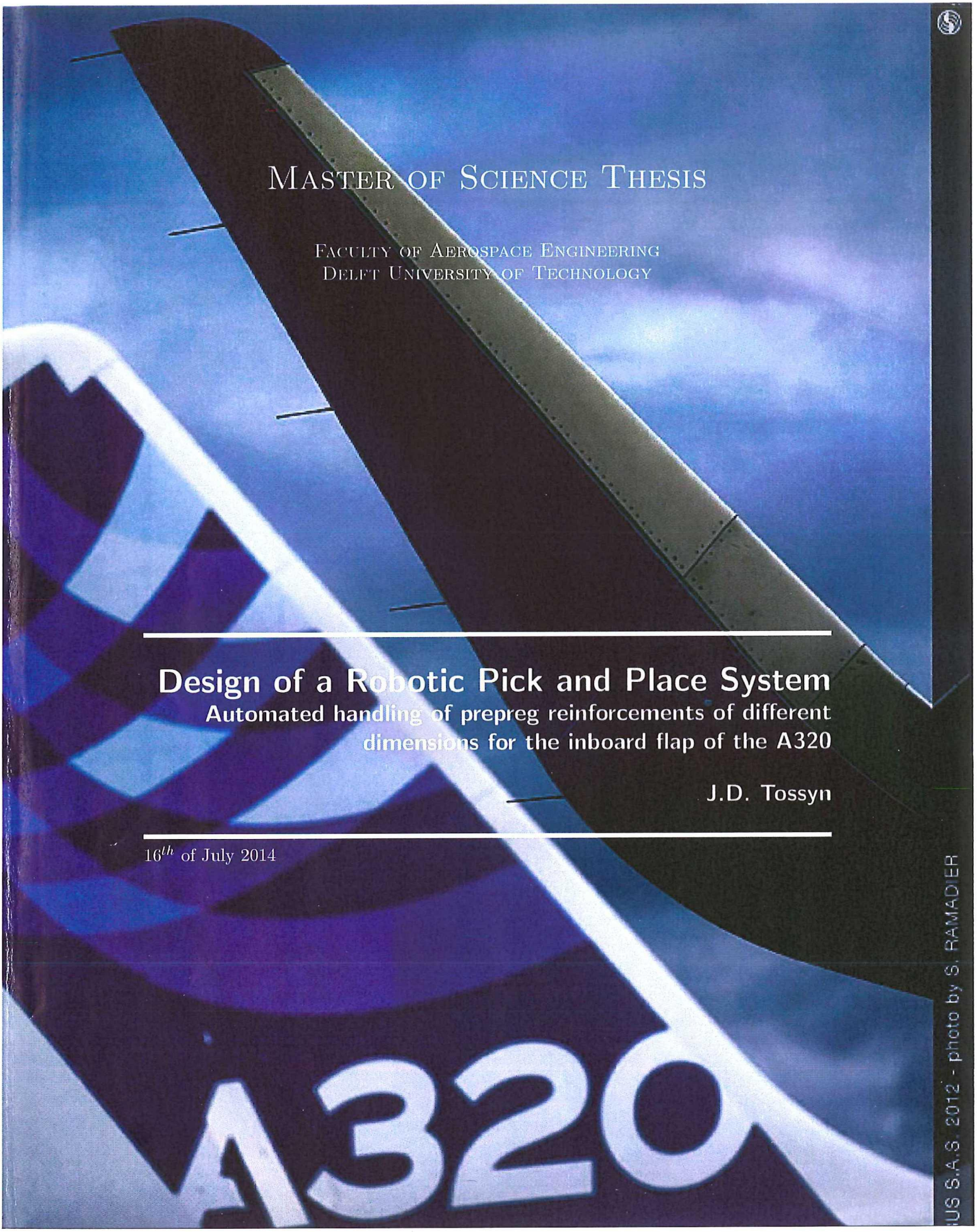

MASTER OF SCIENCE THESIS

FACULTY OF AEROSPACE ENGINEERING
DELFT UNIVERSITY OF TECHNOLOGY

Design of a Robotic Pick and Place System

Automated handling of prepreg reinforcements of different dimensions for the inboard flap of the A320

J.D. Tossyn

16^{th} of July 2014

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For obtaining the degree of Master of Science in Aerospace Engineering at Delft University of Technology

J.D. Tossyn

16^{th} of July 2014

Faculty of Aerospace Engineering · Delft University of Technology

DELFT UNIVERSITY OF TECHNOLOGY
DEPARTMENT OF
AEROSPACE STRUCTURES AND MATERIALS

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Summary

Automation of manufacturing processes is essential to justify the use of expensive carbon fibre materials and reduce the overall manufacturing costs. Besides reducing the processing costs, automation will result in a lead time reduction and an improved quality and repeatability. To attain these advantages, an option is to develop an automated robotic handling system. The system is able to handle prepreg reinforcements and will change the manual lay-up process to an automated process. The part focused on is the inboard flap shell of the A320.

The main goal of this project is to develop a conceptual design which is able to handle prepreg reinforcements of different dimensions. The main challenge of this project is to handle a large variation in dimensions. Next to the handling of the reinforcements, the system should be able to remove the backing paper on both sides of the reinforcements. This way a complete automated system can be achieved. Until today no solutions are either publically available in research, nor at Airbus.
In this research, an individual solution is designed which can be implemented in current production lay-out. Different design choices were made because of its superior expected results and comply with the requirements. To be able to meet the required range of the ATL, an integrated bridge is opted for. To handle all prepreg reinforcements, a multi-actuator handling system will be used. This is a vacuum box in which all holes in the perforated plate can be individually opened and closed using bi-stable solenoid valves. The backing paper challenge is divided into peel initiation and peel continuation. Peel initiation can be achieved by injecting compressed air between the prepreg material and backing paper. To continue peeling movement, an aluminium vacuum roll will peel the backing paper.

