0.00%		0.00%		0.00%		0.0%
--> Stb side boom wall		0.00%		0.00%		0.00%		0.00%		0.0%
--> Bulkheads		0.00%		0.00%		0.00%	120	1.92%	120	0.5%
Gooseneck assembly		0.00%		0.00%		0.00%	120	1.92%	120	0.5%
--> cover plate		0.00%		0.00%	120	2.04%		0.00%	120	0.5%
Vang assembly		0.00%		0.00%		0.00%		0.00%		0.0%
--> vang lug	120	1.74%		0.00%		0.00%	60	0.96%	90	0.7%
--> tube		0.00%		0.00%		0.00%		0.00%		0.0%
--> Tang		0.00%		0.00%		0.00%		0.00%		0.0%

APPENDIX III- MULTI-CRITERIAL ANALYSIS

Most of the decision making throughout this project has been performed by first determining the most important criteria that need to be considered. The criteria have been gathered through interviews with experts of the aerospace composite industry. These are: Joachim de Kijlk from the Netherlands Aerospace Center (NLR), Tahira Ahmed from Airborne Composites and Researcher Rik Tonnaer from the TU Delft Aerospace faculty. These criteria have also been discussed with members of the composite department at Rondal BV to ensure that the company's interest is reflected in the decision making.

Once the main criteria have been identified the concordance technique has been applied to obtain an understanding of the dominance of one option to the other. It compares the individual options to one another without directly requiring specific details of each option or any ranking of the criteria. The technique in this appendix are based on the description by Rogers and Duffer in Chapter 14 of their book (2012).

III.1.1 Choosing an automation method

The first concordance analysis is performed to determine which of the automation system is the most dominant based on the given criteria and hence the most feasible for this project.

The criteria concluded for the first multi criterial analysis are given in the following table.

Table - III-1: Criteria for Choosing an Automation Method

Ref. #	Criteria
1	Ability to implement with current process
2	Reduction of labour spent on the product
3	Specialist knowledge required
4	Lead-time saving
5	Number of products
6	Investment cost
7	Facility requirements (area)
8	Running cost
9	Scrap material
10	State of development of automated system

The comparison between options takes place on a pairwise basis, comparing ATL, AFP and P&P. It is done for every of the ten criteria. Looking at the formula below, if criteria a is at least as good as b in the given category *j* it receives a sore of 1 otherwise 0.

$$C_i(a, b) = 1 \ or \ 0 \text{ where j= 1, 10}$$

Table - III-2: Concordance Multicriterial Analysis to Choose an Automation System

Concordance score		Description	Concordance score	
Batch 1				
C1(TL,FP)	0	Both techniques require equivalent amount of product and process redesign.	C1(FP,TL)	0
C2(TL,FP)	1	Due to the smaller material strips of AFP more information needs to be inputted into the robot to prepare the program for AFP	C2(FP,TL)	0
C3(TL,FP)	1	ATL deals with simpler shapes so the specialist knowledge is also less demanding than for AFP	C3(FP,TL)	0
C4(TL,FP)	1	ATL lays wider strips, so the layup time is faster	C4(FP,TL)	0
C5(TL,FP)	0	Results from the analysis show that more parts can be produced by AFP than by ATL	C5(FP,TL)	1
C6(TL,FP)	0	Both systems have equivalent cost	C6(FP,TL)	0
C7(TL,FP)	1	Both systems have similar equipment	C7(FP,TL)	1
C8(TL,FP)	1	The material cost for AFP is higher since smaller strips have to be manufactured	C8(FP,TL)	0
C9(TL,FP)	0	AFP cuts smaller material strips, less waste material is created for trimming	C9(FP,TL)	1
C10(TL,FP)	1	ATL is the older, both methods are commonly used, but ATL has been more researched	C10(FP,TL)	0
Batch 2				
C1(TL,PP)	0	No change in process or design needed for P&P	C1(PP,TL)	1
C2(TL,PP)	0	Programming of the P&P takes much less time	C2(PP,TL)	1
C3(TL,PP)	0	Programming of P&P is less complex	C3(PP,TL)	1
C4(TL,PP)	0	P&P option is faster (view calculation below) *	C4(PP,TL)	1
C5(TL,PP)	0	Result from the quantitative analysis show that P&P can produce more parts	C5(PP,TL)	1
C6(TL,PP)	0	P&P is set to cost 30% less then ATL	C6(PP,TL)	1
C7(TL,PP)	1	P&P requires more surface area for the equipment	C7(PP,TL)	0
C8(TL,PP)	1	Overall running costs are less on ATL, due to less apparatus used and scrap is better controlled.	C8(PP,TL)	0
C9(TL,PP)	1	P&P cuts out parts from plates, AFP only trims	C9(PP,TL)	0
C10(TL,PP)	1	ATL is much more developed than P&P	C10(PP,TL)	0
Batch 3				
C1(FP,PP)	0	No change in process or design needed for P&P	C1(PP,FP)	1
C2(FP,PP)	0	Programming of the P&P takes much less time	C2(PP,FP)	1
C3(FP,PP)	0	Programming of P&P is less complex	C3(PP,FP)	1
C4(FP,PP)	0	P&P is faster than ATL, so also faster than AFP	C4(PP,FP)	1
C5(FP,PP)	0	Result from the quantitative analysis show that P&P can produce more parts	C5(PP,FP)	1
C6(FP,PP)	0	P&P is set to cost 30% less then AFP	C6(PP,FP)	1
C7(FP,PP)	1	P&P requires much more surface area (cutter, buffer, de-bulking and stacking)	C7(PP,FP)	0
C8(FP,PP)	1	Overall running costs are less on AFP, due to less apparatus used and scrap is better controlled.	C8(PP,FP)	0
C9(FP,PP)	1	P&P cuts out parts from plates, AFP only trims	C9(PP,FP)	0
C10(FP,PP)	1	AFP is much more developed than P&P	C10(PP,FP)	0

* Mast Head Side plate (Balstic 175)

Material weight	600	g/m^2
Number of layers	42	layers
Area	3,24	m^2
Weight per layer	1,94	kg/ layer
Weight	81,6	kg

Capacity of ATL

			Time per layer		**Time per part**	
Min Rate	8,6	kg/h	13,6	min	9,5	h
Max rate	13	kg/h	9,0	min	6,3	h

Capacity of the P&P option

Plies to lay down	279	Assuming that the same material as currently is used.		
Cutting	6	s/ply	0,47	h/ set for all plies
P&P	6	s/ply	0,47	h/ set for all plies
Buffer	6	s/ply	0,47	h/ set for all plies
Film removal	8	s/ply	0,62	h/ set for all plies
Total time per part			2,02	h

To be able to compare each of these criteria according to their importance they are given a score of 1 or 2. A high core of 2 is given to each criterion that has direct impact onto the implementation of the system whilst 1 score is given to criteria that is more of a long-term requirement. It has to be noted that the judgment upon some criteria has more certainty than on others. The criteria 1,5,7,9 and 10 have more factual support though literature and the nature of the automation system than all other criteria that are chosen on a more subjective basis.

Table - III-3: Concordance Ranking of Criteria for the Automation Options

Ref. #	Criteria	Score	Normalized weight
1	Ability to implement with current process	2	0,118
2	Reduction of labour spent on the product	2	0,118
3	Specialist knowledge required	2	0,118
4	Lead-time saving	2	0,118
5	Number of products	2	0,118
6	Investment cost	2	0,118
7	Facility requirements (area)	2	0,118
8	Running cost	1	0,059
9	Scrap material	1	0,059
10	State of development of automated system	1	0,059

Each of the normalized weight scores are multiplies by the concordance score and that has previously been determined and summed up in a concordance matrix. A sample calculation comparing the ATL to the AFP is as follows:

Normalized wt(Criterion 1)* Score + Normalized wt(Criterion 2)* Score+ Normalized wt(Criterion 3)* Score + Normalized wt(Criterion 4)* Score+ Normalized wt(Criterion 5)* Score + Normalized wt(Criterion 6)* Score+ Normalized wt(Criterion 7)* Score + Normalized wt(Criterion 8)* Score+ Normalized wt(Criterion 9)* Score + Normalized wt(Criterion 10)* Score= concordance row and column dominance indicators

$$0.118*0+0.118*1+0.118*1+0.118*1+0.118*0+0.118*0+0.118*1+0.059*1+0.059*0+0.059*1 = 0.59$$

Table - III-4:Dominance Matrix for the Automation Options

	ATL	AFP	P&P
ATL	-	0,59	0,29
AFP	0,29	-	0,29
P&P	0,71	0,71	-

The sum of the rows indicates the most dominant option, whilst the value summed up on the columns indicate by how other options are better than the given method. So, the higher the row sore and the lower the column score the better the option. Subtracting the column score from the row score therefore should leave at least one option positive. This is indeed the case as can be seen below with the score of the P&P option.

Table - III-5: Concordance Analysis Results for the Automation Options

Options	Row score - Column score
ATL	-0,12
AFP	-0,71
P&P	0,82

The sensitivity of this result is analysed by assuming that all subjective criteria are wrong. Hence, if all the comparative dominance scores for the criteria 2,3,4,6 and 8 are interchanged the concordance analysis results are changed to: -0.118, 0.354 and 0.059 for the ATL, AFP and P&P respectively. This result means that if all the subjective criteria estimations are wrong it could impact the final choice of automation.

III.1.2 Choosing a product type for the simulation

The second concordance analysis is performed to determine which of the product types is the most feasible to demonstrate the performance of the automation option.

This multi-criterial analysis applies the same method as just described.

Table - III-6:Concordance Ranking of Criteria for the Products

Ref. #	Criteria	Score	Normalized weight
1	Performing each of the investigated steps	2	0,22
2	Repeats the steps in large frequency with coordination/orientation alterations	1	0,11
3	Large number of part type in production	2	0,22
4	Data availability for comparison	2	0,22
5	Cost impact of part	1	0,11
6	Potential of full automation of part	1	0,11

The concordance scores are derived with the following reasoning.

Table - III-7:Dominance Matrix for the Products

Concordance score		**Description**	**Concordance score**	
		Batch 1		
C1(T1,T2)	1	Type 1 & 2 will both provide opportunity to show the shaping step	C1(T2,T1)	1
C2(T1,T2)	0	Type 2 has two moulds so overall steps will be repeated more often	C2(T2,T1)	1
C3(T1,T2)	1	There are more product Type 1 made than Type 2	C3(T2,T1)	0
C4(T1,T2)	0	The Spreader manufacture has been observed first hand so more detailed information is available	C4(T2,T1)	1
C5(T1,T2)	0	It is known that the spreader manufacture has a greater impact than the plates due to the man hours but it is not known how much impact Type 1 products have	C5(T2,T1)	1
C6(T1,T2)	1	At current state of automation Type 1 products are closest to be fully automated	C6(T2,T1)	0
		Batch 2		
C1(T2,T3)	1	Type 2 has the extra shaping and the assembly step to perform	C1(T3,T2)	0
C2(T2,T3)	0	Type 3 products include more plies, so there is more repeatability	C2(T3,T2)	1
C3(T2,T3)	0	There are more type 3 in production than Type 2	C3(T3,T2)	1
C4(T2,T3)	0	There is more detailed data available on the plates (T3)	C4(T3,T2)	1
C5(T2,T3)	1	Hollow parts such as spreader add up to 16% of the man hours and composite cost for the mast which is more than the 3.5% of plates	C5(T3,T2)	0
C6(T2,T3)	1	Currently, Type 3 products are closer to be fully automated	C6(T3,T2)	0
		Batch 3		
C1(T1,T3)	1	Type 1 provides the opportunity to show the shaping step	C1(T3,T1)	0
C2(T1,T3)	0	Type 3 products repeat steps more since they consist of more plies	C2(T3,T1)	1
C3(T1,T3)	0	Type 3 has more numerous type of products in production	C3(T3,T1)	1
C4(T1,T3)	0	There is much more data available on products Type 3	C4(T3,T1)	1
C5(T1,T3)	0	No information is known about the cost impact of Type 1	C5(T3,T1)	1
C6(T1,T3)	0	At current state of automation Type 3 products are closest to be fully automated	C6(T3,T1)	1

Resulting in a concordance matrix of the following.

Table - III-8: Dominance Matrix for Products

	T1	**T2**	**T3**
T1	-	0,56	0,22
T2	0,67	-	0,33
T3	0,78	0,67	-

From this it can be deducted that Type 3 is the best product to focus the simulation of the automation upon.

Table - III-9:Concordance Analysis Results for Products

Options	**Row score - Column score**
T1	-0,7
T2	-0,2
T3	0,9

APPENDIX IV- FILM REMOVAL TOOL

This appendix is a detailed report on the reasoning, making and use of the protective film removal tool. It elaborates on the testing performed during the design process as well the electronics on which the tools mechanisms are based. It also acknowledges potential areas for future research required so that this tool can be placed into a real production environment.

IV.1.1 Background

The protective film removal methods have been considered in various ways. Whilst smaller projects have been worked by for instance a collaboration of Airborne Composites and a Delft Hochschool (Vijverberg, 2017) to remove protective film (Figure - IV-2). Linköping University has published a paper demonstrating a working tool that can be applied in a pick and place (P&P) robot cell for backing paper removal as seen in Figure - IV-1 (Björnsson, Lindbäck, Eklund, & Jonsson, 2015) after having completed research on backing paper detachment methods together with s paper-prepreg separation station (Björnsson, Lindback, & Johansen, 2013).

Rondal does not make use of paperbacks but instead uses polibacks. This helps the manual layup of the plies on double curved surfaces, as they are often found in Rondal products. Paperbacks are too rigid and would not make it more difficult to place the plies properly.

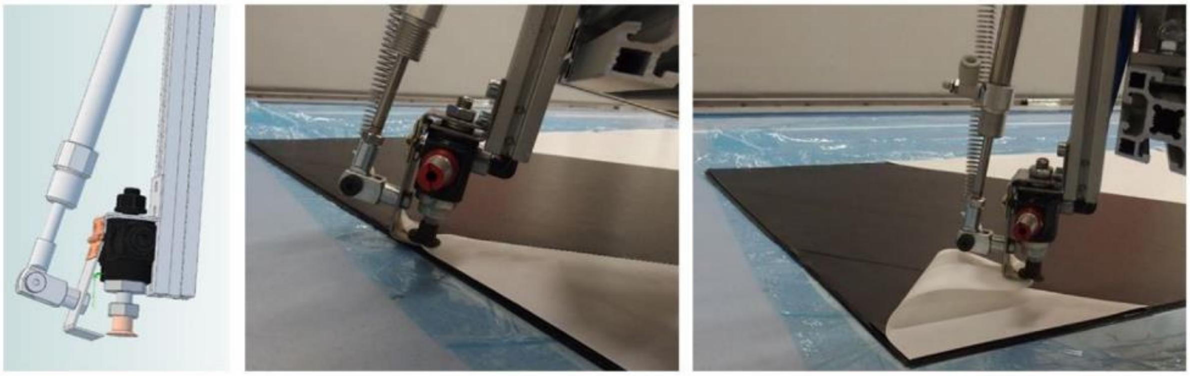


Figure - IV-1: Film Removal Tool (Björnsson, et al., 2015)

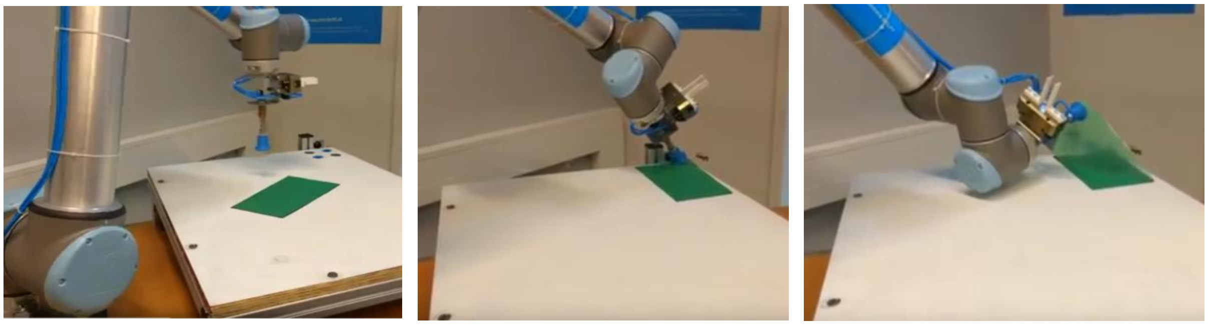


Figure - IV-2: Film Removal Tool (Vijverberg, 2017)

The Björnsson provides more detailed information about their removal process. It can be split into three parts: the initiation stage, the continued peeling stage and the quality checking system.

The initiation stage very much dependent upon the kind of prepreg and the type of protective material used. What might work with one type of prepreg, might not necessarily work with the other, due to the difference in tack and adaptation to the environmental conditions. The continued peeling stage has been successfully tested using a pinch tool to grip the protective layer whilst it is pulled off. Finally, the inspection systems is an important stage in the final process, ensuring the required quality of laminate is achieve. It verifies that no protective film ends up in the laminate, preventing a proper bond from being formed.

Initiation stage

Different methods of performed testing on similar material are:

1. Spray the material with liquid coolant (either nitrogen or chemical coolant) to reduce the tack of the prepreg locally. In that area, the suction cup will be able to detach the protective layer more easily.
2. Inject air under the protective layer to provide an easier initialization of the vacuum suction.
3. Mechanically bend a corner to cause the protective layer to be partially detached from the prepreg and using a suction grip to remove the protection.

It has to be noted that the protective layer of the prepreg used in these tests was paper based, which is thicker and more rigid than the plastic film, hence also easier to remove. Additionally, concerning the UD material the more rigid option also prevents splitting which often occurs due to its anisotropic nature. (Björnsson, Lindbäck, Eklund, & Jonsson, 2015). As a compensation, the UD is covered on both sides when using the thin film, thereby also requiring an extra step in the removal process.

Continued peeling stage

The peeling action occurs due to the movement of the robot. However, it has to be ensured that during this action the protective layer does not slip off the suction cup. This is achieved using a simple pinching mechanism. Björnsson designed the tool to be attached to the robot head, so that the peeling process is performed by lifting the protection off the stationary ply. In another design suggestion of his tool is the stationary entity in the cell. The robot head uses the tool to help detach the ply by passing over it. The set-up can be seen in Figure - IV-3.

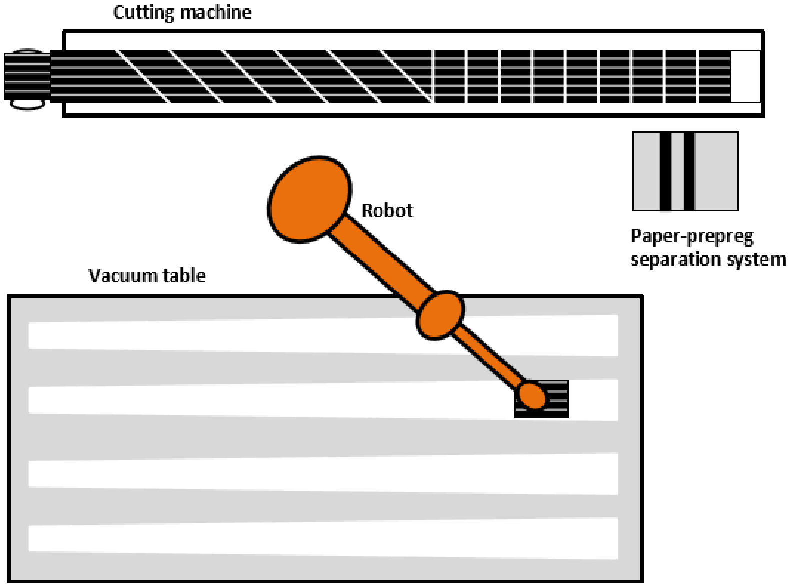


Figure - IV-3: Layout of Björnsons Conceptual Test Cell

Inspection system

Inspection can be done through sampling or 100% inspection. Dependent on the type of products, some risk acceptance is given to be able to apply sampling inspection. In the application on this tool, sampling is not recommended since all ties are combined into one laminate. Even one improperly peeled ply can cause the laminate to lose its material properties.