From this research it can be concluded that by automating the manual lay-up of the skin, doublers and front and aft spar reinforcements a lead time reduction from 307,5 to 50,79 industrial minutes is achieved. This scenario results in a positive business case for Airbus. A positive business case means that the system has a return of investment within a maximum period of two years. New technologies should meet this killer requirement before being implemented and further developed.

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Delft, The Netherlands
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J.D. Tossyn

List of Abbreviations

Abbreviation	Explanation
AIPI	AIrbus Process Instruction
AIPS	AIrbus Process Specification
ATL	Automated Tape Layer
CEO	Current Engine Option
CFRP	Carbon Fibre Reinforced Polymer
CNC	Computerized Numerical Control
DLR	Deutsches Zentrum fr Luft- und Raumfahrt
IBF	InBoard Flap
IM	Industrial Minutes
LL	Lower Left
LR	Lower Right
NDT	Non-Destructive Testing
NEO	New Engine Option
OBE	OutBoard Flap
Prepreg	PreimPregnated Fibres
ROI	Return Of Investment
SA	Single Aisle
SAP	Systems Applications Products audit
SCARA	Selective Compliant Articulated Robot Arm
UD	Uni-Directional
UL	Upper Left
UR	Upper Right

List of Symbols

Symbol	Unit	Explanation
a	-	Material constant
a	m/s^2	Acceleration
A	mm^2	Contact surface between gripper and laminate
A_n	mm^2	Area of the needle
A_r	mm^2	Contact area
d	mm	Thickness of the dielectric gripper
F_g	N	Total grasping force
F_l	N	Lifting force
F_r	N	Repulsion force
F_{TH}	N	Holding force
g	$\frac{m}{s^2}$	Gravitational constant
h	mm	Height between gripper and laminate
k	-	Material constant
m	N	Mass of prepreg reinforcement
N	-	Number of operations
n	-	Number of suction cups
n_n	-	Number of needles

Symbol	Unit	Explanation
P_{atm}	Pa	Atmospheric pressure
P_u	Pa	Vacuum pressure
P_{vac}	Pa	Vacuum pressure
Q	$\frac{m^3}{s}$	Volumetric flow
r	mm	Radius of the suction cup
r_{ext}	mm	Plate radius
r_{int}	mm	Nozzle radius
S	-	Safety factor
V	V	Applied voltage
V_s	l/min	Required suction rate per suction cup
W_{si}^{ad}	J	Adhesion work
α_n	°	Penetration angle needle
δ	mm	Layer thickness
ϵ	-	Dielectric
γ	°	Leading edge angle
ρ	$\frac{kg}{m^3}$	Air density
σ	N	Surface tension

Definitions

Basic definitions of words used throughout the entire report.

- *Delamination*: Separation of plies from each other.
- *Laminate*: Any fiber-reinforced composite consisting of plies with one or more fiber orientations with respect to a reference direction.
- *Lay-up*: Stack of material in specific sequence and orientation including laminate, breather material, backing material, etc, and so on as required for forming, compaction or curing.
- *Porosity*: Accumulation of small voids in a composite structure
- *Preimpragnated material of prepreg*: Woven fabric or unidirectional tape impregnated with a matrix resin and suitable processes (e.g. B-staged) for storage, handling purposes and curing by heat and pressure without further additives.
- *Rework*: Removal of production and assembly related non-conformances with the aim of reaching the required component condition defined in the engineering documents.
- *Storage life*: The maximum time that the material may be used when stored under the conditions specified in the relevant material specification, excluding work life.
- *Tack life*: The maximum time in normal work conditions as specified in relevant material specification, that the material has sufficient tack to be used for manufacturing.
- *Unidirectional tape*: Semifinished reinforcement material with the reinforcing fibers oriented in the same direction.
- *Void*: Empty space within the fiber-resin system not on the part surface
- *Work conditions*: Environmental conditions, in particular temperature and relative humidity, under which uncured material is processed before start of cure.

- *Work life*: The maximum in normal work conditions as specified in the relevant material specification that the material can be used for manufacturing until starting to cure. Deviations of work conditions, as hot forming process or application of heat for tack improvement, can affect the work life .

Contents

List of Figures

List of Tables

Chapter 1

Introduction

The aerospace industry continuously strives towards weight savings in order to reduce the fuel consumption for airliners and to reduce aviation's impact on the environment [1, 2]. To achieve these weight savings composite materials have gained interest over the years, especially the use of carbon fibre reinforced polymer (CFRP) materials has increased exponentially during the last years as shown in figure 1.1 [3].

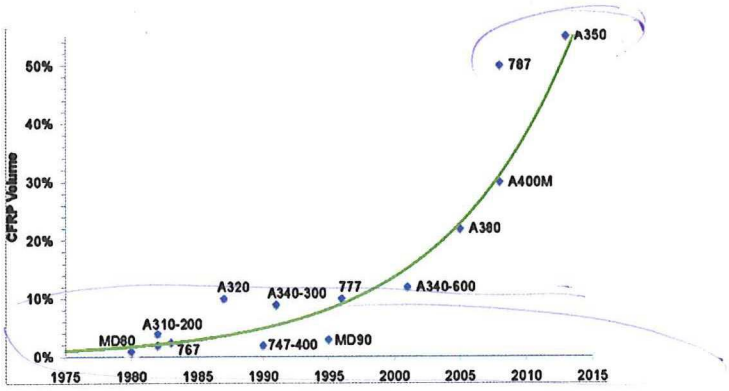

Figure 1.1: Development of carbon fibre reinforced plastic in aircrafts.

As can be seen in the figure, the latest example of the exponential increase of CFRP materials use is the new Airbus A350. The A350 has about 50 % of the structural weight made of composite materials [4]. CFRP materials are mainly used for their low weight and high specific strength and stiffness. For the manufacturing of CFRP materials special manufacturing methods are needed in a cost-effective way. The automation of the manufacturing processes is a must to justify the use of expensive CFRP and reduce the manufacturing costs. Besides a reduction in process costs, automation will lead to reduced lead time, reduced need for inspection and an improved product quality and repeatability [5, 6]. Until today only few sub processes were automated, namely automated tape laying, automated fibre placement and trimming of parts [8].
Airbus, a leading aircraft manufacturer, is the principal of this research. One of the sub

processes which can be automated to achieve these advantages of an automated process is by an automated pick and place robotic system. This robotic system should be able to pick up prepreg reinforcements from a cutting table and stack these laminates in the right sequence and orientation on a mold [4, 9, 10]. The focus of this research is to reduce the lead time of the production of the inboard flap of the Airbus A320 by developing a pick and place robotic system for the stacking of the skin, doublers and front and aft spar reinforcements. Later on the solution can be translated to the production of other parts. To achieve this a complete robotic system has to be designed. This robotic system has to be integrated in the current production lay-out. It is important to know that a tailored solution is needed for each application. Solutions can differ in many ways, different end-effectors, components, control, etc. are possible. It is of great importance to achieve the advantages by investigating the best pick and placement robotic solution for the production of the IBF shells.

Chapter 2

Literature review

In this literature review both the knowledge publically available and the internal research at Airbus have been explored. The aim is not to give a summary, but more a critical thinking. What is known and what is still unknown? Out of this, some questions that need further research can be formulated.
For this critical thinking the literature database Scopus and ProQuest were utilised using a combination of different terms "automation prepreg", "pick and place" and "robotic system composites". From this first research deeper and more detailed research evolved. The Airbus documentation included manufacturing instruction for FRP materials, process instructions and qualification tests.
Today the manufacturing processes using composite materials are still labour intensive. At this moment they can still be performed at reasonable cost and quality. For this reason there is no need for new developments. Therefore only few processes are automated and the equipment of these automated processes is still very expensive. The automation of more sub processes will lead to lower process costs, a reduction in lead time, reduced need for inspection and an improved product quality and repeatability [5, 6]. The automated pick and placement of prepregs can also achieve these advantages.
In this chapter first the robotic pick and place systems are discussed first in section 2.1. Next, the robotic handling movements are reviewed in section 2.2, followed by a short description of the different end-effectors in section 2.3. After that the differences concerning pick and placement of prepreg laminates are evaluated in section 2.4. Then different methods for evaluation the robotic systems and the current research status at Airbus are reviewed in sections 2.5 and 2.6. Finally in section 2.7 it is determined which knowledge is required but is not available either internally of publicly and should therefore be developed.

2.1 Robotic pick and place system

Robotic system lay-out For the design of a robotic system a complete system lay-out should be designed. This system lay-out will vary for different applications. In literature mainly two systems could be defined, first of all a fixed robot mounted on a ceiling or floor and the second one is a robot which is able to move along the ceiling or floor.

Types of robots For the robotic system different industrial robots are available. These robots differ in degrees of freedom, range, kinematics, maximum payload, accuracy, repeatability, motion control, sources of electrical power and finally compliance [7].
Degrees of freedom are the independent motions in which the end-effector can move in three-dimensional space. Possible motions are forward and back, left and right, up and down and may be combined with rotations. The range of the robot is the maximum horizontal distance the robot is able to cover. The kinematics of an industrial robot are the actual arrangement of the rigid arms and joints. This arrangement determines the possible motions. The kinematics are related to the degrees of freedom, the different kinematic classes that can be distinguished are articulated robot, cartesian robot, parallel robot and SCARA robot. The maximum payload of the robot is determined by the load it can carry without losing it accuracy at maximum speed. The maximum payload for different industrial robot types and classes is specified by the robot manufacturer. The accuracy of a robot is defined as the difference between the wanted point the robot aims for and the actual point the robot reaches. The repeatability is the ability to repeat the same motion for the predetermined path. Motion control includes the setup of the robot's limits, offsets, feed rates, etc. Finally compliance is the deviation in angle or distance that the robot's axis will move when force is applied on it.
In total 4 main robot types exist, each of them differ in the parameters defined here. All these robots have their pro's and con's. In total 4 main robot types can be defined; an articulated robot, a SCARA robot, a cartesian robot and a parallel robot.

Robot programming Robot programming is needed to teach the robot from where and to where it has to move and in which manner the movement should be made. To teach this to the robot positional data and procedures need to be programmed. For this teaching different strategies are available. The first teaching method is by possitional commands, the second method is teach dependent and the final method is off-line programming.
The first method, positional commands, works by teaching different x, y and z coordinates to the robot by a computer or a graphical user interface which is connected to the robot. The second teaching method, is teach dependent. It works by manually moving the robot to the desired positions. With this method one can choose to memorise the path followed manually by the robot, so it is able to execute the path in the next cycles. The other option is not to memorise the path and just manually move the robot to the desired positions. This method is mainly used if the robot isn't programmed yet. Finally off-line programming is available; here the robotic cell and all the machines can be graphically mapped with a program that can be bought from the robotic supplier. It is possible to program all the motions of the robot with great accuracy relatively easy.

2.2 Robotic handling movements

This section reviews the main movements the robot is able to perform during the pick and placement of different dimensions. But first of all, what is handling? According to Buckingham [11], handling is the movement of a laminate from a cutting table to a mould or lay-up table.