Options such as ultrasonic inspection are also possible however these are restricted in the area covered by one inspection as well as the location at which the, to be inspected object, has to be placed. It is mainly applied for products with constant dimensions. The most flexible option for the inspection of the film removal is a visual inspection (Groover M. P., 2008). These involve image acquisition, digitization, processing and interpretation stage. Since the protective films are of different colour to either the carbon or the glass prepreg, they are able to be distinguished upon an image given the correct lighting. An alternative inspection method that has been suggested by Björnsson (2013) involves the weighing of the peeled material to analyse if all material is still present.

This inspection will not be included into the design of the tool since visual inspection systems are common in industry in combination with automated manufacture. As such it I therefore not anything novel which is why it is considered out of the scope of this project.

IV.1.2 Design Process

Due to the R&D nature of this tool the design process largely involved testing and adaptions of the design to be able to meet all its intended design requirements. This section describes the different stages undergone throughout the building process.

Requirement

With regards to the purpose that this tool should achieve to successfully be implement into the final automation cell, the design requirements are as follows:

- The tool needs to be a separate, stand-alone unit, which is not controlled through the robot, but rather used by it to help perform achieve the end task. That way it is independent of the type of robot the final automation process will be choosing and does not need to be interconnected. Consequently, it will require to sense the approach of plies and trigger its own working mechanism.
- The tool needs to be able to achieve the initialization and peeling operation without human input requirements.
- The tool should minimize the contact to the plies to reduce damage, contamination to the prepreg or any other kind of action that can impact the material properties of the final laminate.

In later stages, a more industrially applicable tool will also have to:

- The tool needs to be a design that can handle a large verity of ply sizes, yet be small enough to be able to be placed within the robot cell.
- The tool need to be sturdy enough to handle forces acting upon it at full operational speed
- The tool needs to have a safely system in place that at least stops the process if the peel has not been performed successfully.

Comparison to excising designs

This part analysis the suitability of different aspects of existing designs to the design requirements of this tool and hence establishes weather some of these design aspects are to be taken over into the design of this tool. It should be noted that all analysis on the Airborne project is based on information of their automation engineer Casper Hofstede and the video provided from them.

Based on this most of the design ideas for the initial concept have been developed.

Table- IV-1:Comparison of Film Removal Tool Designs

Design aspects	**Linköping University (2013 solution)**	**Linköping University (2015 solution)**	**Airborne Composites**
Independence of robot	+ Picked ply is simply moved over the separator station	- requires robot arm to carry the tool over the prepreg surface	- requires robot arm imitate human peeling movement
Manage protective film	- unknown, described with use of more rigid backing paper	- unknown, described with use of more rigid backing paper	+ has been proven to work on packing film
Impact on prepreg	- paper removal method involves air injection and mechanical bending which causes direct contact with the material	+ no direct contact with prepreg required, hence no damage	- suction and clamping of ply show deformation of ply; contamination of surface possible
Both sided removal	- backing paper is usually only placed on one side of the prepreg, hence additional step required	- backing paper is usually only placed on one side of the prepreg, hence additional step required	+ Is able to handle the removal of the bottom and the top film in one process cycle
Process speed	- unknown	- unknown, however during the clamping of the paper the robot needs to halt. Additionally, the robot head is required to be changed to adapt for the gripping tool, or a second robot arm is required.	- slow since the attachment to the film is based on the suction cup only
Integration into robot cell	+ the tool is small enough to be placed in the robot cell	+ the process can be performed on the cutting table - a changeover of tool heads or a second robot arm is required	- requires an extra table within the robot cell
Handling large size variation	+ any ply size can be handled, as long as it is in reach of the robot	+ any ply size can be handled, as long as it is in reach of the robot	- restricted to plies the size of the table. Wider plies might require a larger downwards rotary motion of the robot which might result in a collision of the robot joint and the table surface

Primary Design Idea

As a deduction from the previous me previous section, the initial idea has been based on a combination of the two Björnsson tools. Whilst the location location within the cell as well as the orienation and general workflow of the tool is to imitate the 2013 tool the mechnical set-up is based on the 2015 tool. Yet a spot cooler has been added to realize the initialization stage. The entire design runs all entities pneumatically and will be built from an aluminium profile to which parts can early be adjusted. The schematics on how the mechanism are to be interconnected are shown in

The individual components of this initial design are as follows:

- A vacuum pad controlled by a solenoid valve. Test performed on different types of suction cups can be found
- A pneumatic cylinder pushing on a hinge to clamp the foil into place, also being controlled by a solenoid valve
- A spot cooler, a vertex tube that uses compressed air to split the air flow into a hot and cold airflow, that cools the surface for the initial detachment step (capable of cooling down to -34 degrees of its inlet temperature). The air stream can also be used to ease the separation between the two surfaces.
- The activation of the entire apparatus is to be performed by a IR distance sensor that activates the individual actuators when a ply is approached.

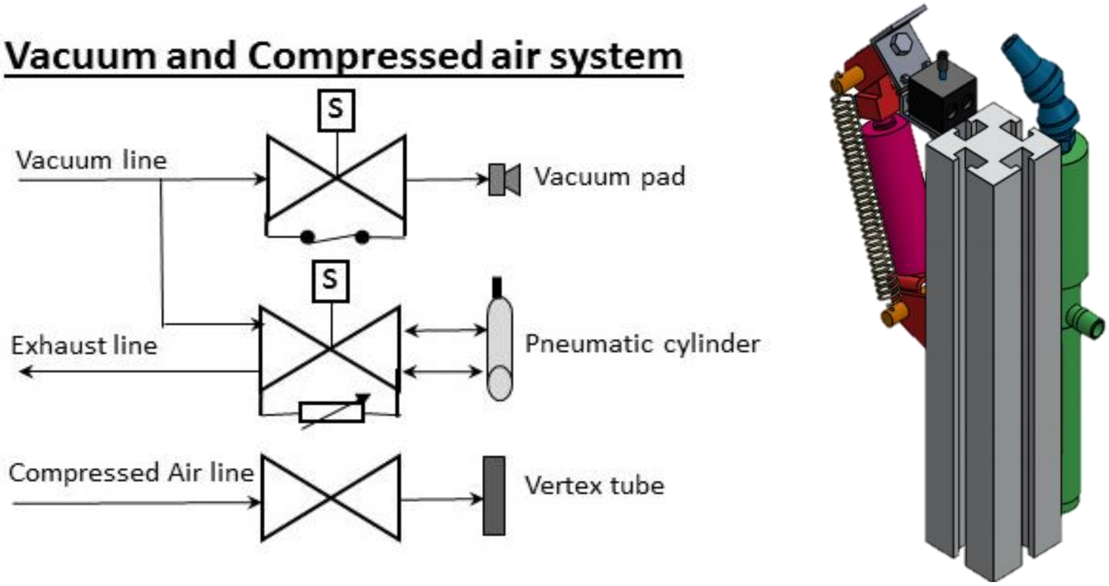


Figure - IV-4: Primary Design Idea

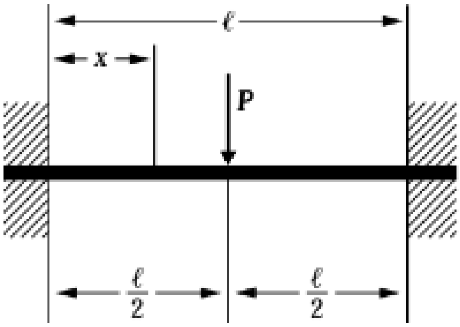
Design Calculations

The design calculations are mainly related to bending and strength calculations of materials for the prototype. Brief calculations related to the cooling rates are given in the design alteration section where the cooling methods are discussed. To be able to make appropriate calculations related to the Adhesive force the clamp needs to overcome the material tests results need to be considered.

The full report in which all the different test results can be found is given in Appendix IV. These show that full size plies as they will be handled by the Robot with width up to 1.5m will have a maximum adhesive force of 337N between the surfaces. Width of plies that size is seldom. Most plies are approximately 500mm width, therefore an adhesion force of 10kg is set as a design force.

MDF Shelf

The calculations are done for a beam fixed at both ends with a concentrated load at the centre. This is not necessarily the case since the objects will be distributed over the length of the shelf. Yet doing the calculations like this will ensure a sufficiently strong shelf without exactly knowing yet where all the apparatuses is located.



$$\Delta_{max} = \frac{Pl^3}{192EI}; M_{max} = \frac{Pl}{8}; I = \frac{bh^3}{12}; \ \sigma_{max} = \frac{M_{max}}{I}$$

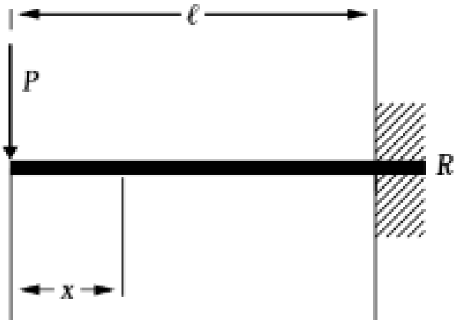
Given:
Weight (valves, casing and own weight): 2.21kg
Height: 6mm, Width: 300mm; Length: 690mm
Assuming properties of MDF:
Elastic modulus: 3500N/mm^2
Tensile strength: 80 N/mm^2

Figure - IV-5: Bending Sketch of MDF Shelf

Calculated:
Second moment of Area of I= 5400 mm^4
Deflection of $\Delta_{max} = 2\ mm$
Bending Moment of $M_{max} = 1872\ Nm$
Stress $\sigma_{max} = 0.346 N/mm^2$
Safety factor of 231

Steel Clamp

The material available to cut the material out off is 1mm thick. It needs to be a ferrous material since it has to be attracted by the magnetic field created by the electromagnet.



$$\Delta_{max} = \frac{Pl^3}{3EI}; M_{max} = Pl; I = \frac{bh^3}{12}; \ \sigma_{max} = \frac{M_{max}}{I}$$

Given:
Withstand force of sample with width 100mm: 5N
Length: 300 mm, Width: 35 mm, Thickness: 0.8 mm

Assuming properties of Steel:
Elastic modulus: 206000N/mm^2
Tensile strength: 285 N/mm^2

Figure - IV-6: Bending Sketch of Steel Clamp

Calculated:
Second moment of Area of I= 2.9 mm^4
Deflection of $\Delta_{max} = 8.7\ mm$
Bending Moment of $M_{max} = 717 Nm$
Stress $\sigma_{max} = 245\ N/mm^2$
Safety factor of 1.15.

If a thicker plate is used it can easily be adapted to a higher force range, however for the purpose of this test it was not deemed necessary.

Aluminium Guidrail

The material available for the laser cutting of the guiderail is 2mm thick. It is designed so that it will force the clamp down onto the surface of the suction cup bed. Therefore, the conditions are set to a uniformly distributed load acting over the surface of the clamp onto the rail. The smallest cross section has been calculated for failure which is in the corner of the arm of the rail.

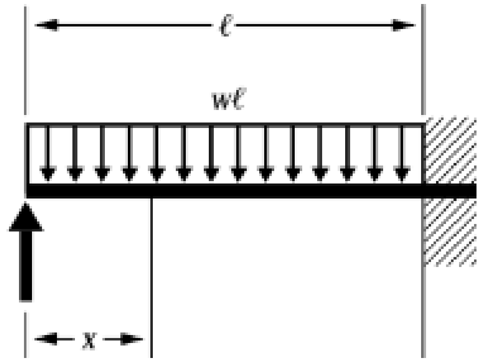


Figure - IV-7: Bending Sketch of Aluminum Guidrail

$$\Delta_{max}=\frac{wl^4}{185EI}; M_{max}=\frac{wl^2}{8}; I=\frac{bh^3}{12}; \sigma_{max}=\frac{M_{max}}{I}$$

Given:
Withstand force of sample with width 100mm: 5N
Length: 70 mm, Width: 2 mm (cross section), Thickness: 6 mm (cross section)

Assuming properties of Steel:
Calculated:
Elastic modulus: 69000N/mm^2
Second moment of Area of I= 36 mm^4
Tensile strength: 110 N/mm^2
Deflection of $\Delta_{max} = 0.25\ mm$
Bending Moment of $M_{max} = 127\ Nm$
Stress $\sigma_{max} = 3.5E - 7\ N/mm^2$
Safety factor of 1E8.

Design alterations

Throughout the design process design challenges had to be solved to be able to resolve issues to create a working tool. The alterations made to the design throughout this process are explained here following.

Clamp

The vertical clamp rotation has been replaced by a horizontally approaching of a clamp plate. This alteration makes the tool less dependent upon the distance x between the film and the prepreg (Figure - IV-9). Test have shown that this distance varies dependent upon the prepreg. Now, the required distance only needs to be the width of the plate, instead of the radius created by the hinge plate.

The downwards force of the clamp cannot be performed by the servo alone. The addition of an electro magnet will achieve that downwards force. To prevent the electromotor to have to resist the upward force on its own, a guide rail is added which forces the plate into the clamping position.

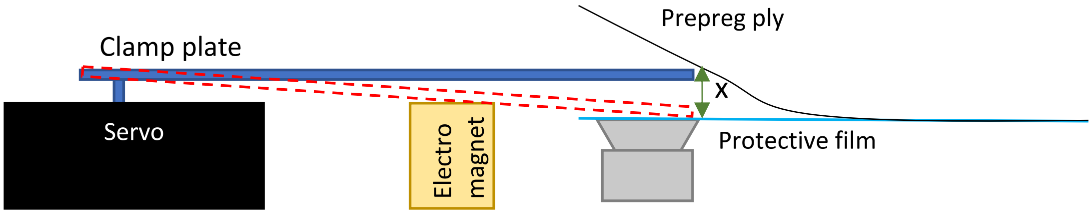


Figure - IV-9: Clamping Mechanism

A further point that needs to be addressed is the adjustment of the clam plate. Björnsson used backing paper which is less thicker than foil the protective film dealt. It has to be taken care that no shat edges are contained within the plait that could become a danger of damage to the foil. A cut could causing a tear along the entire length of the ply and result in an incomplete peel.

The last concern regarding the clamp is that the surface fo the steel is smooth which provides no grip for the film during the peeling action. It has to be ensured that this grip does not damage the foil but merely increaces the fiction between the surfaces. This could be chieved by adding a hard rubber pad or some velcro to the bottom tip of the clamp.

Orientation

The decision of transforming the tool from a vertically to a horizontally oriented tool was based on the fact that, all the actuators could not be allied with sufficient distances if only one vertical profile is used. Further, the horizontal orientation also provides stability to the tool structure. The full operating speed of the robot lies at 2m/s, hence the structure should be able to withstand the accelerations of the tool when clamping the film. This however, does not mean that the entire film removal operation will be performed at these high speeds.

Clamp drive

The pneumatic cylinder controlling the has been replaced by a servo motor. The disadvantage of the pneumatic cylinder is that it has less accurate control. This is not an issue with the initial design, since it is only used to push the plate that is attached to the hinge. However, the new orientation of the clamp requires accuracy in approach, thereby calling for a servo motor is more appropriate. Adding a servo is not an issue since electronics have to be set-up for the solenoid valves anyway and the Gertboard has sufficient connectors to accommodate the servo.

Cooling

The cooling stage is the most important step of the process, since without sufficient cooling the initialization stage cannot be started. Unfortunately, it also proved itself to be the most challenging to achieve. In the early stages of the design tests have been performed with a chemical cool spray (Cold Spray PRF 101, cooling down to -55°C) to see if the cooling concept is viable. The tested showed indeed success and from it a cooling temperature of -20 degrees was recorded as surface temperature (for more details view Appendix I). This approach is not desirable to be integrated into production since it is reliant on the fluid cans that need to continuously be replaced. This is not only expensive due to the chemical cans that need to be purchased but also labour intensive to continuously replace the cans. This then defeats the point of the tool to operate autonomously. The following cooling alternatives have been considered and tested.

Adjustable spot cooler

The spot cooler is a vortex tube that is powered by compressed air. It splits the air into a hot and an extreme cold air stream. It is able to create a temperature drop of -34 °C to the compressed air inlet temperature. Test with the equipment have shown that the temperature at exit of the tube is indeed as specified, however the airflow at these low temperatures is so weak that its cannot propel the air far towards the target. Instead most the heat transfer into the air is so fast that the plies can only be cooled down to 2 °C surface temperature. As the Table- IV-2 show this cooling also takes extremely long hence, it is unsuitable for the process since removing the film; by hand is significantly faster only between 3-5s.

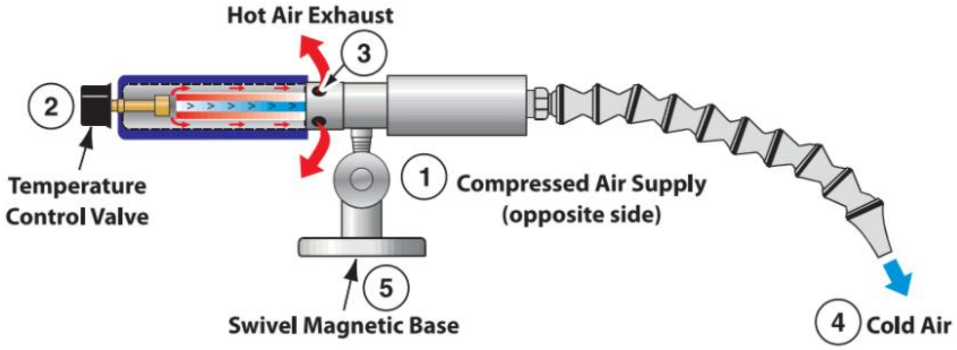


Figure - IV-10: Adjustable Sport Cooler

Yet, the air blow of the spot cooler at less cold will still be used to help detach the film from the prepreg during the pealing process. Test that support this have been performed and can be found in Appendix IV.

The tests with the spot cooler that have been summarized in Table- IV-2. They have been performed at a distance 5 cm to the ply and the temperature measurements have been taken with a laser thermometer.