Pick up After the dry composite sheets or prepreg laminates are cut, the robotic system should be able to pick up the prepreg. For the pick up of the prepreg, the main task of the robotic system is to pick up and if needed separate the material. The separation from the lay-up table should occur without interference with other prepregs. This interference may be present if two laminates overlay or clipping between laminates is present. This clipping is a mechanical locking between two pieces of laminate, caused by non straight cutting [12]. Angerer [13] also supports this statement and has experienced several difficulties for clearing dry CFRP textiles from a cutting table. These pick up difficulties for dry CFRP textiles are present, since the textiles are permeable to air and highly anisotropic. Angerer also defined that the pick up of a dry textile surrounded by scrap material or other textiles is still a hard process to automate. The clearing of dry textiles which vary in dimensions complicates the clearing even more.

Pick up strategies For the pick up of these dry textiles Seliger defined some pick up strategies. In total 4 different pick up strategies are available, as can be seen in figure 2.1. In figure 2.1.a a plane ply movement orthogonal with all over attachment pick up strategy is shown. Figure 2.1.b shows a parallel pick up strategy. Here a gripper grips the textile and moves paralell to the underlying textiles to clear it from the table. The third pick up strategy (figure 2.1.c) is a peeling ply movement along non-linear paths. Here a roller moves along the textile and in this way it can pick up the textile. The last strategy, as can be seen in figure 2.1.d is a combination of the strategies mentioned above in successive and simultaneous order.

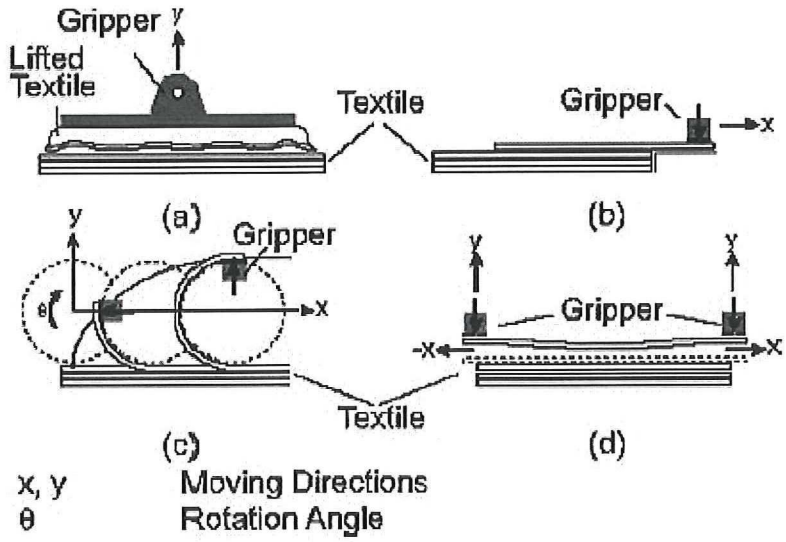

Figure 2.1: Pick up strategies of dry textiles from a flat table.

Placement Once the textile or prepreg is lifted and transferred, the robot needs to lower the textile or prepreg and place it on a flat surface or curved mould and position it securely [11]. The placement can have two different forms, namely the placement of the laminate against the mould which is treated with release agent or either the placement on

top of another layer of laminate [14]. Seliger also defined that the main functions during placement are the positioning and orientating of the laminates on the mould or on top of another laminate.

Placement strategies In general for double curved moulds the initial placement point should be in the middle of the mould or laminating table and yield towards the outer side of the laminate. Another placement strategy can go from one side of the laminate to the other, in order from left to right. By following these strategies, bubbles and wrinkles in the laminate are eliminated. Seliger [14] concluded that for the placement of prepreg laminates proper first contact is needed and inclusion of air pockets during pressing the laminate on the mould or another layer of prepreg should be avoided. Figure 2.2 shows five different placement strategies are shown. These five different strategies have diverse approaches of placing the prepreg laminates on a flat table. The strategies also differ in first contact points and lay-up strategies.

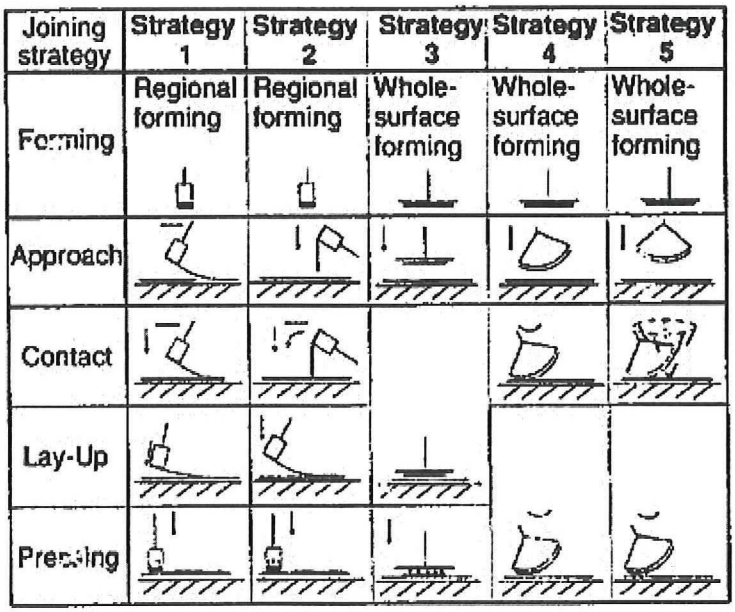

Figure 2.2: Placement strategies of dry laminates on a flat surface.

2.3 End-effector

The end-effector is a device at the end of the robot arm which is able to pick and place composite materials. Lots of research on different end-effectors is available. This research mainly includes the gripping of dry carbon textiles and leather plies used for non-aerospace applications. A great variety of end-effectors is present. These end-effectors differ in connection types, effect and physical principles. The variety of end-effectors can be seen in figure 2.3.
The main working principles and holding forces of the end-effectors have been investigated and are briefly discussed in this section. The end-effectors reviewed are the mechanical

gripper, the suction gripper, the Bernoulli gripper, the needle gripper, the adhesive gripper, the hydro adhesive gripper, the electrostatic gripper and finally the carden gripper.

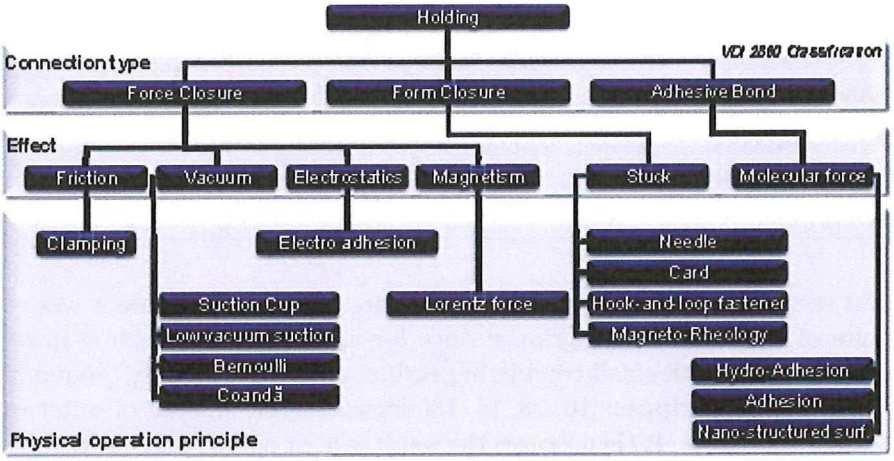

Figure 2.3: Overview of different end-effectors systems.

The needle gripper [10, 11, 13, 15, 16, 18] is an end-effector that uses needles to penetrate the laminate or fabric at a certain angle. The main drawback might be the damage to the carbon fiber materials. In the literature there is no real consensus on whether damage is present if needle grippers are used. However one of the research studies shows no reduction in structural integrity of the carbon fibre material. To test this, large loads were applied to the laminate. However for uni-directional (UD) prepregs relative motion of the fibres may be present, which can lead to lower precision of the laminate fibre orientation [17].
The second end-effector is the **vacuum gripper** [10, 11, 13, 15, 18, 23]. It uses a suction cup in combination with vacuum to lift the laminate. Problems may be present depending on the surface roughness. The higher the roughness of the surface, the higher the chance leakage is present. Besides this, if the suction force is too high, permanent deformation of the laminate can occur, which is of course unwanted. For this application the surface roughness is determined by either the backing paper or the surface of the prepreg. Both are smooth and therefore the vacuum gripper is recommended for the pick and placement of prepreg material [18].
The **Bernoulli gripper** [10, 13, 24], uses instead of a suction force a repulsion force that is applied at the nozzle. If the gripper is positioned at the right distance from the dry textile or prepreg, the gripper will be able to lift it without actual contact.
The **Adhesive gripper** [10, 11, 13] uses an adhesive that sticks to the laminate and because of the adhesive force it can pick it up. This method has two main drawbacks, namely the adhesive force decreases over time and will therefore need maintenance; and second the glue is transferred to the laminate, which might be unacceptable.
The **electrostatic gripper** [10, 15, 18] is able to lift electrical conducting materials. Carbon fibres are an example of an electrical conducting material. The lifting force can be achieved by electro adhesive forces between the end-effector and the laminate. It is important for electrostatic grippers that the electronic circuits are protected from dust at all times. This has to be ensured for proper function of the electrostatic gripper. From

Table 2.1: Gripper principle and corresponding holding force

Gripping principle	Holding force
Needle gripper	$F = \sigma A_N n_n$ [17], where $A_N = \frac{\delta^2 tan(\frac{\gamma}{2})}{sin\alpha_N}$
Vacuum gripper	$(P_{atm} - P_{vac})\pi r^2 > mg$ [26]
Bernouilli gripper	$F_g = F_l - F_r = (\frac{1}{2}\rho\frac{Q^2}{2\pi h^2}[ln\frac{r_{ext}}{r_{int}} - \frac{1}{2}(\frac{r_{ext}^2 - r_{int}^2}{r_{ext}^2})]) - (\rho\frac{Q^2}{\pi r_{int}^2})$ [24]
Adhesive gripper	$F = aN^{-k}$ [18]
Electrostatic gripper	$F = \frac{\epsilon AV^2}{2d^2}$ [18]
Cyro gripper	$F_h = \frac{W_{si}^{ad} A_r}{\delta} = \frac{\sigma_l g(1+cos\theta)A_r}{R_z}$

literature it seems that high electrical potentials are wanted. Therefore it was concluded that the use of the electrostatic gripper since lay-up areas where carbon materials are used is contaminated with small conducting carbon particles which fly around [25].
The **hydro adhesive gripper** [10, 13, 15, 18] deposits a low amount of water vapour on the dry textile or prepreg. It then freezes the water vapour and by this a contact surface is created and the textile or laminate can be lifted. To release the textile or laminate again the ice is heated and the water evaporates. When heating the ice, the resin can melt a bit which is unwanted [18]. Furthermore it is possible that the water droplets permeates the material and influence the mechanical properties.
Finally **Mechanical grippers** come in different varieties, in contrast to all the other gripping methods it actually get a grip on the textile or laminate. Different mechanical grippers available are tension jacks, clamps, flexible fingers, etc.