Table- IV-2: Cooling Tests

Initial surface temperature (°C)	*Cooling time (precooling of apparatus 20 min) (s)*	*Final surface temperature (°C)*
22	10	5
22	10	8
22	10	5
24	20	6
23	20	4
23	20	9
22	30	5
22	30	5
22	30	7
26	40	6
24	40	7
24	40	5
25	80	3
24	80	5
25	80	2

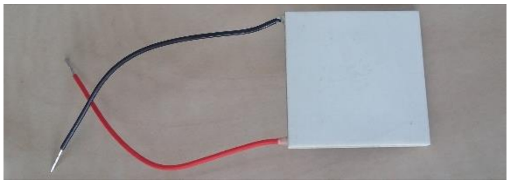


Figure - IV-11: Peltier Element

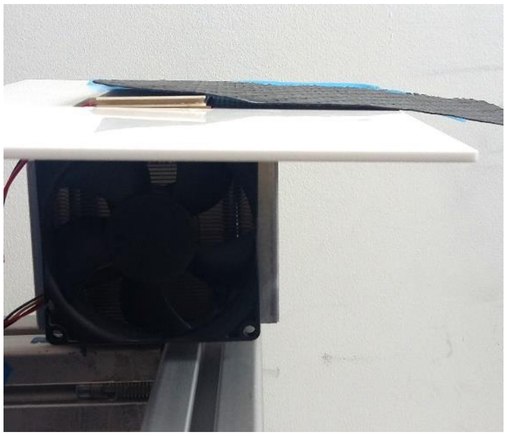


Figure - IV-12: Peltier Element with Fan

Peltier Element

The Peltier element is commonly used in watercoolers or camping fridges. It is based on the thermoelectric cooling effect which uses DC current cause a heat flow between two plates. Heating one side and cooling the other. (Brown, Dirks, Fernandez, & Stout, 2010) It is extremely important to properly extract the heat otherwise the Peltier elements falls apart due to the self-induced heat. Thereby, it has to be operated with a fan that can remove the heat from the immediate vicinities of the heat surface. Additionally, due to the fact that heat rises, a boundary has to be created surrounding the cold side to insulate it from the heat. As seen from Figure - IV-11: Peltier Element this has been created with an acrylic plate. The advantage of this approach is that it cools by conduction which should be much is meant to improve the cooling speed. Figure 20 shows the performance of the 79W heat exchange (15V, 8.5A) Peltier element is theoretically able to create temperature difference of 75°C, with a Th of 50 degrees this was calculated to be sufficient for the surface cooling of the prepreg.

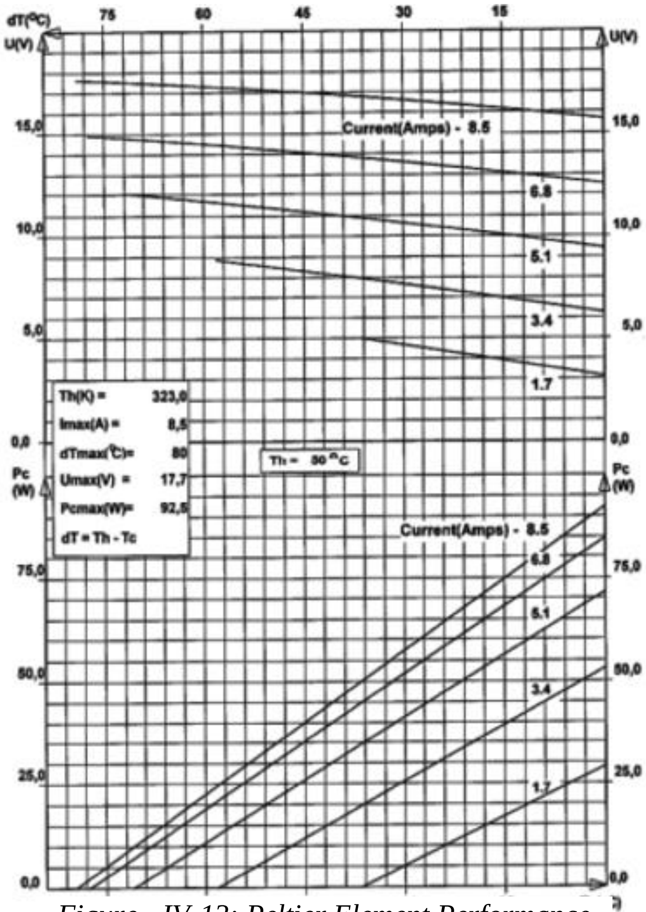
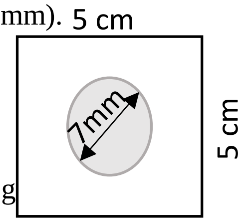


Figure - IV-13: Peltier Element Performance

The heat calculations show that theoretically the cooling of the carbon surface to -20 °C should take approximately 3.5s.

Assuming that: an area of 25cm² is to be cooled surrounding the carbon ply of a thickness of 1mm (usually prepreg ply thicknesses used at Rondal vary between 0.2 and 0.6mm).

Material properties:
Specific Heat: 1.13 J/g°C
Density: 1.49 g/cm³
Volume= 2.5cm³→ Mass= 3.725g



Assuming a temperature difference (dt) of 75°C (-20°C to 55°C) and max. heat transfer capacity of 92,5W, as indicated on the graph.

Mass*dt* Specific heat= 313.6 J
Watts/Joules= 3.39s

In ideal conditions, the Peltier element should be able cool the surface down to -20°C in less than 4s of contact. The presence of the film has been neglected in these rough calculations since the film is much thinner than the ply. Additionally, plastic has a lower specific heat than carbon, which means it will be cooled faster. In practice, this has however not shown to be the case. Whilst the surface temperature of the Peltier element was measured to be as low as -20 °C. The surfaces temperature of the ply surface was not able to be recoded below -15°C. These temperatures do reduce the tack, however not sufficient to cause the required self- detachment by the film from the ply.

From these two tests, it can be concluded that the temperature drop to -20°C, is not an accurate temperature aim for the detachment of the foil. Within the time of the spraying and the thermometer measurement the surface temperature must have risen again by 10 to 20°C.

Liquid Nitrogen

In further search for a solution, tests with liquid nitrogen have been performed. It was clear the temperature drop was going to be sufficient to achieve the film detachment, but the aim of these test was to find out if the extreme cooling could cause the foil to reach a state of solidity, that would cause it to become brittle and be fractured into pieces. This was shown not to be the case. On the contrary, even at temperatures recorded as slow as -120 °C the film became stiffer but always stayed flexible.

From this it can be concluded that liquid nitrogen can be used for this tool without worries to impact the peeling performance through brittle failure of the foil. More information about the detachment of foil could also be gathered; the first detachment could be observed at approximately 30°C as seen fromFigure - IV-14. This value is used with caution. Spraying liquid nitrogen onto the surface of the film is a possible solution to the cooling problem, since liquid is easy to come by and not that expensive. But, the storage is expensive and only worth wile considering if it is used in a larger quantity than it will be done for the testing of this prototype. Furthermore, the spraying of the liquid requires specially insulated and pressurized equipment mostly used in the medical sector.

Figure - IV-14: Liquid Nitrogen Test

In conclusion, it is can be said that it is a feasible solution for the end tool but should be taken further if the tool is to be implemented in actual manufacturing facilities. The proof of concept for this prototype will nevertheless be performed using the chemical spray solution. An important aspect that needs to be taken under further investigation is the moisture build up within the ply due to the shock cooling.

In general practice prepreg is left to defrost in a closed envelope for 24h after taking it out of the freezer to ensure no moisture build up within the material. This is the case because rolls of prepreg have a build-up of laminate upon them which means it requires this time to defrost all the way to the centre. The testing showed that the plies warm back up to room temperature within minutes of the cooling. Further, it has to be considered that only a very small area of the prepreg is actually going to be affected by the shock freezing. The entirety of the ply should therefore be warmed back to room temperature by the time the robot stacks the ply. Another argument for the use of liquid coolant is that the liquid is not actually in contact with the carbon fibres or the resin but only with the foil, so no contamination should occur. All these cooling liquids also evaporate within seconds of having been sprayed without, according to the manufacturers, leaving any remains. The liquid coolant solution therefore probably does not have much impact on the material properties of the prepreg. Yet this hypothesis needs to be experimentally proven through material testing before it can be applied in industrial manufacturing conditions. Such test are out of the scope of this project and would have to be performed if this prototype is taken to a further stage of development.

IV.1.3 Working of the Final Tool

This section provides a visual overview of the equipment used to make up the tool as well as its overall working principles. It also describes the electronics so that it can easily be adapted in the future for further development to be performed on it.

Physical Set-up

Some particularities that have not yet been specifically named about the set-up are for instance that a rubber adhesive surface has been glued on the bottom of the clamp to increase the friction and reduce the likelihood of the film slipping out of grip. The IR sensor is mounted low upon the frame to ensure at least 10 cm distance is left between the peeling ply and the sensor. Since that is the specification requirement for its use. The suction cup that causes the initialization if the peeling is imbedded within the acrylic plate. This has been done to ensure that the pressure is distributed over a larger area and that the clamp can smoothly slide between the ply and the film.

Figure - IV-15: Clamp Set-up

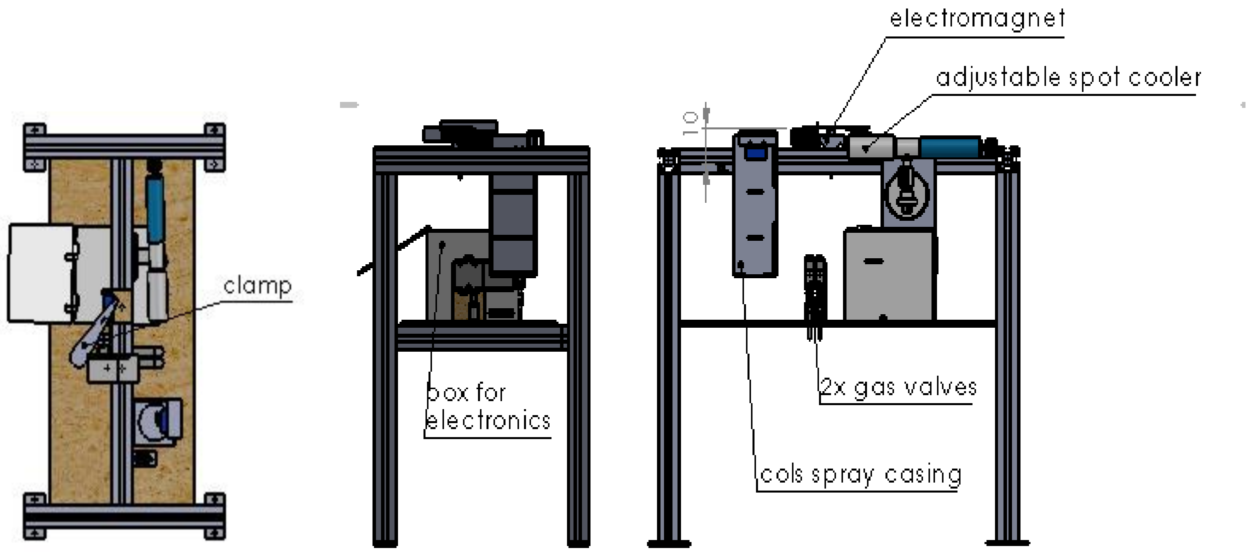


Figure - IV-16: Set-up of the Entire Tool Prototype

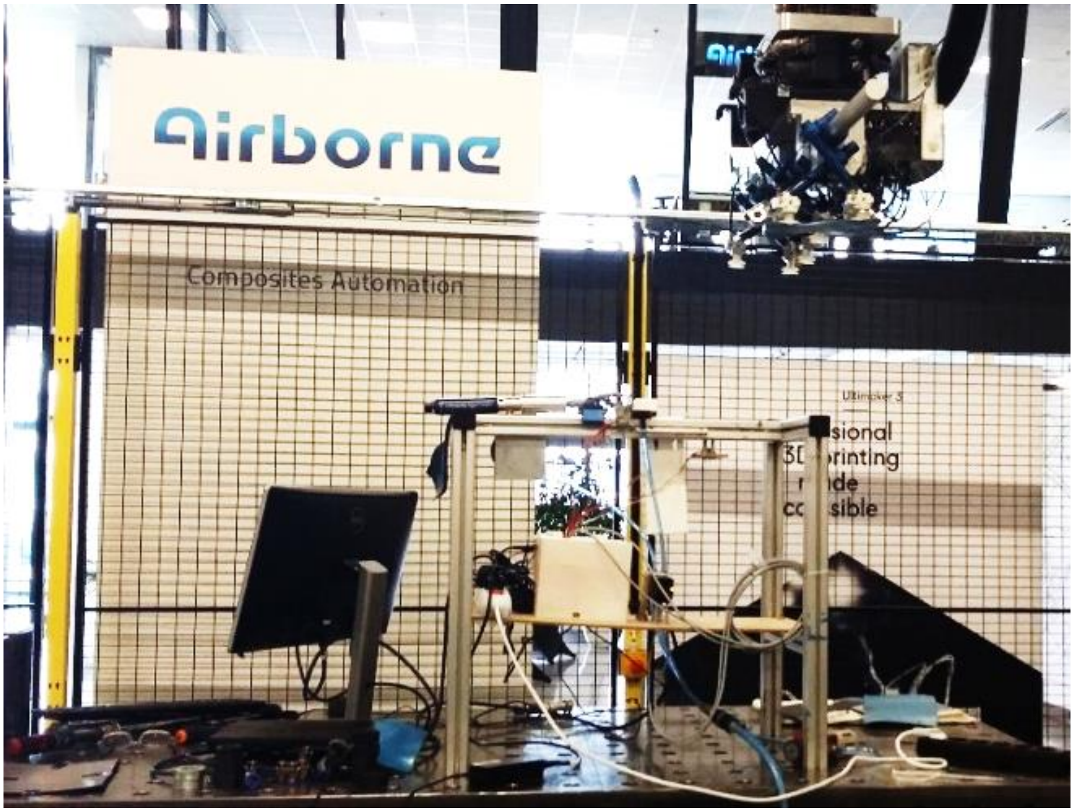


Figure - IV-17: Testing at Airborne

Actuators used

IR Sensor

The infrared distance senor (GP2Y0A21YK0F) operates at a range of 10 to 80 cm and provides an analogue output. It is run at 5V with a current 0.3A. To obtain correct readings the sensor has to be located perpendicularly to the movement of the object.

Some data analysis has been performed with the analogue data recorded by the raspberry pi to determine what values different distances have in the sensor recordings. Through those it was also possible to determine the consistency of the readings. The results of these have been used to consider the safety loop and operational range of the tool itself. The results are as follows:

Even though the range of the sensor is specified to be between 10 and 80cm the ‘in range values’ identified within the tool are set between 10cm and 50cm. Only 16 % of all samples taken during the test in the range of 10-50 cm drop below 60.

Table- IV-3: Sensor Reliability Test

Distance (cm)	**drop to 0**				
	T1	**T2**	**T3**	**T4**	**T5**
10	84%	0%	0%	0%	0%
20	0%	0%	0%	0%	0%
30	0%	0%	0%	0%	0%
40	0%	0%	0%	0%	0%
50	0%	0%	0%	0%	0%
60	0%	16%	0%	0%	88%
70	0%	88%	0%	0%	60%
80	88%	92%	0%	46%	94%
90	76%	90%	36%	82%	84%

Distance (cm)	**drop below 60**				
	T1	**T2**	**T3**	**T4**	**T5**
10	92%	0%	0%	0%	0%
20	38%	0%	0%	0%	0%
30	38%	0%	0%	0%	0%
40	0%	0%	0%	0%	60%
50	0%	86%	0%	32%	66%
60	88%	88%	92%	90%	96%
70	94%	94%	86%	86%	86%
80	100%	98%	92%	96%	98%
90	100%	100%	92%	98%	94%

Servo Motors

Both servos are Power HD digital 20kg servos. At 4.8 V (operated at 5V) these have a torque capacity of 16.5 kg-cm, speed of 0.18s and a working frequency of 333hz.

Table- IV-4: Servo Motor

Electromagnet

The specifications of the electromagnet are unknown. It has been provided by the TU Delft measuring shop. To determine Teslar is a challenging experiment, so it has not been performed, the only known fact is that it is run on 5V and with a current between 0.6 to 0.8 Amps.

Selenoid Valves

The solenoid valves used to control the vacuum and the compressed air for the spot cooler are from Festo and of the type MH4-MS1H-3/2G-QS-8. These are fast switching valves (3ms) running on 24V, with push in connectors for tubing with O.D. of 8mm. They are designed for a pressure range between -0.9 to 8 bar and can handle a flowrate of 400 l/min. The valve for the vacuum has a silencer stuck in the second outlet to ensure the best vacuum conditions.

Table- IV-6: Selenoid Value

Work Flow

As can be seen by the process flow chart in Figure - IV-18, the process is dependent upon four actions performed by the operator, robot or the tool itself. The process is split into 6 stages:

Stage 1: Initialization stage of the tool

This is performed before the robot is activated to start its movements within the cell, since a human operator has to physically switch the tool on.

Stage 2: Initialization stage of the peeling

This is the stage as described in the background in section A of this chapter in which the initial foil separation occurs.

Stage 3: Continued peeling stage

This is the stage as described in the background in section A of this chapter. This phase may vary in time dependent upon the size of the ply and the speed of the robot. To achieve this phase most efficiently the robot needs to be moving along the centreline of the ply to ensure the peeling force is evenly distributed across its surface.

Stage 4: Film ejection and reset stage

This stage help to eject the removed film with help of the still ongoing airflow. The film simply detaches from the clamp and falls into a bin located below the tool. This stage also ensures the tool is ready for the next ply to be approached.

Stage 5: Circumstantial step

This is a purely circumstantial stage which is as such not relevant for the tool, yet for the overall process flow it is. The robot knows how many more plies it needs to lay down. So, when the robot stops working, this stage will be surpassed.

Stage 6: Power down stage

This once again needs to be initiated by a human operator that presses a button. This stage ensures that the files of the code on the Raspberry pi do not corrupt.