Holding force All the end-effectors need to ensure proper gripping of the dry textile or the prepreg. From research different formulas were found to calculate the holding force of the end-effector depending on its influencing factors. The holding forces of the end-effectors are summarized in table 2.1.

Conclusion end-effectors It can be concluded from literature that there is no ideal end-effector. To find a suitable end-effector a trade-off should be made. The end-effector depends mainly on the material it needs to pick up. For example dry textiles are limb, permeable to air and isotropic [13], where prepregs are more rigid and airtight.
It can also be concluded that different factors influence this end-effector trade-off. The influencing factors can be divided into two main groups, namely robot factors and second material influencing factors [17]. The robot influencing factors are the type of movement, robot speed, robot acceleration, the number of end-effectors, the temperature and finally the humidity. Where the material influencing factors group the laminate dimension, the thickness of the material, the mass per unit area, the air permeability, the surface quality and the material rigidity.

2.4 Prepreg materials

One may ask: what is the main difference between the pick and placement of prepregs and dry textiles? Prepreg materials are mainly used in high quality markets, such as the

aerospace industry. High quality, measurable and repeatable parts are required in the aerospace industry to reduce rework and guarantee reliability. The pick and placement of prepregs contributes to an increased part quality, however it is still a rather unexplored field. The main difficulties found in literature compared to the pick and placement of dry textiles are the tack, the rigidity of the prepreg and finally the presence of backing paper on both sides of the prepreg to prevent contamination.

Prepreg tack Prepreg tack is a challenging paramater for the pick and placement of prepregs. In contrary to dry fabrics, prepreg materials are a sticky material for which no suitable end-effectors can be purchased off the shelf right now. However, several researchers recommend the use of vacuum grippers for the pick and placement of prepregs [10, 5, 11]. The tack of the material is related to the surface wetting of the fibres by the resin. This tack is affected by different factors, namely the resin type, fibre to resin ratio, the distribution of resin and the temperature. The tack will also influence the end-effectors, because, if no backing paper is present, resin may be left on the end-effector.

Rigidity Contrary to dry fibre sheets, prepreg sheets are more rigid. This increased rigidity has several implications for the robotic pick and place system. First of all because of the higher rigidity of the prepreg, will implicate that some pick up methods are hard to achieve or even impossible. Because of its higher rigidity, the prepreg is not that flexible. Therefore it will be harder to drape the prepreg compared to dry textiles.
The rigidity of the prepreg is influenced by the temperature of the clean room. A higher temperature will lead to more tack and in its way to decreased viscosity [17].

Backing paper The prepreg laminate is either covered with a protective foil on one or two sides of the laminate. The backing paper is present to protect the prepreg from contamination. An automated pick and place system should therefore also be able to peel this backing paper from the prepreg. Buckingham states that "peeling is an intrinsically difficult process to automate on the factory floor" [11]. Also Lindback [5] concluded that the removal of the backing paper from the laminate is still a difficult process and needs future investigation. Peeling itself can be divided into two main steps, namely initiation and continuation. So the question rises, what is the best method to remove the protective foil? Review shows that the initiation step causes the difficulties. Some requirements for the removal of the protective film are stated by Buckingham [11]:

- The prepreg must be held down, the down force must be greater than the normal component of the peel force to stop the prepreg lifting from the lower surface.
- Tags, vacuum and needle grippers are effective ways of initiating the removal of the backings, although manufacturing the tags by having to cut through the prepreg, but not through the backing paper makes this method unattractive. The use of needle grippers for removal is overtaken by several authors [11, 14].
- Peeling is best initiated at a corner of the laminate and once initiated, peeling should follow a direction that minimizes the width of the peel front. UD material should be peeled along the direction of the fibres and profiles along their length.

- Peeling of the backing paper from the prepreg is best peeled off at an angle of between 90 and 135 degrees and at speed of 0.1 m/s.
- Lowering the temperature at which peeling occurs is advantageous, especially with high tack prepregs. Afterwards visual inspection is needed to check whether no protective foil is left on the laminate.

Besides protecting the prepreg from contamination, backing paper is present to prevent delamination of the prepreg during handling. This especially holds for UD materials [11]. Backing paper is also important for UD materials to avoid tear initiation. Tear initiation could occur during cutting and therefore the prepreg is covered with backing paper on both sides of the laminate. UD material tends to delaminate under low loads [11].
For the automated removal of the backing paper different concepts are present. Monkman concluded that the use of a needle gripper can be used. Another option is presented by Sarhadi [28], he used a pinch roller or a spiked wheel to separate the backing paper from the laminate.

Prepreg storage life The prepreg storage life of an prepreg can be divided into three main components, namely shelf life, tack life and out life. The Shelf life of a prepreg laminate is the maximum storage life of the prepreg laminate in a sealed bag in a freezer at -18 degrees Celcius. The tack life is the time that the prepreg possesses enough tack for the lay-up at room temperature and finally the out life is the maximum time the laminate can be kept at room temperature after removal from the freezer.
The shelf life of a CFRP prepreg averages around 12 months. After removal from the freezer it can be kept out of the freezer for a maximum of 30 days out. This is called the out life. However the prepreg possesses enough tack for the lay-up for about 10 days.

2.5 Evaluation of robotic system

To evaluate the performance of the robotic system different possibilities were present in literature. The first option is to test the technical feasibility of the entire system and the section to test smaller subsystems of the entire system.
For the technical feasibility study of the entire robotic system a working prototype or simulation can be made. For the prototype an industrial robot and end-effector is needed, an actual lay-out can be replicated and tested. For the simulation of the robotic lay-out, simulation software can be used. This simulation software is provided by robot manufacturers and can later on be used for off-line programming of the robot. The simulation software visualizes and simulates all the robotic movements and cycle times.
In literature it was found that different studies of smaller subsystems are available. These studies of the subsystems include a prepreg inspection study, a gripper study, a lay-up and consolidation study, a backing paper removal study and a commercial viability study. The prepreg inspection study ranges from inspection of the prepreg itself to the measuring of the tolerances after lay-up and whether the tolerances are met [11]. The gripper study compares and evaluates different end-effectors. The end-effectors holding principles and

forces are tested. Besides this the theoretical holding forces are validated with experimental data. The lay-up and consolidation study evaluates the accuracy and orientation of placement on the lay-up table or mould [11]. The backing paper removal study evaluates the peel initiation and continuation methods. Finally Buckingham checked the commercial viability of a robotic pick and place system and concluded that for his application the automation was economically viable [11].

2.6 Current situation at Airbus

Until today there is only a limited amount of attention for the pick and placement of carbon fibre materials at Airbus. The research performed by Airbus, almost perfectly fits the findings in literature. Namely no research in the field of pick and placement of prepreg is present and only small developments for dry textiles are available. Research performed by Airbus includes an investigation of the damaging effect of different end-effectors on different dry fabrics.
Within Airbus no research was found for the pick and placement of prepregs. For the pick and placement of prepregs, compared to dry textiles, one should take into account the prepreg tack, need for backing paper removal and prepreg tack during placement. Within the factory some pick and placement systems for cured parts can be found. However these systems are simply bought from other companies.
Internal documents at Airbus gave insight in different requirements for the manufacturing of CFRP monolithic panels. Requirements are set for the CFRP material, prepreg cutting, the lay-up and the lay-up area. It is important that the robotic system will operate within these requirements.

2.7 Conclusion

The aim of this literature review was to define what knowledge was already available and what needs to be developed. The principles for pick and placement of dry fabrics are understood widely. The pick and placement of prepregs is still a rather unexplored field for Airbus, as for the academic world. Besides this every pick and place system comes with its own difficulties. Therefore there is no fixed solution for each problem and an individual solution for this problem should be found.
From the literature review two possible research areas arose. First of all the design of a robotic system which is able to pick and place prepregs of different dimensions. Second, placement of the prepregs on a double curved mould. It is judged that the need for a robotic system is the first big step in the automation of the lay-up process and that the placement of the prepregs on a double curved mould is another research topic. Hence the objective of this research becomes:

"Design of a pick and place robotic system which is able to pick and place prepregs of different dimensions and remove the backing paper on both sides of the laminate."

With this different research questions have to be answered:

- What is the best robotic system lay-out and what are its functions and attention points?
- How can the end-effector handle prepregs of different dimensions and which end-effector should be used best?
- When and how should the backing paper be removed from the prepregs?

The research is broken into four phases, as illustrated in figure 2.4. It starts with the conceptual design; here different concepts for the robotic system, end-effector, handling of different dimenions and backing paper removal will be evaluated. At the end, the different concepts will be traded on different criteria. Afterwards the final concept is validated. For this a simulation of the entire robotic solution will be made. Next to this, the backing paper initiation concept will be tested and an economic analysis will be used to validate its economic viability. In the final phase conclusions for this research, future actions for Airbus are determined. A more detailed illustration of the work packages and time frame of these work packages can be found in appendix A.

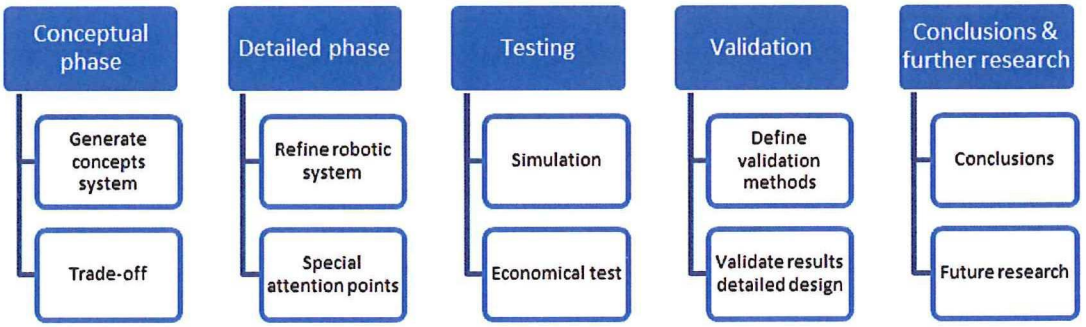

Figure 2.4: Research structure.

Chapter 3

Current production Airbus

Airbus Stade is a part of the Airbus group and is a global leader in aeronautics, space and defence related services. The Airbus group is located all over the world, but the manufacturing is mainly based in Europe, more particularly in France, Spain, the United Kingdom and Germany. Airbus Stade in Germany is the leading center in the use of CFRP materials and employs 1800 people. Airbus Stade is responsible for the production of the vertical tailpane of the entire airbus family, including the A400M, the in and outboard flap for all single-aisle programs, except for the inboard flap of the A321, the spoilers of the A330 and A340, the pressure bulkheads for the A320, A330 and A380, the wing panels of the A400M and as of recently the upper wing shell of the new A350XWB, which is the largest CFRP part for Airbus. The focus of this research is the lead time reduction of the inboard flap of the A320. First the inboard flap is shown to get better understanding of the part and after the main processing steps are shown in respectively section 3.1 and 3.2. After, the need for automation is explained in section 3.3 and finally the requirements for the automated manufacturing of the flap are summarized in section 3.4.