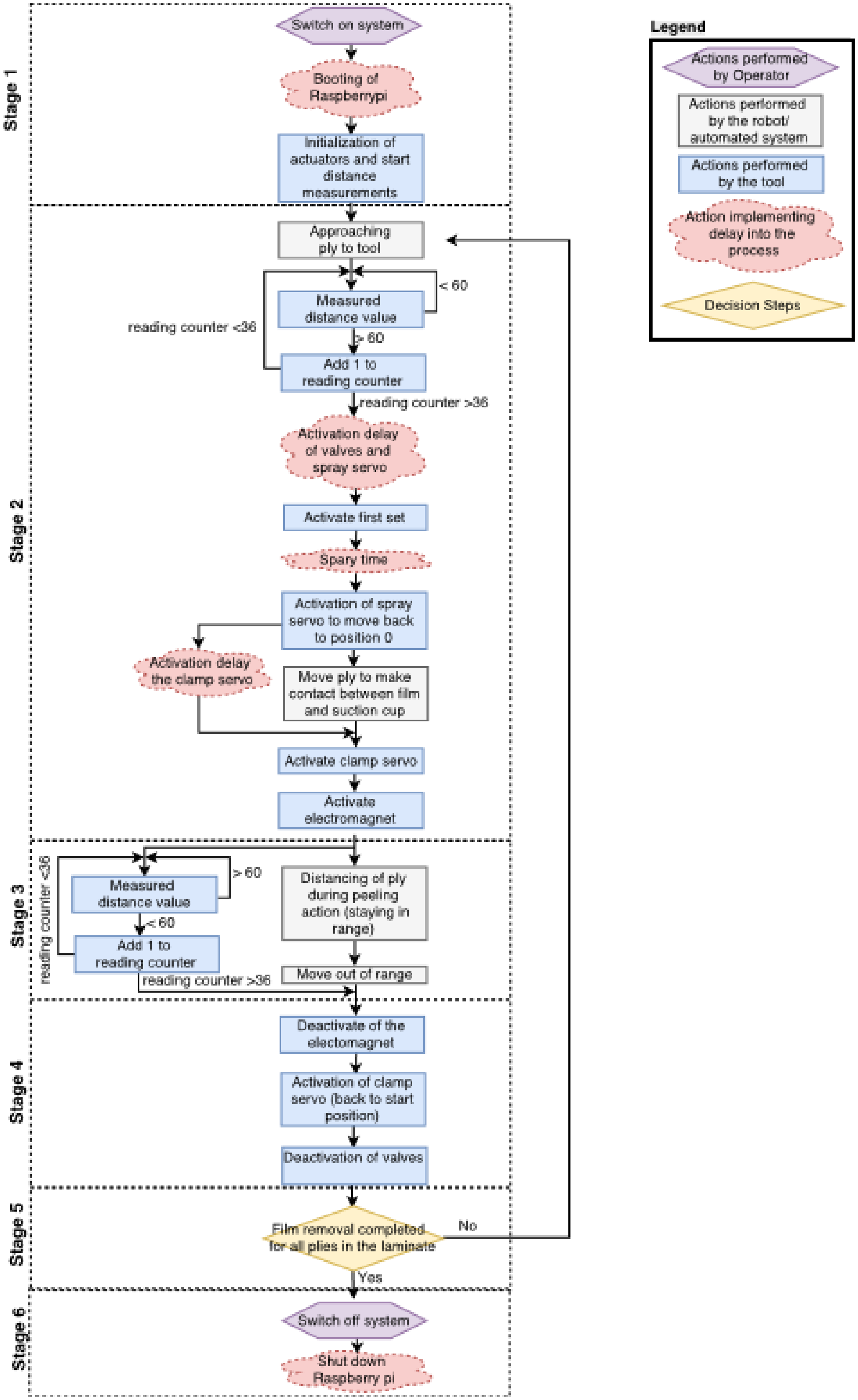


Figure - IV-18:Film Removal Tool Process Flow Chart

IV.1.4 Electronics

The electronics of this tool are based on a Raspberry pi mini-computer connected with a Gertboard to provide sufficient amount of ports to connect all the different actuators. (Figure - IV-19)

The set-up of the electronics is shown in Figure - V-19. Both servos as well as the IR sensor are running over the integrated Arduino whilst all other actuators are only connected to the Gertboard. The program of the Gertboard is written so that it reads the sensor information from the Arduino and based on the value runs into a safety loop that prevents the tool to react at every inconsistency in reading. This is further explained in the code section.

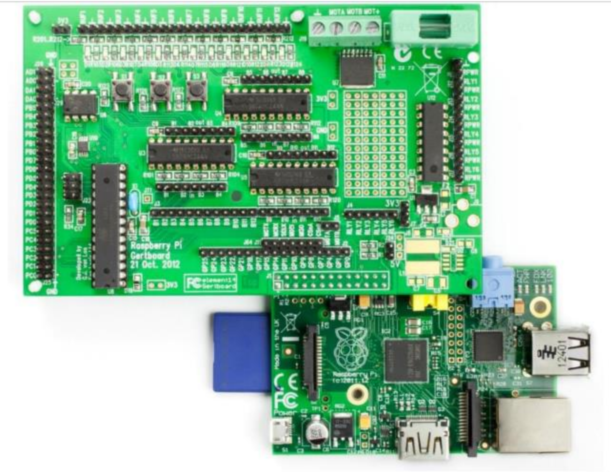


Figure - IV-19: Gertboard Connected to a Raspi

It can be noted that the diode that is set parallel to the electromagnet is wired with the cathode against the current direction. This is a safety mechanism so that the board does not get short circuited. The introduction of the electromagnet will cause there to be current running backwards though the magnet to keep the magnetic field up once shut down. The Diode protects the board from this current by leading it back to the mainline.

Another aspect to note is that all relays are connected in parallel, so by connecting the 5V power supply for the Electromagnet the 24V can no longer be connected to that same line without causing damage. For this reason, the two 5V to 24V relays have been added for the valves to become operational.

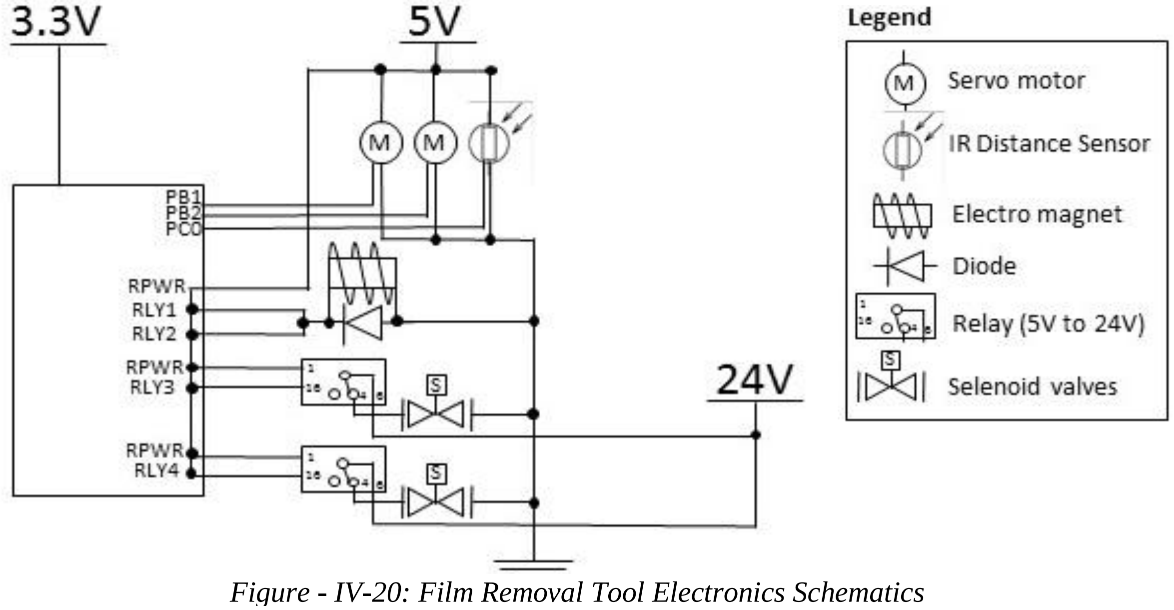


Figure - IV-20: Film Removal Tool Electronics Schematics

Wiring

This provides a description of the physical wiring of the Gertboard as seen in Figure IV-20 and the perpose of the different connections to be able to adapt the coding or add further actuators if need be. The jumper on the J7 pins ensure that there is a 3.3 V power supply to all components that will be connected to the Gertboard. Id components require more power it needs to be supplied by an extrenal power suply.

In order to program the Arduino (ATmega chip) on the Gertboard the SPI bus found on GPIO pins 8 through 11 need to be connected to the J23 header, as indicated by the orange connectors on the diagram. For any alterations in the program update these need to be present, once programming is complete these can be removed.

GPIO14 and GPIO15 are the pins that the Raspberry Pi uses for the serial port that is able to generate the PWM signals for the servo motors. This ensures that the data transmitted by the Arduino is received by the Raspberry Pi. The two servos the need to be connected to the PB1 and PB2 pins.

For the Arduino to be able to read and print the analogue data values, that the IR distance sensor is creating, to the serial port by connecting the sensor to the PC0 pin. Using the serial port for the reading also requires a baud rate to be set. In this case, it was set as a default to 9600.

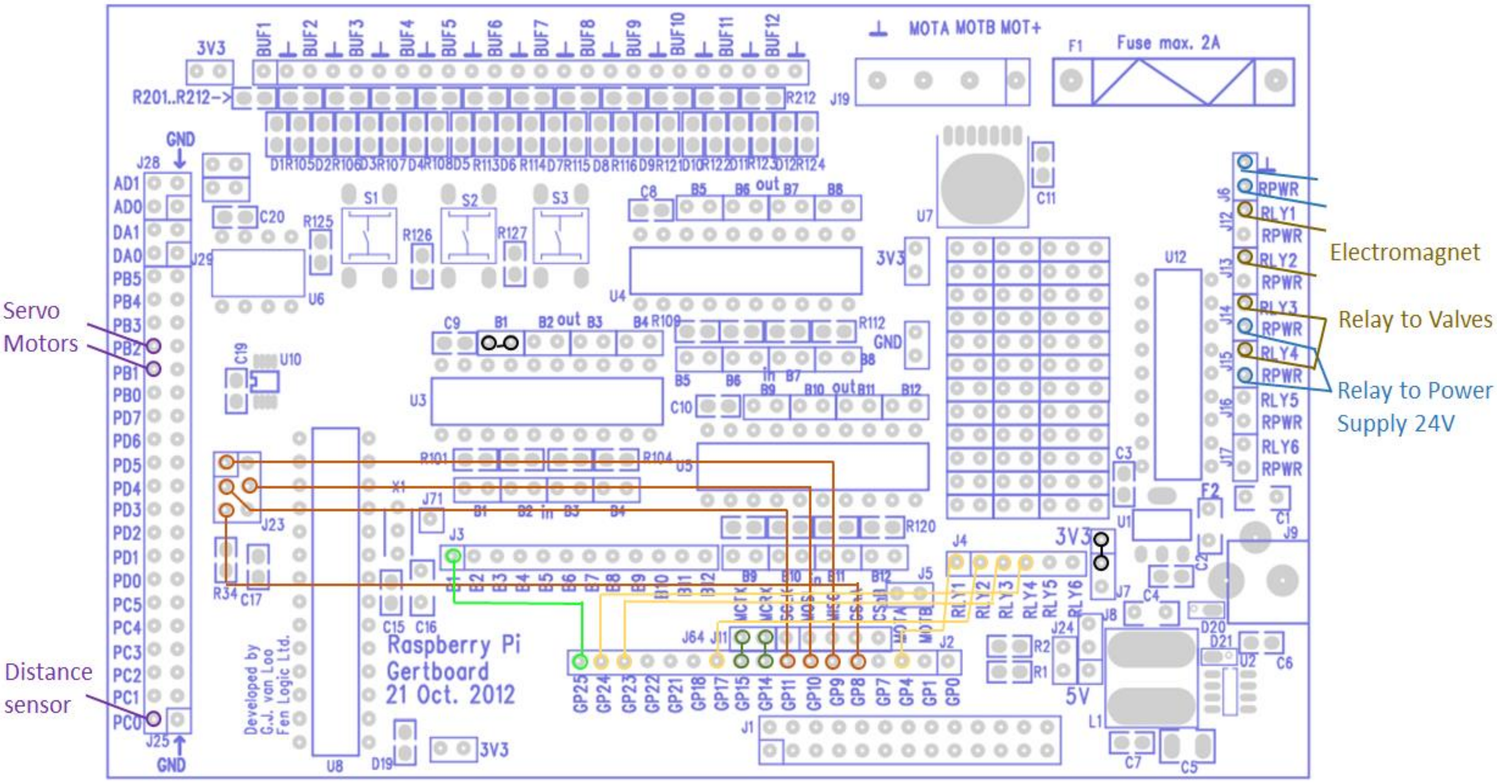


Figure - IV-21: Wiring of the Gertboard

To connect open controllers to the relay outputs J12 through J17, The GPIO pins need to be connected to the header J2. The Electromagnet requires a higher current that 0.5 Amps. To be able to allow for that yet simultaneously not to fry the Gertboard, two relays are placed in parallel, making it possible to run 0.5+0.5= 1 Amp of current though them. Additionally, it is important to know that the power supply for all relays are run parallel, so relays are required to convert the 5V to the 24V required for the valves to operate.

The last connections seen upon the Gertboard schematic is the connection for the button S1. For this to be active a jumper has to be placed on the two B1 pins (next to the C1 pins). The GRIO pin GP25 has to linked with the B1 pin in the J3 block. This button is used to safely shut down the system without corrupting any files. The wiring of all these components can be seen in the electronics schematic in Figure- V-21.

Code

The code is set-up in two parts. The first part runs over the Arduino chip and controls the servos as well as provides readings of the IR sensor. The commands for the reading of the sensor value is set to ‘D’(distance), the first movement of the clamp is set as ‘F’ (final), whilst the movement back to its starting position is given the letter ‘S’ (start). The activation motion of the spray servo is denotated as ‘C’ (cold) whilst the set back to resting position is ‘R’ (room temperature). These are called upon by the python3 code that is read by the raspi. For more details about the code please view the comments in the section Arduino.

For any alterations to the Arduino code make sure to enable the following features within the Arduino interface:

- Board: Gertboard ATmega328
- Serial port: /dev/ttys0

The programming on the raspi is done through the GPIO library. The python3 code calls upon the previously indicated control letters. It also switches the relays on, which activate the valves. As seen from the flow chart, the python code has implemented a safety feature that allows up to 35 consecutive falls readying fails readings by the sensor, which is worth together 1/5 s since readings are taken every 7ms. That time is the duration it takes for the robot to approach the distance of 50cm at its full speed of 2m/s. This allows feature to ensure that the mechanisms are triggering with fault readings. This value can easily be changed as one sees fit.

The raspi is set-up to run the python3 script right after it is finished booting. The delays built into the code will have to be adapted based on the speed of the robot. When teaching the robot the moved distance can be determined using the coordinates. The able below gives the delays needed for a series of distances covered.

Table- IV-7: Time Delays

Speed		**Delay needed (s)**					
m/s	**%**	50 mm	100 mm	150 mm	200 mm	250 mm	300mm
0,04	2	1,25	2,50	3,75	5,00	6,25	7,50
0,2	10	0,25	0,50	0,75	1,00	1,25	1,50
0,4	20	0,13	0,25	0,38	0,50	0,63	0,75
1	50	0,05	0,10	0,15	0,20	0,25	0,30
2	100	0,03	0,05	0,08	0,10	0,13	0,15

Arduino

This is the code the Arduino runs.

```
const int DelayClamp =500;
const int DelaySpray =500;
// these delays are simply placed so ensure all positions
are reached before the program breaks. The actual clamp and
spray delay are tuned and adjusted in the python3 code.
const int analogInPin = A0;
Servo myservoclamp;
Servo myservospray;
int pos = 0;                   // store position
byte inByte=0;                 // command byte
void set-up()
{
 Serial.begin(9600);           // initialize serial
communications at 9600 bps:
```

```
 myservoclamp.attach(9);     // attaches the servo on pin 9
to the servo object
 myservospray.attach(10);    // attaches the servo on pin 10
to the servo object
}
void loop()
{
  if (Serial.available()>0)
  {
    inByte=Serial.read();
    switch (inByte)
    {
     case 'D':
       Serial.println(analogRead(analogInPin));
       break;
     case 'S':
         pos=0;                // Servo to position 0 degrees
         myservoclamp.write(pos);
         delay(DelayClamp);
         break;
     case 'F':
       pos=176;                // Servo to position 176 degrees
(straight)
       myservoclamp.write(pos);
       delay(DelayClamp);
       break;
     case 'C':
       pos=30;                 // Servo to position 30 degrees
       myservospray.write(pos);
       delay(DelaySpray);
       break;
     case 'R':
       pos=0;                  // servo to position 0 degrees
       myservospray.write(pos);
       delay(DelaySpray);
       break;
    }                          //case inByte
  }                            //if Serial.available
}
```

Gertboard

The following lines are the code that the Gertboards runs.

```
# Module for ser serial to communicate on the Gertboard to regulate
the AVR
# 17 maart 2017
# E.H.M. Ulijn & A.P.Colling
import serial
import RPi.GPIO as GPIO
from time import sleep
import sys
import getch
```

```
import os

DelaySuction_on = 0
DelaySuction_off = 3
# Delay between the finish of the spray and the activation of the
clamp DelayBlow_on = 8.5
DelayBlow_off = 0
SprayTime = 2
# To compensate for the time in which the system is triggered and the
ply actually reaches the right location for spraying
DelaySprayIntoPlace= 2.5
# 2070504
# Original library used: WiringPI. It stoped working so change over to
GPIO lib.

ser = serial.Serial('/dev/ttyS0', 9600)
go = True
distance_sensor_value = 0
distance_inrange = 270
# was 60 changes depended on daily conditions, therefore needs to be
adjusted if not working properly
max_wrong_readings = 35
print('Erik debug:\n')
print(GPIO.VERSION)
print(GPIO.RPI_INFO)
print('High = ',GPIO.HIGH)

GPIO.setmode(GPIO.BCM)                       # initialise RPi.GPIO
GPIO.set-up(4, GPIO.OUT)
GPIO.set-up(17, GPIO.OUT)
GPIO.set-up(23, GPIO.OUT)
GPIO.set-up(24, GPIO.OUT)
GPIO.set-up(25, GPIO.IN)
GPIO.set-up(25, GPIO.IN, pull_up_down=GPIO.PUD_UP)
GPIO.add_event_detect(25, GPIO.RISING) # Add rising edge detection

def alinaReady(countdown):
    GPIO.output(4, GPIO.LOW);
    GPIO.output(17, GPIO.LOW);
    GPIO.output(23, GPIO.LOW);
    GPIO.output(24, GPIO.LOW);
    GPIO.cleanup()                # resets all GPIO ports used by this
program
    ser.write(b'S')
    ser.write(b'R')
    ser.flush()
    ser.close()
    print('program finished',end='\n')
    print('shutting Down',end='\n')
    for i in range(1,(countdown+1)):
        sleep(1)
        print(i,' ')
```

```
    os.system('poweroff')

if ser.isOpen() == False :
   ser.open()
print('Program alina.py starts\nHit CTRL-C to quit program')
GPIO.output(24, False)
GPIO.output(23, False)

try:
    while go==True:
        if GPIO.event_detected(25):
            alinaReady(10)
        print('Out of range')
        GPIO.output(17, False)
        GPIO.output(4, False)

        reading_counter = 0 # reading good or bad values
        # Check if ply is in range ( > distance_range)
        # only 3 consecutive will trigger the servo
        ser.write(b'S')
        ser.write(b'R')
        while (reading_counter<max_wrong_readings):
            ser.write(b'D')
            distance_sensor_value = int(ser.readline())
            print(distance_sensor_value)
            if GPIO.event_detected(25):
                alinaReady(10)
            if (distance_sensor_value > distance_inrange):
                reading_counter = reading_counter +1
            else:
                reading_counter = 0
        ser.write(b'C')
        sleep(SprayTime)
        ser.write(b'R')
        GPIO.output(23, GPIO.HIGH)                # switch port 23 on
        GPIO.output(24, GPIO.HIGH)                # switch port 24 on
        sleep(DelayBlow_on)
        sleep(DelaySuction_on)      # delay between suction cup and
servo
        ser.write(b'F')
        print('In range')
        GPIO.output(4, GPIO.HIGH)                 # switch port 4 on
        GPIO.output(17, GPIO.HIGH)                # switch port 17 on
        reading_counter=0
        while (reading_counter<max_wrong_readings):
            ser.write(b'D')
            distance_sensor_value = int(ser.readline())
            print(distance_sensor_value)
            if GPIO.event_detected(25):
                alinaReady(10)
            if (distance_sensor_value < distance_inrange):
                reading_counter = reading_counter +1
```

```
            else:
                reading_counter = 0
        GPIO.output(4, GPIO.LOW)          # switch port 4 off
        GPIO.output(17, GPIO.LOW)         # switch port 17 off
        sleep(0.2)
        ser.write(b'S')
        GPIO.output(24, GPIO.LOW)           # switch port 24 off
        sleep(DelaySuction_off)     # delay between servo and suction
cup
        GPIO.output(23, GPIO.LOW)           # switch port 23 off
        sleep(DelayBlow_off)   # delay between suction cup and cooling
off

except KeyboardInterrupt:          # trap a CTRL+C keyboard interrupt
       print ('CTRL C pressed\n')
```

IV.1.5 Application within Robot cell

The programmed path of the robot is made with reference to the removal tools legs. That way the tool can be placed anywhere within the cell and the robot will recognize what to do. The path of the robot above the tool is split into seven different steps:

1. Approach to tool and trigger the sensor, the final approach position stops above the spray.
2. Wait 2s above the stray (position 1)
3. Approach diagonally to the suction pad
4. Wait 1s to ensure good contact between foil and suction pad (position 2)
5. Lift the ply up vertically by 4mm to ensure sufficient space is given to the clamp
6. Wait 1s to ensure the clamp has properly slid between the ply and the foil (position3)
7. Start the peeling action by moving away diagonally. The duration of this motion is dependent upon the length of the ply. This diagonal motion is oriented in such a way that the clamp is located along the central axis of the ply, so that the peeling force is spreading evenly along the length of the ply.

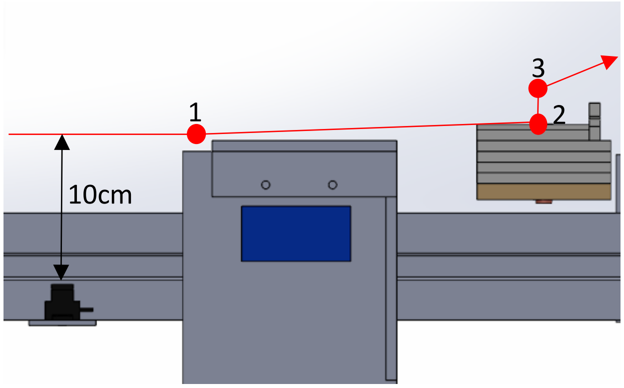


Figure - IV-23: Robot Path Steps

Based on this process path steps an estimation on the process time can be made. For a ply example of 1200mm in length the peeling action will take less than 5 s at full speed. A consideration at teaching speed should not be necessary since the motions should be preset by a standard program.

Figure - IV-24:Suction Cup with Stroke

The trial in the Airborne robot cells showed that the correct gripper (end effector) is a crucial factor for the peeling process. It needs to be able to have sufficient grip of the ply during the peeling action. As can be seen from Figure-IV-24.

; large, widely spread suction cups are not able to keep hold of the prepreg ply whilst the film is peeled off. Additionally, the large suction cups cause larger deformation areas on the surface of the prepreg once released. Hence the end effector to perform this action successfully requires numerous and smaller suction cups are needed to keep better control over the entire ply. The same test has been performed on another end effector with smaller suction cups that have a larger stroke (Schmalz FSG 14, diameter: 15.5mm). For IP reasons, the end effector cannot be photographed. The suction sups are similar to the one seen in Figure-IV- 24. The same suction on a smaller area means more grip on that same area. More importantly is that the stroke of the suction sup is able to adapt to curvature within the surface without losing grip of the surface. Finally, this end effector had suction cups at closer spacing therefore had 4 cups spread over the entire surface in contrast to just one in the original test.

Furthermore, it was noticed that different the overhang of end effectors varies greatly dependent on their design. End effectors with a marge overhang can cause premature tool activation by triggering the IR sensor before the ply is in the right position. The tests showed that to obtain fully successful peeling results an end effector will most likely have to be specially designed for the plies.

Figure - IV-25: Grip test Performed at Rondal

IV.1.6 Improvements and recommended of further development

The film removal tool still requires quite some work before it can be successfully used within the automation system. This section discusses some of the weaknesses of the current design and provides some improvement ideas, as well as recommended areas for further research if the development of this tool is to be continued.

There are two main weaknesses identifiable in the current design of the tool, both of these are related to actuators. The first weakness is fairly simple to resolve and has to do with the IR sensor. Even though test have been performed on the values of the IR sensor and had seemed to be fairly consistent, throughout the further development of the tool these values have shown to vary daily based on the light ambient light intensity and probably other unknown factors. These cause the tool to be triggered even though a safety mechanism is installed into the code. This sensor is designed for model build hobbyist; hence it could easily be interchanged by one with more consistent output values. Using a different type of sensor, such as ultrasonic sensors could also prove to be a suitable solution. To resolve the issue regarding the early triggering of the sensor due to overhang on the end effector, a second sensor could be added at a different location of the tool and only cause the system to trigger once both sensor obtain record a signal.

The second and more important weakness of the current design is that the clamp is not able create enough pressure on the top side of the film to keep it fixed in place for the entire gripping operation. The rubber on the steel surface of the clamp and the roughened surface in which the suction cup is imbedded, does not provide sufficient frictional resistance to prevent the film to slip out. A potential solution for that is a camp (Figure- IV-26) that can automatically be tightened. Yet, clamping the film in only one corner can also lead to failure of the film, which leads to the next point of consideration for further development.

For small plies keeping hold of the ply in only one corner during the peeling seldom causes tearing of the film, since only fairly low forces are required. When dealing with larger plies however and the peeling force increases further with the increasing length of the film as the ply get peeled, there is a high chance the film will tear and results in incomplete peeling. Which is why it is important to firstly determine the failure strength of the film itself as well as to find a method to keep a certain amount of tension between the adhesion interface and the removed film. Such a solution would provide much better control over the peeling action itself. There are two ways to achieve this either by causing an object to put the film under tension by placing it in the path of the peeling or by ensuring a fairly constant distance between the peel interface and the tool.

The first is achieved by inserting a rod along the width of the ply, after the initialization has occurred that forces the film downward as it moves along the length of the surface. On one hand, this done not necessarily need the robot to move during the peeling, however it would mean that a tool the size of the longest ply would be required. A simple sketch of the idea is given is given in Figure-IV-26.

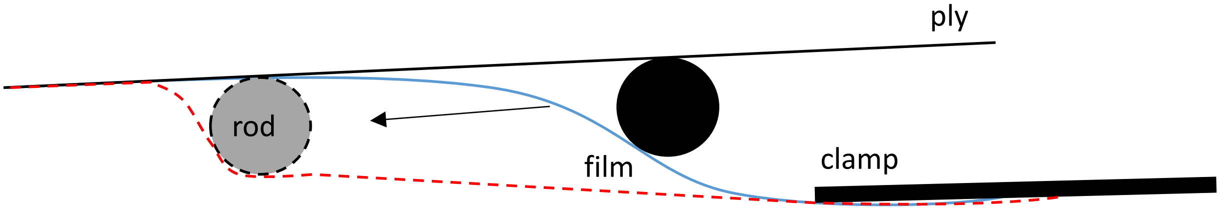


Figure - IV-26:Alternative Clamp Solution

To keep a constant distance between the tool and the ply it is necessary to reduce the length of the film as the peeling progresses, this can for instance be done by a drum onto which the film is would. The original initiation is still performed by a clamp that then slots into a winding drum. The advantage of this is that not only is the distance reduced to improve control over the peeling but also is the peeling force spread over the entire length of the film instead of only the single clamping point. Hence there is less risk of tearing the film. This also means that the orientating of the air blow has to be performed on a much larger surface area. So, a different way of air disruption should be considered. A simple sketch of the winding idea is given below.

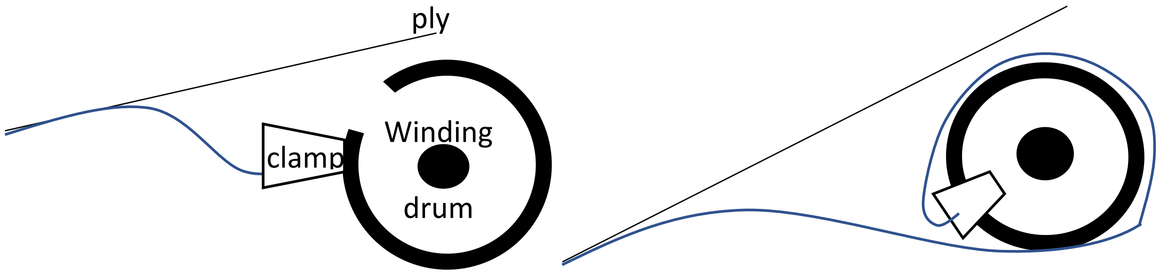


Figure - IV-28: Ply Tension Solution

Another very important topic of research and development that has to be covered is the inspection system as mentioned in the background reading. Without it there is no mean of determining the quality of the laminate, since the process is not stopped if a fault peel has occurred. It is absolutely necessary to have a safety proportion that can at least stop the continuation of the process until the peeling problem has been resolved manually.

Another peeling aspect that needs to be addressed is the centralized peeling of plies. This becomes particularly important the larger and more complex shapes become. It is not directly related to the working system of the tool itself, since it has to be controlled by the robot, but it greatly impacts the end result of the peel. An algorithm has to be created that instructs the robot to follow a specific path dependent on the robot knowing what ply it currently holds. To be able to now the paths for more complicated shaped, test will have to be performed upon which the algorithm is based. Two sample sketches of ply shapes below.

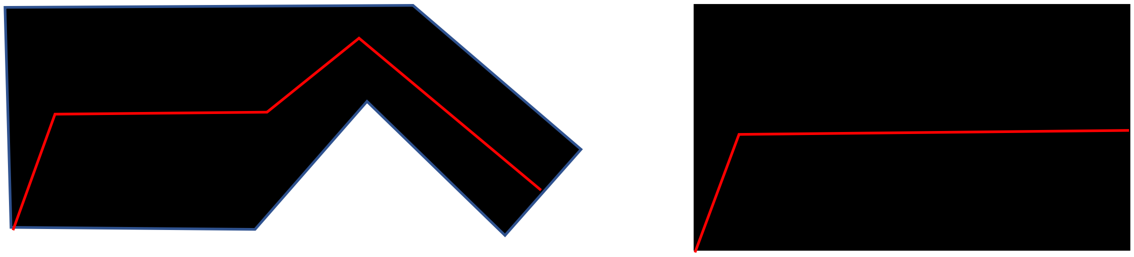


Figure - IV-29:Ply Centerline for Peeling

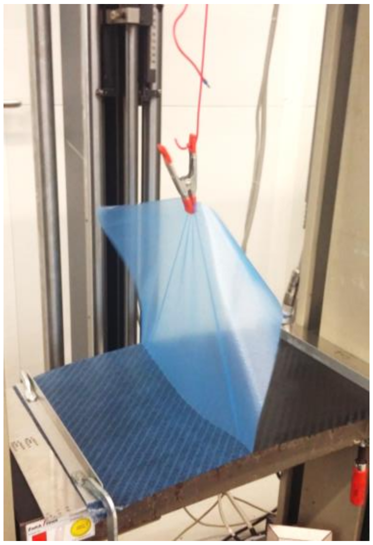
A last point of improvement and further research for this part of the project regards, the end effector. As seen by the working with the end effector with the smaller suction cups, it is advisable to build it out of transparent material. This will make teaching actions for the robot more precise and faster, since the final destination can actually be seen from a perpendicular point of view. The end effector design is specially designed to handle all plies dealt with. Making a decision on the end effector is a separate project of its own.

IV.1.7 Conclusion

The work performed on this tool can be summarized by the following remarks. The film removal tool is the vital tool required to be able to bring the different process steps within the automation cell together. The approach of shock cooling the film is a viable solution for the application within the marine industry. There are also further methods to help reduce the tack between the surfaces, however any development of this tool will require adjustment dependent on the materials used. The two most significant aspects that need to be dealt with before such a tool can be implemented in an actual industrial environment is improved control over the ply when dealing with large plies and the inspection step to ensure the quality of the laminate.

APPENDIX V- ADHESION TEST

Lab Report



By: Alina Colling

Lab date: April 4th 2017
Last edited: May 17th 2017
Company: TU Delft/ Royal Huisman/ Rondal

V.1.1 Problem

A tool is to be developed that can be placed into a robot cell and autonomously removes the protective film of the prepreg with help of the robot. To ensure this tool is designed to required specification of all types and sizes of material used material testing need to be performed to determine the adhesive forces between the protective film and the prepreg in different circumstances.

The main questions this testing will have to answer are:

- What are the adhesive forces between the film and the prepreg? (both carbon and glass fibers fabrics)
- How much does the adhesion increase with an increase in temperature (comparing wintertime 15°C to summer time 30°C surface temperature)?
- Does the addition of a spot cooler (air blow between the surfaces) significantly reduce the adhesion forces?
- How does an increase in surface area impact the adhesive forces? (compare different sizes)

Hence the following test are aimed to be performed:

As a base test, the speed needs to be established making that part 0.

Part 0- Samples of woven carbon fibre are being peeled at different rates. This way not only can it be decided upon at what rates the tests will be performed but also an impact of the speed on the adhesion differences can be determined.

Part 1- Samples of glass fibre prepreg are tested to compare them directly to the woven carbon.

Part 2- Test with different surface temperatures are performed thereby directly comparing the influence of increasing temperature on the prepreg.

Part 3- An airflow is applied during the test to determine if it significantly reduces the adhesive forces between the surfaces.

Part 4 -A range of different size plies are tested to be able to obtain an understanding of a translation of the adhesive forces on larger size plies.

V.1.2 Background

The research on the removal of the protective layer prepreg has mainly been done in the setting of Automated Tape Laying (ATL) automation. The protective layers of the prepregs used for this process is backing paper which is more rigid and hence easier to handle than the thin films which are used for these tests. Furthermore, the process is performed within the head of the tape layer, hence the width of the peeled material is very narrow in comparison to the plies that will be handled by the tool designed from this test (Crossley, Schubel, & Warrior, 2013). Modern ATL robots additionally deposit the prepreg with help of heat to increase the tack between the layers, which means the peeling of the paper is also performed at a higher temperature than expected for the film removal. Comparing results from these test to the film removal tool design should be done with caution since, as Björnsson (2015) mentions in his experience with film removal tools, the peeling performance is largely dependent on the kind of materials used.

Crossley, Schubel and Warrior (2013) identified the two aspects needing consideration during peeling to be temperature and feed tare. A rise in temperature naturally impacts mainly the tack, whilst the feed rate alters the “cleanness” of the peel and the distribution of the resin within the material. Their experiments showed that a slow federate causes non-uniform peeling since the resin has time to gather at the peeling front of the interface between the surfaces and is partially peeled off the prepreg together with the protective paper. The resin destribution and content in the material at slow rates is inferior to the ones at faster federates. Figure - V-1 shows the difference in surface smoothness.

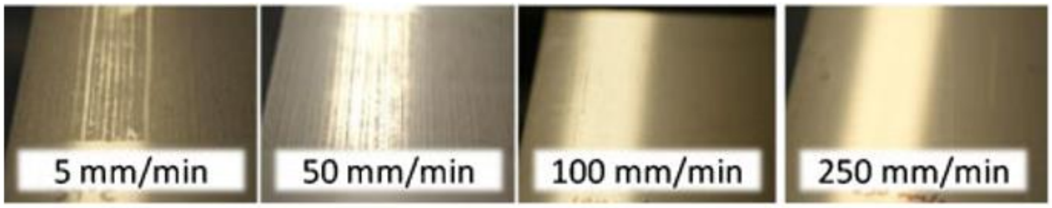


Figure - V-1: Difference in Surface Smoothness with Different Peeling Rates

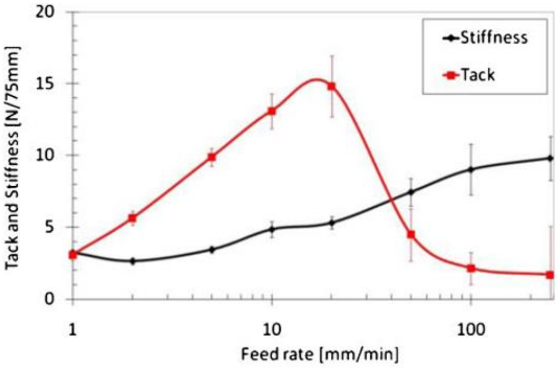


Figure - V-2: Tack Variation with Different Peeling Rates

From Figure V -2 it can be seen that the tack peaks at a feed rate of 20 mm/min, whilst the stiffness of the material continuously increases with the faster removal rates.

The temperature is another influences the “cleanness” of the peel. As seen in the graph of Figure - V-3 the tack of the resin peaks at a temperature of 27°C. That is hence also when it leaves the most resin remaining on the removed paper. The tack does not rise above 15N/75mm, which means a tack of 0.2 N/mm is the main indictor for comparison.

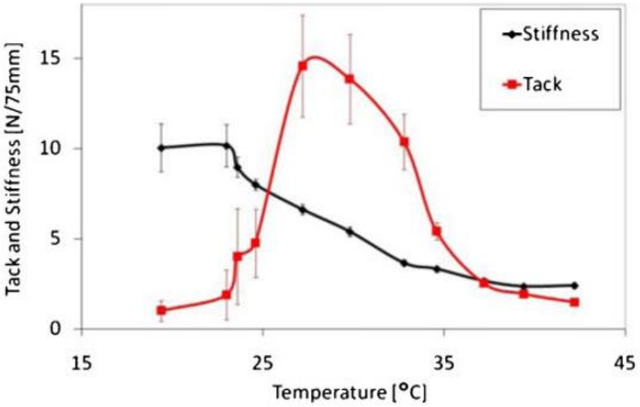


Figure - V-3: Tack Variation with Different Environmental Temperatures

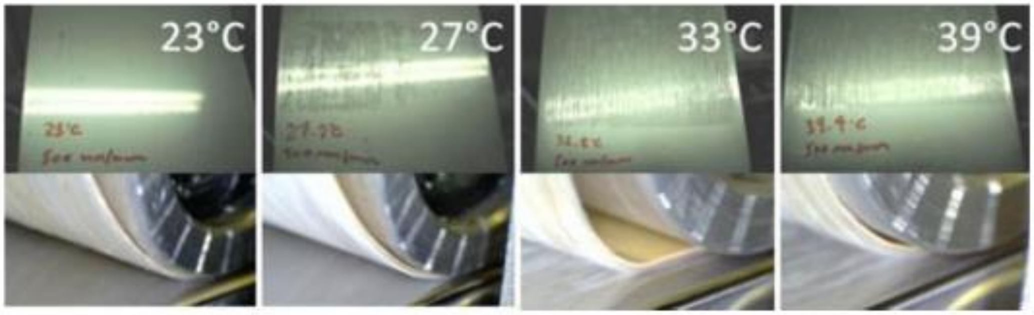


Figure - V-4: Tack Variation with Different Environmental Temperatures

V.1.3 Hypothesis

Base on this background research, hypotheses are set-up for the individual test scenarios. The following statements explain the expected outcomes of the tests.

Part 0- The smoothness of the peel is expected to be significantly reduced at lower peeling rates, which will also increase the peel forces since there is more resin accumulates at the peeling interface.

Part 1- The adhesive forces are expected to be similar, since the same type of resin is used in both types of prepregs.

Part 2- It is expected that the tack will rise significantly with increasing temperature.

Part 3- The air blow will most likely help the detachment of the foil, since only forces of 0.2 N/mm are expected.

Part 4- The adhesion is expected to increase proportionally to the size of the test sample. Hence from the testing, one should be able to determine the forces that need to be withstood by larger plies.

V.1.4 Variables

Manipulated variable:

The manipulated variables change throughout the test stages. First it is the peel rate, then the type of material, followed by the surrounding temperature, the addition of a cold air stream and finally the size of the samples becomes the manipulated variable.

Responding variables:

The responding variable of all the test runs is the tack measured and the amount of resin leftover on the surface of the film.

Controlled variables:

The controlled variables are opposing to the manipulated variables during the different test stages. Whilst during the base and first test the environmental conditions and size are controlled, for the second and third part the fabric and size stay the same. Finally, for the fifth part both the environmental conditions and material are controlled again.

V.1.5 Materials

Test material:

The test only make use of two different types of prepreg to ensure that the consistency stay as similar as possible, both of these materials are given in the table below.

Ref. #	Material Type	Backing film
1	SE84LV/RC416T/1270/42%	Blue diamond shaped pattern
7	SE84LV/XE905/1270/35%+/-3%	Blue diamond shaped pattern

All materials tested have been taken out of the freezer less than six week prior to the testing.

The amount of material used are dependent upon the tests:

Part 0: 6x 10x15cm woven carbon prepreg
Part 1: 3x 10x15cm woven glass prepreg
Part 2: 12x 10x15 cm woven carbon prepreg
Part 3: 3 x10x15 cm woven carbon prepreg
Part 4: 3x 34x51 cm woven carbon prepreg
3x 23x34 cm woven carbon prepreg

Some spare test samples should be at the disposal to do some test trial at the start or if a run goes wrong.

Part 4 of the testing will need a large variety of samples. These are indicated in Figure - V-1. The dimensions have been chosen purposely so that the increase in size is 50%, thereby the results can be compared to one another. The dimensions for all other samples are provided in the table below.

Table- V-1 Comparing Peeling with Different Surface Temperatures

	Length (cm)	Width (cm)	l/w	% increase in size
Original	10.0	15.0	0.67	50%
Sample 1	15.1	22.5	0.67	50%
Sample 2	22.6	33.8	0.67	50%
Sample 3	33.9	50.6	0.67	50%

Equipment:

- A tensile test machine with load cells of an accuracy of 0.04N. The results are recorded and processed into a graph.
- The temperature is measured using a digital thermometer that is places between the film and the prepreg surface.
- The preheating of the samples is done using a heat mat. However, since the samples are surrounded by metal which will conduct the heat quickly away from the sample, some additional heating is needed with a heat gun on the test rig itself.
- The precooling of the samples in done in a temperature chamber that is set to -10 °C. At the rig, the quick rising heat is adapted with a cooling spray (cooling agent Spuitbus, freezer 75, Kontakt Chemie)
- The air blow is provided by a Spot Cooler with an intake pressure of 6 bar.
- A metal plate, two angles and clamps are used to keep the plies in place during the test.

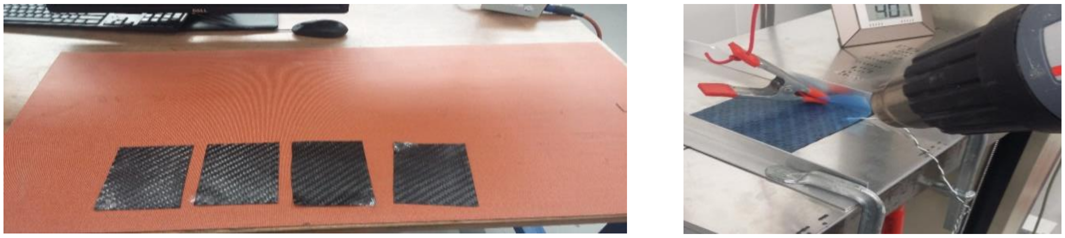


Figure - V-5: Preheated Prepreg Samples

V.1.6 Set-up

Traditional adhesive test equipment such as the Bel test set-up was considered to be used to closely match the values given in the paper. Yet, it was decided to improvise a set-up that provides the possibility to test larger test samples than 75mm width. The data from this test is to provide an estimation of the impact of the adhesive forces with an increase in size. Additionally, the rollers in the Bel test would also not imitate the peeling action that the peeling tool is going to perform.

The set-up of the testing consists of a metal base onto which the sample is fixed into place by two angles. These are clamped onto the plate. Before placing the sample some of the foil is peeled off, so that it can be attached to the peeling clamp. The peeling clamp is attached to the tensile test rig via a cable. This ensures that the clamps position during the testing changes and does not damage the test rig in a transverse motion. This set-up causes the peeling action to be close to perpendicular to the ply, which cause higher peeling forces than in the diagonal peeling motion, especially at the beginning of the test. Even though, the peeling motion performed on the final tool will be diagonal, knowing the forces in a perpendicular peel will ensure that sufficient forces are taken into consideration. A picture of the set-up is given in Figure-V-7.

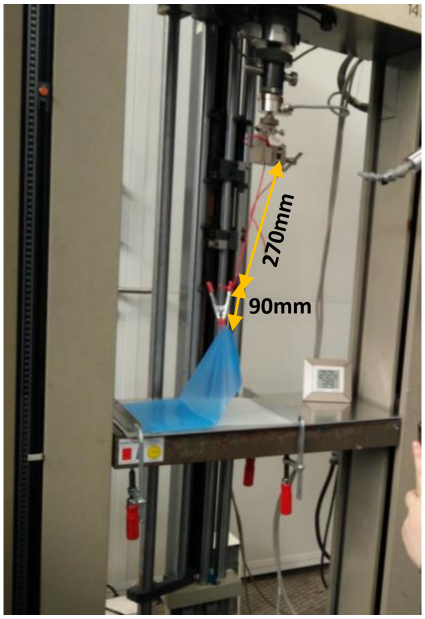


Figure - V-7: Set-up of the Test Rig

V.1.7 Procedure

A pre-test must be performed to determine the value of the preload of the tensile test. This is the load that will bring the film slightly under tension before it starts recording the test values. (determined to be 1N)

Part 0:

- The speeds at which the test can be performed are dependent upon the capabilities of the tensile test machine. Ideally, speeds such as 0.2 m/s (10% of Robot speed), 0.4 m/s (20% of Robot speed), 1 m/s (50% of Robot speed) and 2m/s (100% of Robot speed) ought to be tested. However, the maximum speed the tensile test machine can be performed 12.5mm/min, so the speed values must be adapted. These are set to 0.33 mm/min, 8mm/min and 12.5mm/min. The procedural steps are:
  1. Input the size of the sample into the program
  2. Define speed of the test and intervals at which samples are to be recorded (0.1s)
  3. Fix the sample into the rig
  4. Detach 15mm of foil to attach it to the peeling clamp
  5. Measure ambient temperature
  6. Measure surface temperature
  7. Start test program
  8. Observe and record behaviour of the peeling
  9. At test completion reset rig
  10. Perform steps 3-9 until all three samples are tested
  11. Perform same steps for samples at higher speeds

Part 1:

Repeat steps 3 through 10 from the previous test the glass samples. Use a speed of 12.5mm/min.

Part 2:

The 20°C test is the same as earlier performed test in part 0. For the 15°C test, place the sample in the cooling chamber and all other samples on the heating mat to reach their desired surface temperature.

1. Perform steps 3-5 from part 0
2. Measure the surface temperature, check if it is as needed for the test since the heat exchange with the metal base occurs quickly. If it needs adjusting, either the surface with a cooling spray or heat it with the heat fan.
3. Perform steps 7-10 from part 0
4. Perform the same steps for all verities of temperatures

Part 3:

1. Install the adjustable spot cooler
2. Perform steps 3 -7 from part 0
3. Move the spot cooler along with the peeling at the same rate.
4. Perform steps 8-10

Part 4:

1. Perform Steps 1-10 of part 0 with the first altered size sample
2. Perform the previous steps with all verities of sample sizes

V.1.8 Observations and Recordings

Due to a lack of lab time the measurements for one size difference have not been performed.

Table- V-2: Experimental Record

Part 0				
Sample size stays constant: 10x15 (detachment before peeling 15mm)				
Nr.	**Speed (mm/min)**	**Surface Temp. (°C)**	**Ambient Temp. (°C)**	**Comment**
0.1				
1	0,33	22,4	22,6	Peels at intervals, residue left on film, the ply deflects
2	0,33	22,1	22,5	foil slips out of clamp (~10mm left in clamp)
3	0,33	22	22,6	foil rips partially
0.2				
1	8	22,4	22,7	losses grip (invalid run)
2	8	22,4	22,6	No adhesion residue line on foil, peeling much smoother
3	8	22,5	22,6	
0.3/1.1/2.1/3.1/4.1				
1	12,5	22,2	22,5	smoothest peeling of all
2	12,5	22,4	22,6	film is much better intact than the two other speeds
3	12,5	22,1	22,4	

Part 1				
Sample size stays constant: 10x15				
Nr.	**Speed (mm/min)**	**Surface Temp. (°C)**	**Ambient Temp. (°C)**	**Comment**
1,2				
1	12,5	21,8	22,5	results seem to be slightly higher than with carbon, otherwise no observable differences
2	12,5	22,4	22,6	
3	12,5	22,1	22,6	

Part 2				
Has been performed last of all test since the brackets have to be adjusted to a larger size. For time limitation reasons only the 23x34 and 34x51 samples could be tested.				
2.2				
1	12,5			
2	12,5			
3	12,5			
2.3				
1	12,5	21,5	22,6	from the data recorded it can clearly be seen that the forces required are larger, additionally a lot of ply displacement is observed when peeling the centre of the ply, but due to the way the ply is fixed in place this is expected
2	12,5	21,4	22,6	
3	12,5	21,7	21,7	
2.4				
1	0,4	21,4	22,6	
2	0,4	21,5	21,7	miss run, foil was accidently clamped into
3	0,4	21,6	21,8	a lot of displacement towards the centre, could have an impact on the peeling angle
Part 3				
Sample size stays constant:10x15				
3,2				
1	12,5	23,6	23,7	the blow removes moth of the foil on its own, the film tension needs to be established slowly before the actual peeling by the machine becomes effective
2	12,5	23,1	23,1	
3	12,5	21,2	21,4	
Part 4				
5.2 (15°C)				
1	12,5	16,1	22,6	cooling is very difficult the environmental temperature heats up the ply very fast
2	12,5	15,6	22,6	peeling forces are lower and the peeling is smoother
3	12,5	14,6	22,6	
5.3 (25°C)				
1	12,5	25,1	24	not much visible difference in peeling, only the data records a difference in forces
2	12,5	24,9	23,1	
3	12,5	25,2	23,3	
5.4 (30°C)				
1	12,5	29,8	23,9	there are peeling lines visible on the film alike the ones observed during the peeling at the low rate
2	12,5	30	23,2	foil seems to rip more easily
3	12,5	30,2	23,1	

The data obtained through all these tests is represented in the following graphs. Figure - V-8 shows the summary of all data recorded. It can be seen that the value fluctuates greatly. To improve the visibility of the results and help with later analysis the peaks and drops of each of the runs has been filtered out individually. These peaks are taken within a window of 5 value before and after a given peak or drop. For the determination of the maximum adhesive force these filtered graphs are sufficient information for the analysis. A direct comparison of graph in Figure-V-8 is given in Figure-V-9.

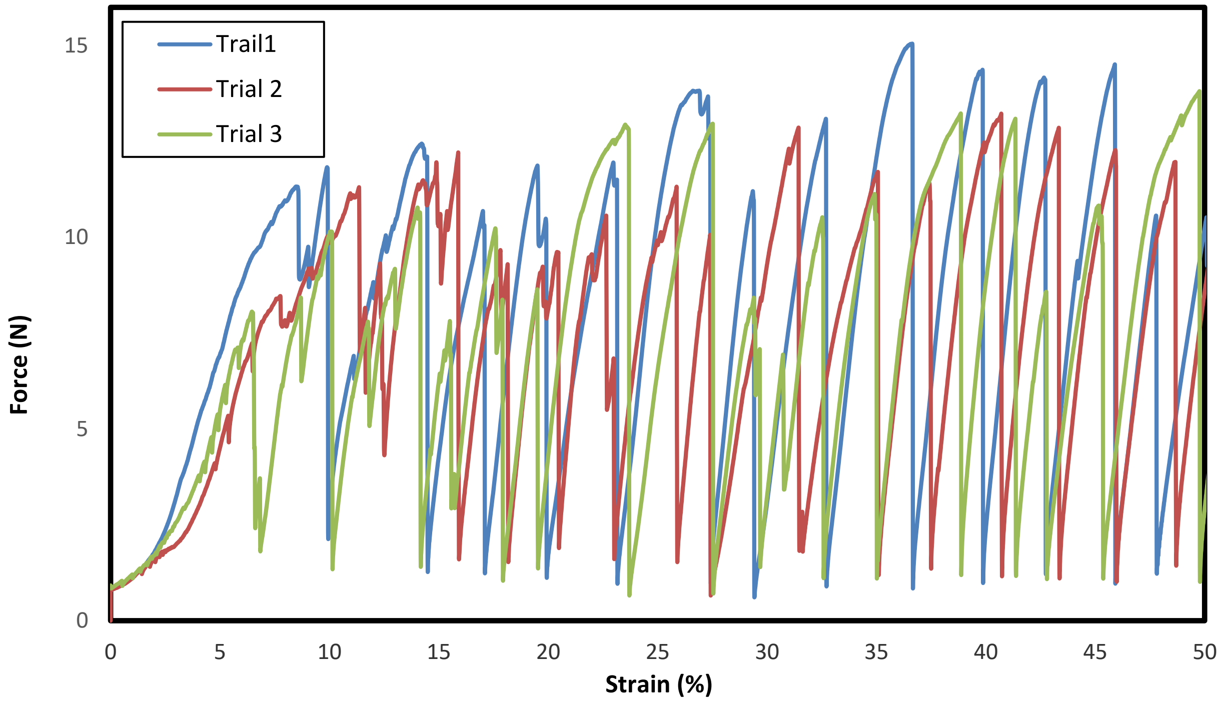


Figure - V-8: Full Data Recorded from Adhesion Testing at a Slow Rate

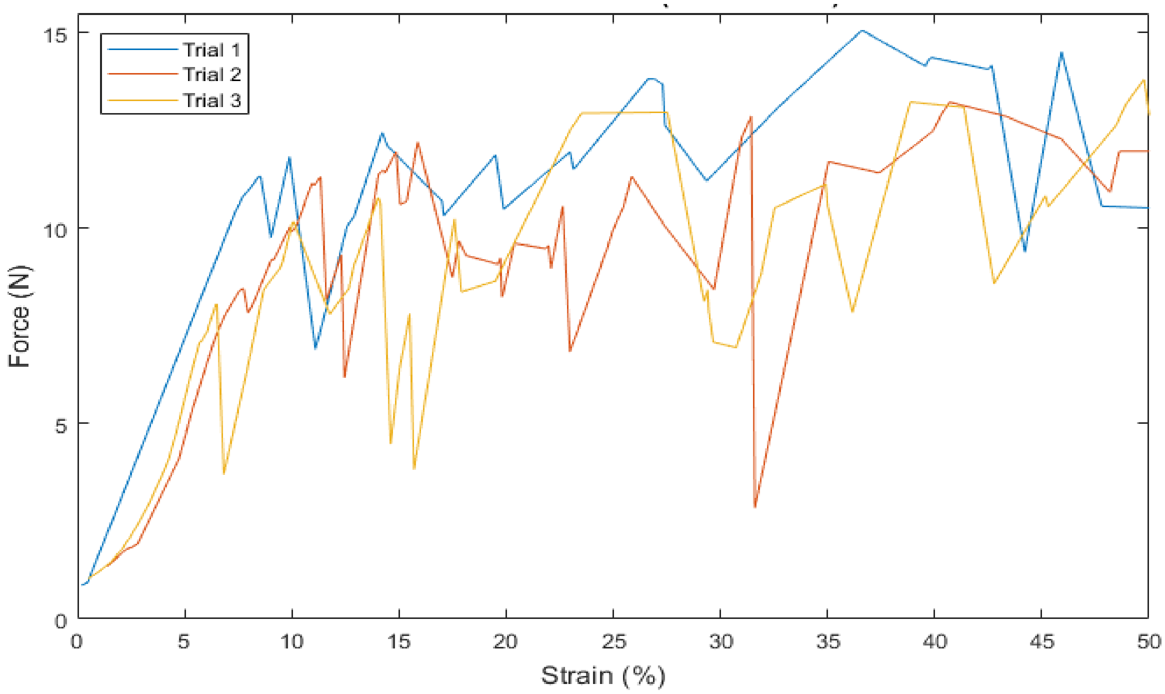


Figure - V-9: Slow Adhesion Test (0.33mm/min)

The following graphs are only visual representation of the data recorded. The analysis and comparison of the results is only done in a later section.

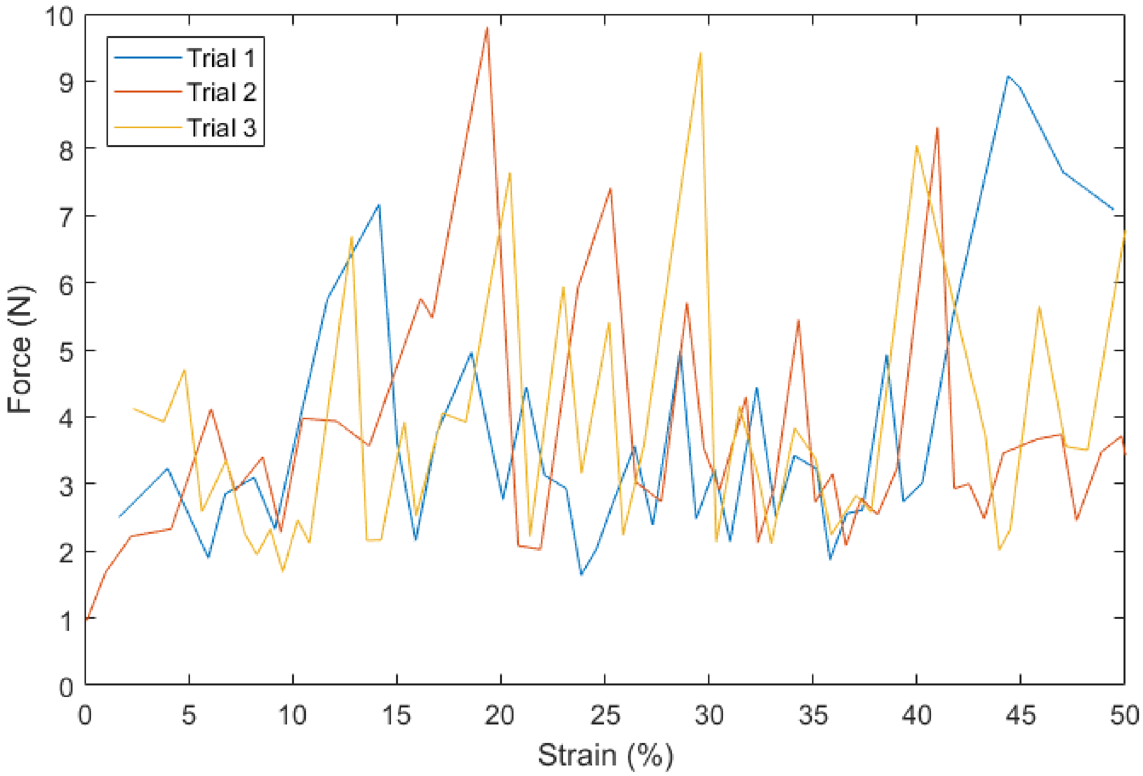


Figure - V-10:Adhesion Test (8mm/min)

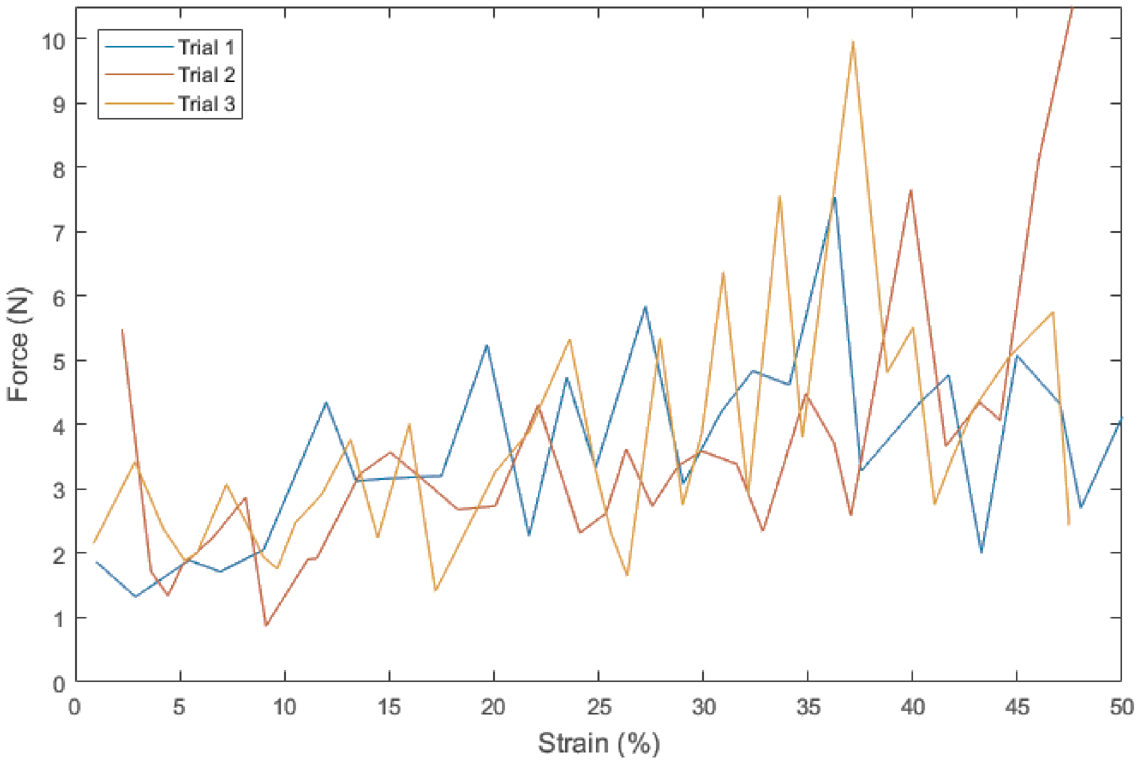


Figure - V-11: Size Adhesion Test (10x15)

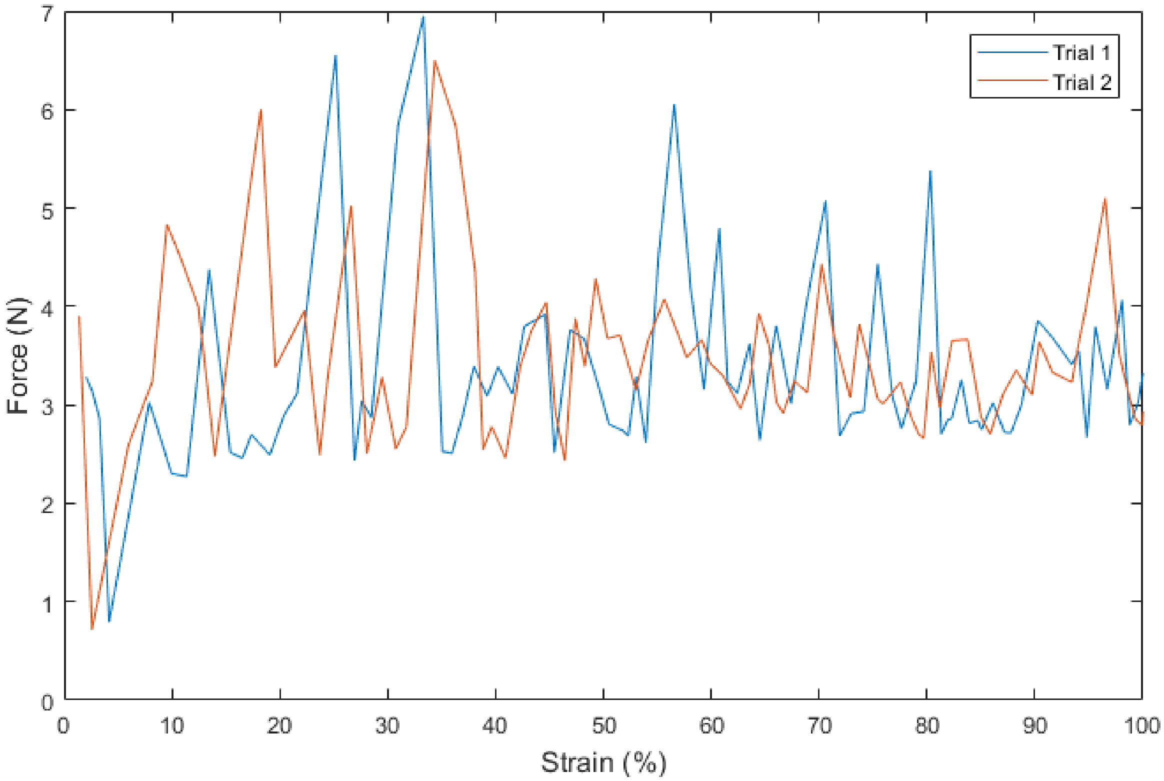


Figure - V-13: Size Adhesion Test (23x34)

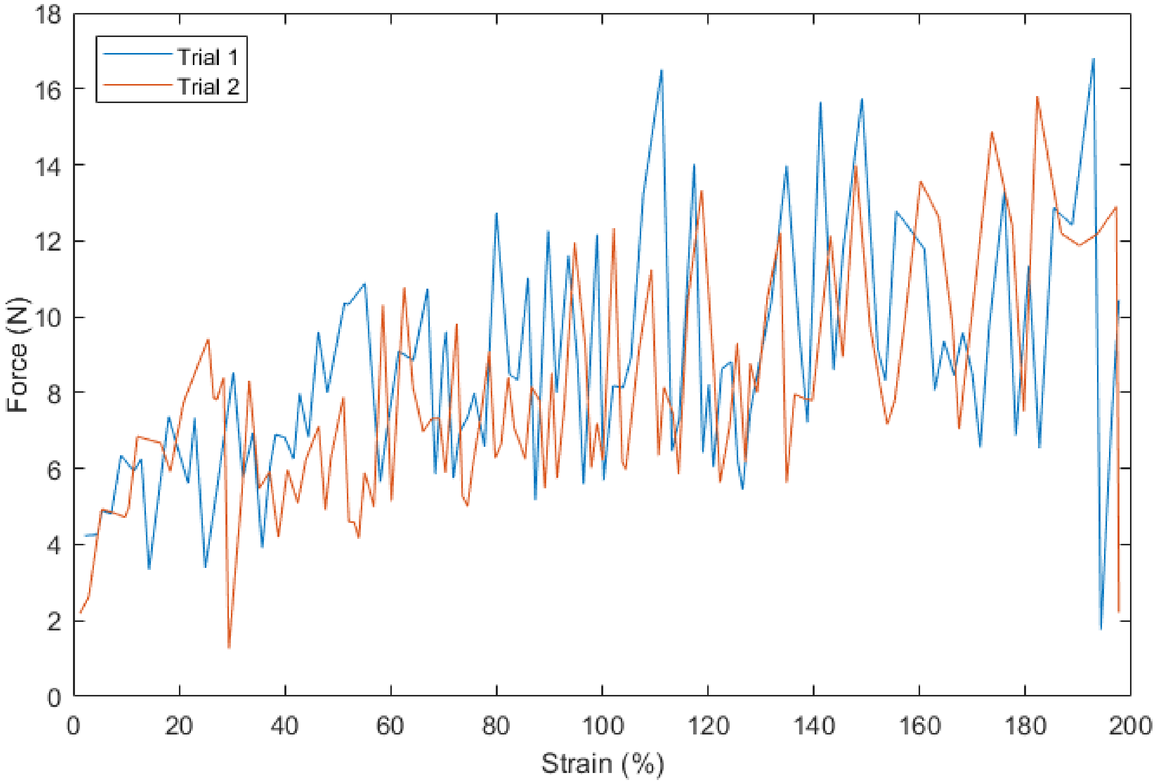


Figure - V-12: Size Adhesion Test (34x51)

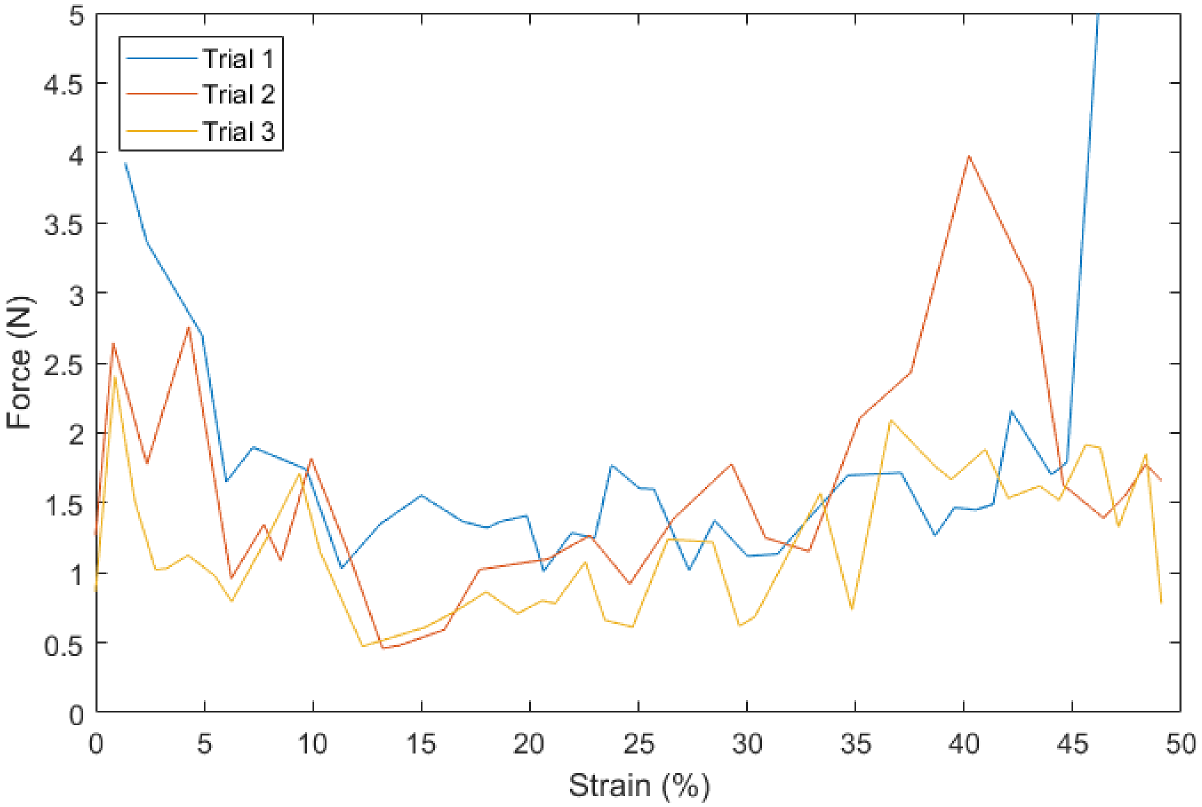


Figure - V-14: Adhesion Test with Air blow

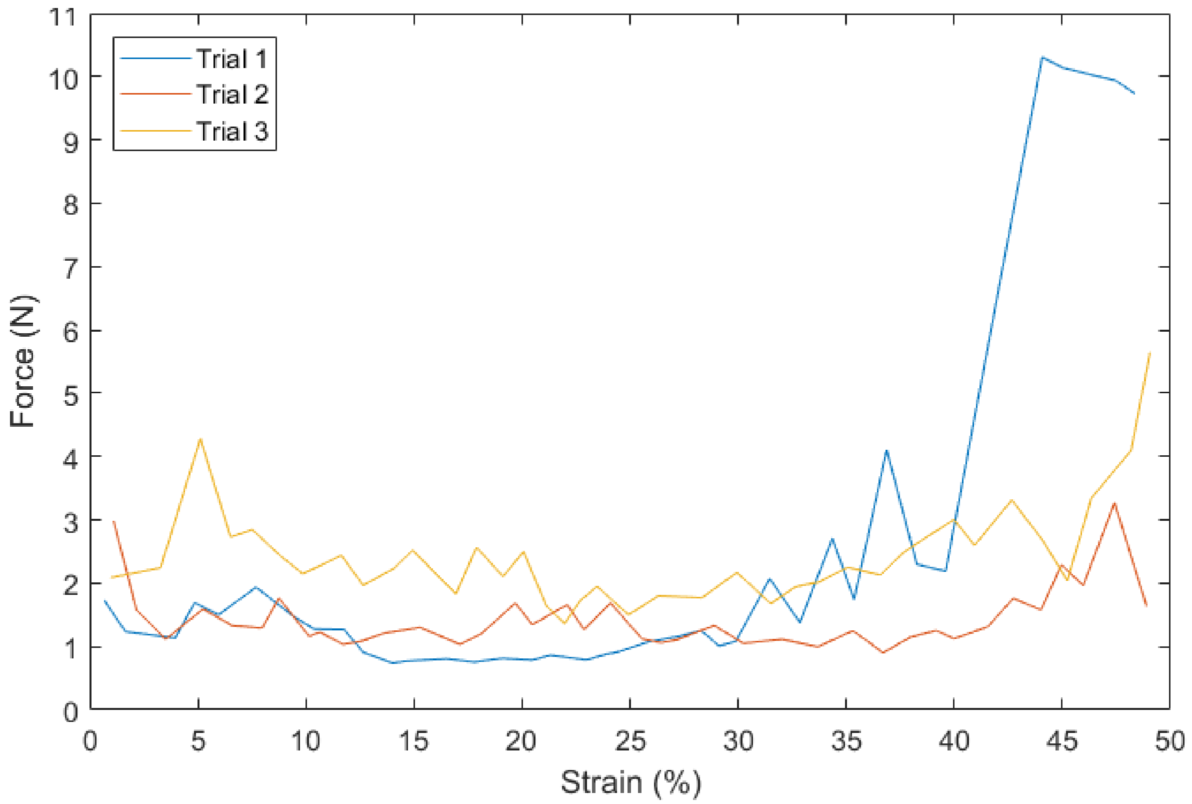


Figure - V-15: Adhesion Test with Surface Temperature of 15°C

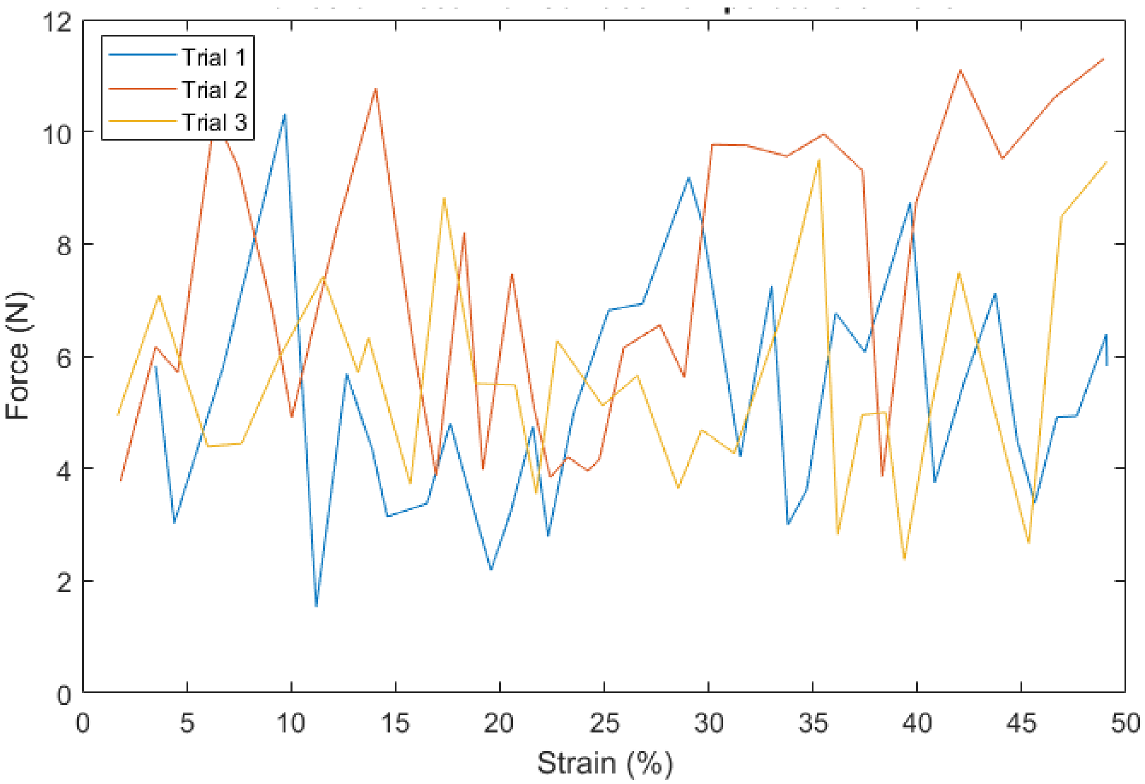


Figure - V-16: Adhesion Test with Surface Temperature of 25°C

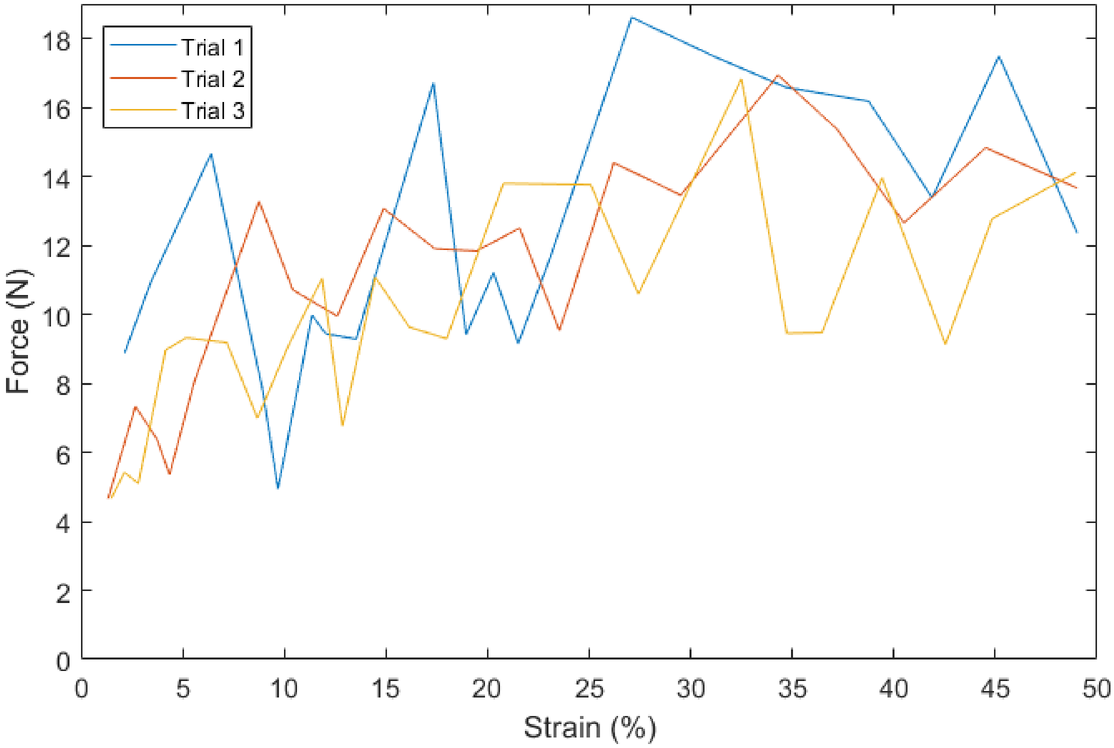


Figure - V-17: Adhesion Test with Surface Temperature of 30°C

V.1.9 Analysis

Before starting the comparison and analysis of the test results a note has to be taken concerning the graphs. Traditional tensile tests are plotted in stress vs. strain. Where the stress is the load over a specific area and the strain is change of length over initial length. However, due to the fact that the length of the film is purposefully increasing, not necessarily perpendicularly to the direction the distance that is measured, and that the film also has some elasticity, the strain value does not provide very much information over the peeled material. Yet, from the speed of the test run and the size of the sample one can estimate the location within the graph. The reason why the graphs are also not plotted in stress, is that the overall force value is much more interesting to these results than the ones compared to the area peeled.

The dataset used for the comparison graphs are the trials with the least outliers and the more consistent results of the three. If all three trials were measured without major outliers the most average value was used to compare to the other conditions.

As it was recorded during the tests at low peeling rates the adhesive gathers at the peeling front causes residue to be left over on the surface of the film. This also leads to much higher forces required, as seen from Figure -V-19, these are 7 times as high as the forces at higher speeds. Whilst the slow curve shows even in the filtered plot, significant peaks and drops within the values, the fast plot shows are much more consistent values, thus reflecting the smoother peel.

This result thereby supports the hypothesis stated earlier that at the peel front adhesive gathers and increases the peel force. It also is a good result regarding the application on the tool since the robot will be much faster than the tested rates. It can even be assumed that the required peeling forces will most likely be even lower than what was measured in these tests.

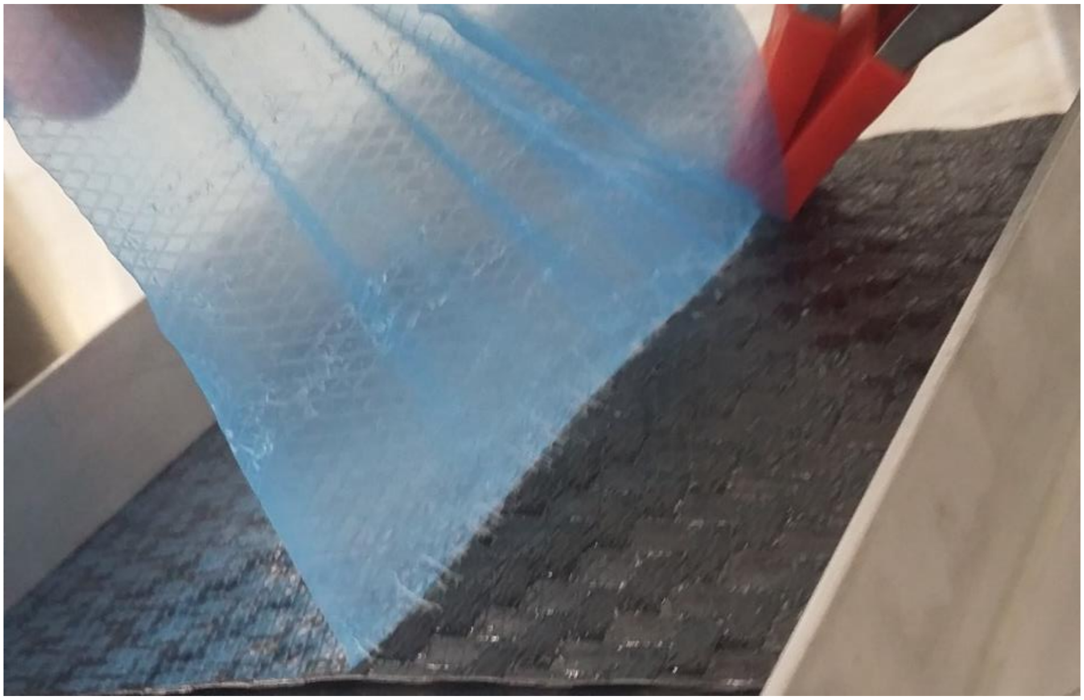


Figure - V-18: Resin Residue from Peeling

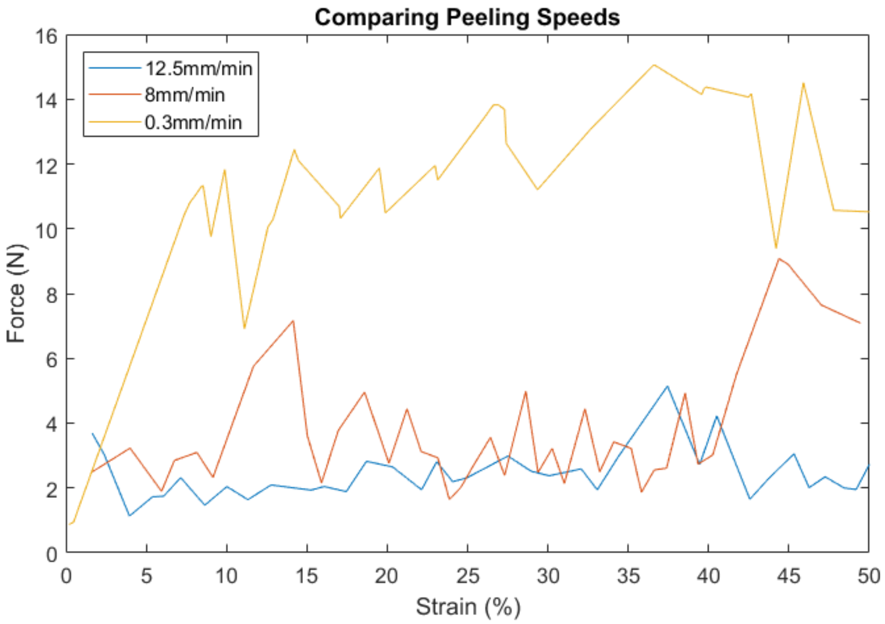


Figure - V-19: Effect of Peeling Speeds on Adhesion Forces

Moving on to the result of the next part of the tests, it can be seen that the glass samples required approximately twice the force the carbon plates do. The drops on the other hand still show to be about the same level. The reason for this is unknown. It could be due to a different impregnation of the resin since the glass mat is thinner than the carbon mat or due to the difference in weave that has not been investigated during the tests. The increase in adhesive force could also be caused by a better surface bond between the fibers and the adhesive than found in carbon mats. However, this is doubtful since usually epoxy resins are especially known for creating the best bonds carbon fibers. Hence, this result does not support the hypothesis but also does not necessarily disproof it since there are many different factors to consider.

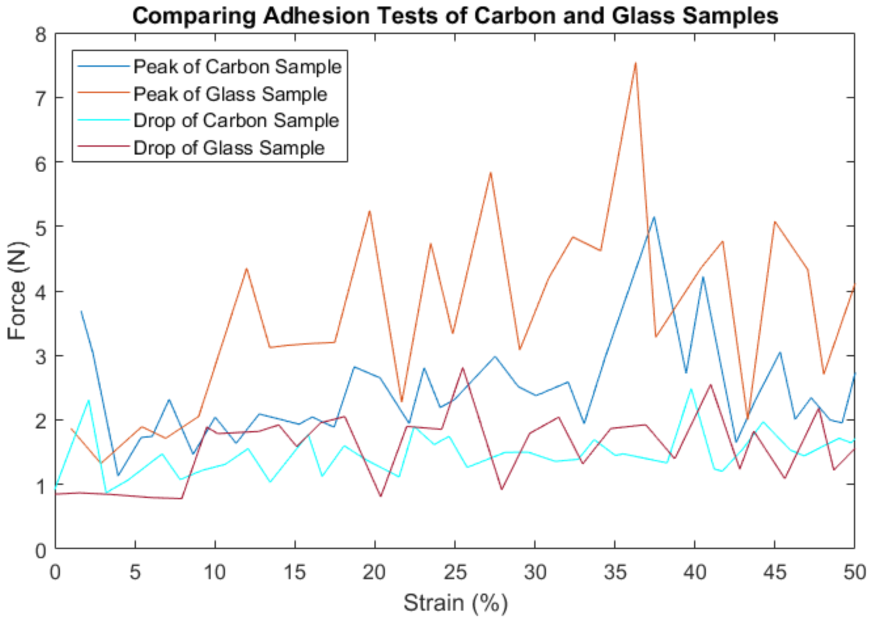


Figure - V-20: Comparing Peeling of Glass and Carbon Prepreg

The air blow test also supports the hypothesis made. As seen from Figure-V-21 adding an external air blow definitely reduces if not halves the adhesive forces. It should however be taken into account that the tested sample had not a very wide span, therefore the blow was able to be affective over the entire length of the width. It is however still to be determined if for larger plies this is also applicable.

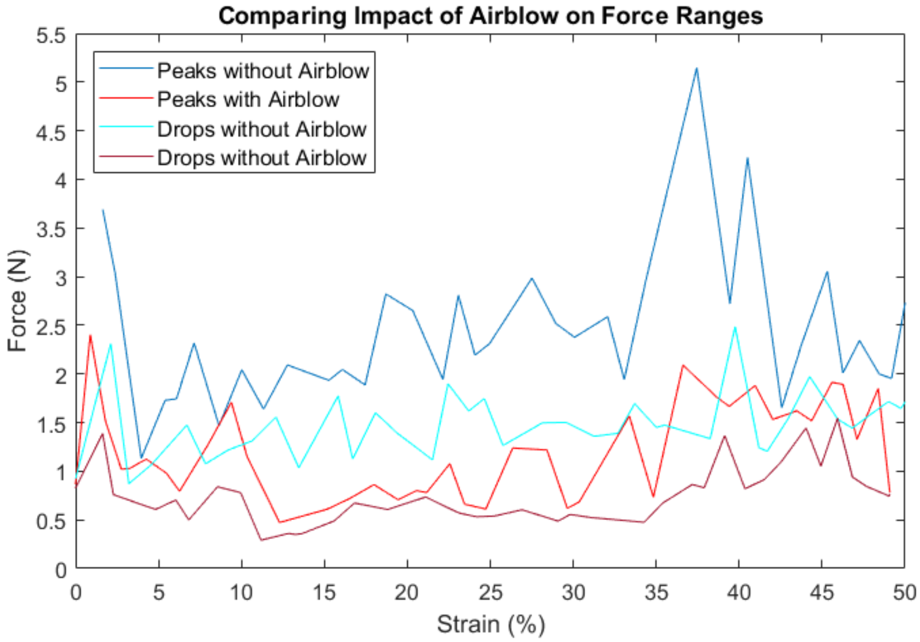


Figure - V-21: Comparing Impact of Airblow on Peeling

The temperature test showed to have a much more significant impact on the overall forces. Whilst at the lowest temperature only maximum 3 N are required, for the same size plate at 30 °C up to 17 N are enquired to peel the film off sucessfully. From the graph, it can be observed that the 4°C difference between 21°C and 24 °C do cause the biggest increase in forces requirements. From these temperature values a general average force per mm at 30°C has been calculated to be 0.175 N/mm. This value will later be ued as a base for the force requirement perdition for larger size plies.

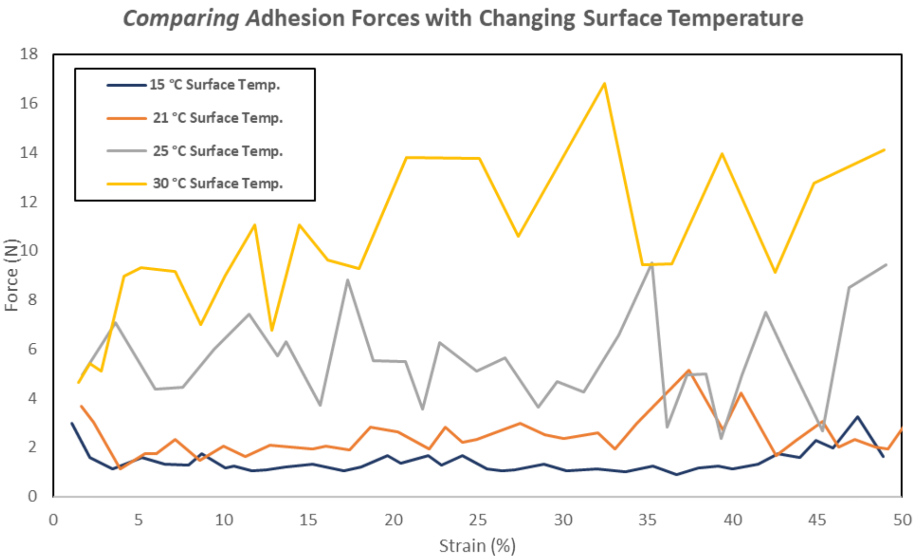


Figure - V-22: Comparing Peeling with Different Surface Temperatures

Finally, the ranges illustrated in Figure - V-23 show the force variations to an increase in size of the ply. It can be confirmed that with every 50% increase of the ply the maximum forces at least doubles. Especially with the lager plies there seems to be in increase in force as the film becomes longer and less control can be exerted over it. The data processing showed that the variety of size all had close force per mm values. These average to 0,05 N/mm. This value is also later used to make predictions for larger plies. These results do support the hypothesis that the relationship between the size and the adhesive force is probably linear.

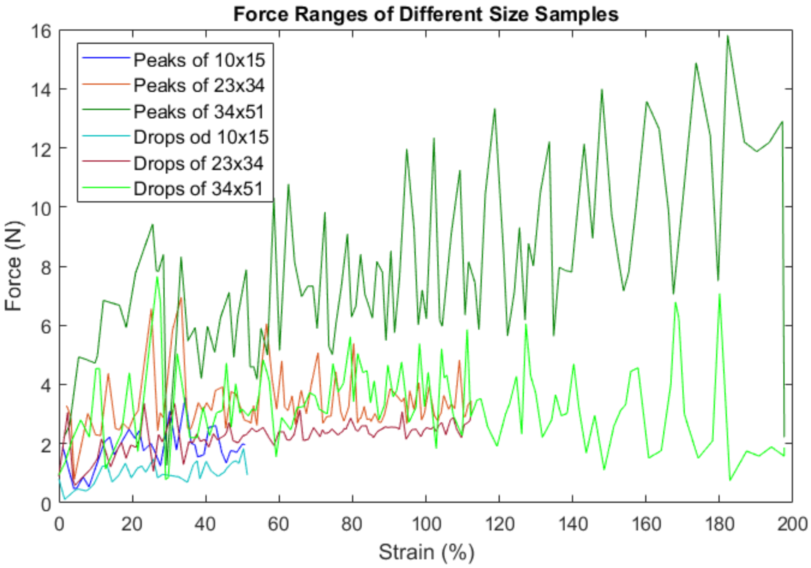


Figure - V-23: Comparing Size Impact on Peeling

From these results predictions are calculated. The prepreg roles used at Rondal do not exceed a width of 1,3m, so a reference graph has been created that includes this width. The graph is illustrated in Figure - V-24. It is not fully correct to add the width and the temperature prediction values, since one partially incorporates the other. This approach at least provides a general idea of the kind of forces need to be dealt with. This graph concludes the tool force requirement to be set to 344N, so that it can handle all plies used at Rondal.

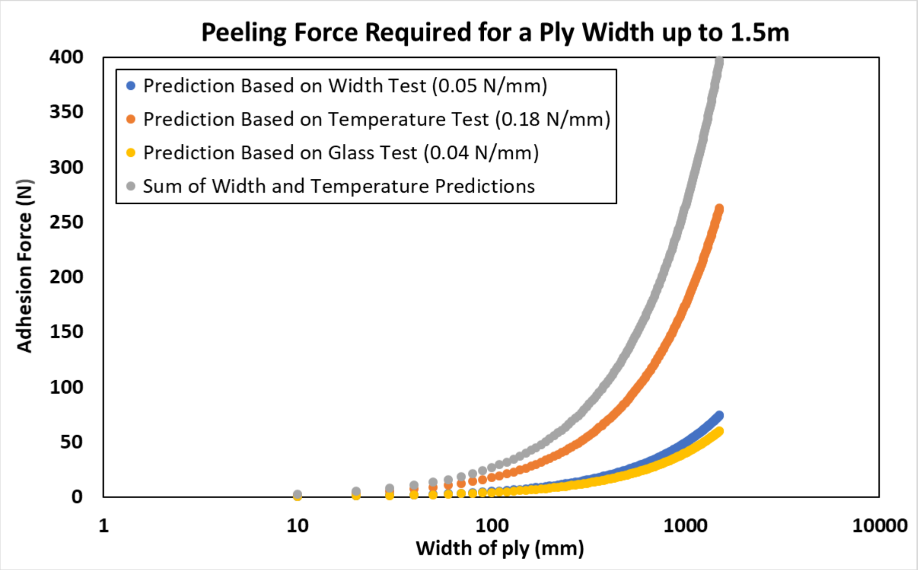


Figure - V-24: Prediction of Peeling Force Requirements

V.1.10 Conclusion

The results of the tests nearly all support the hypothesis that were based upon previous research. The only results that could not support the hypothesis regarding the glass fiber plies, does however support the more general statement made by most researchers: that all results are very dependent upon the type of prepreg used.

To be able to find out more exact requirements than the 344N calculated through the general trends of the behaviors, more test have to be performed looking into the impact of fiber orientations and ply thicknesses. It can be concluded that the width and the temperature are the most significant factors with regards to the peeling of the protective film. The factor of temperature can be altered by ensuring certain environmental conditions via an air-conditioning unit for instance. This shows that the force requirements for a film removal tool are not necessarily equal to the larger adhesion force a prepreg ply creates.