3.1 The inboard flap

The IBF shells are full CFRP stiffened panels. In total 4 different shells can be distinguished, namely upper left (UL), upper right (UR), lower left (LL) and lower right (LR). The left and right shells of either the upper or lower part of the flap are identical. The only difference present is that they are mirrored along the xz-plane. The upper shells consist of 6 stringers, constructed by using 2 L-profiles and 5 U-profiles. The lower shells have 4 stringers and are built up by 2 L-profiles and 3 U-profiles. The stringers are interrupted by a track area; the track area is present to attach the hydraulics. The hydraulics are needed for the extension of the flap from the wing. The shells are slightly double curved, but have a rectangular shape. To get a better impression, the shell of the IBF is shown in figure 3.1.

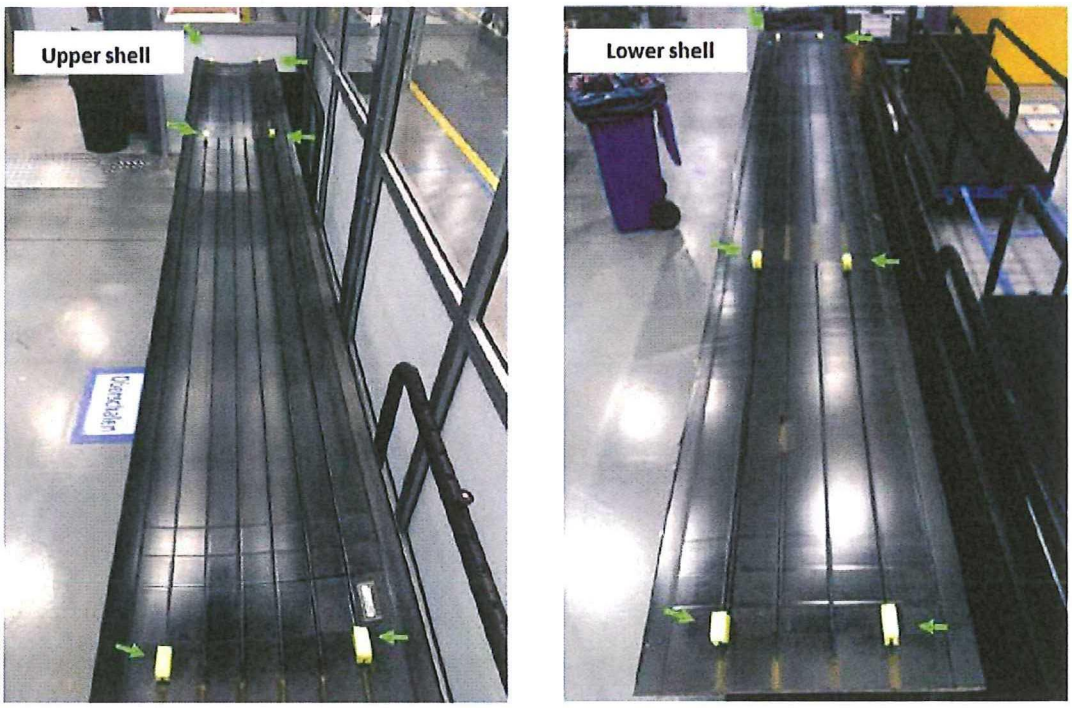

Figure 3.1: Impression of the IBF shells, showing the upper shells on the left hand side and the lower shells on the left hand side.

3.2 Main processing steps inboard flap

To get a good understanding the main processing steps are discussed here. In other words the current production process is reviewed [29, 30].
First the automated tape layer (ATL) lays prepreg carbon fibre tapes on a flat lay-up table. Figure 3.2 shows the ATL and ATL lay-up table. This lay-up table is covered with backing paper to protect the prepregs from contamination. The ATL lays the prepreg carbon fibre tapes over a certain length and orientation on top of each other. The different orientations of the carbon fibre tapes can be either 0°, ± ° 45° or 90°. At the end the prepreg is covered with backing paper on top. The automated tape layer is an automated computer guided robot that lays UD-tapes with a width of 300mm on a flat tooling surface with a length of 27 meters and a width of 5,5 meters. The automated tape layer lays the carbon fibre tape in different orientations on top of each other into one big laminate, as can be seen in appendix B in figure B.1 for the upper shells and in figure B.2 for the lower shells. When the ATL is ready, the CNC cutter cuts three sets of skins, doublers and spar reinforcements out of it. The skins, doublers and spar reinforcements can be seen appendix B in figure B.1 for the upper shells and in figure B.2 for the lower shells.
The next step is to cut the skin, doublers and spar reinforcements from this big prepreg laminate. To cut the laminate an ultrasonic computerized numerical control (CNC) cutter is used. During one ATL cycle three sets of skins, doublers and spar reinforcements can be cut. Such a set can be UR, UL, LR or LL. The lay-up table allows the laying of

prepreg carbon fibre tapes on one half of the table and cutting the big laminate on the other half by means of a CNC cutter at the same time. In other words when the ATL finished its cycle on one side of the table, it can start its next cycle on the other side of the table. When the ATL starts its new cycle, the CNC cutter can cut the sets of skin, doublers and reinforcements.
It is also important to know that no fixed starting position is present for the ATL cycle. The starting point is manually determined by a worker. The ATL then communicates the starting point coordinates to the CNC cutter, so it knows where to start cutting the skins, doublers and spar reinforcements.
Now the actual lay-up of the shells can take place. First the backing paper on the upper side is removed. The prepreg skin is then turned over and placed on the lay-up table. When its layed down the backing paper that is now laying on top is also removed. This strategy is followed for the stacking of the doublers and front and aft spar reinforcements. The doublers and reinforcements are stacked in a predetermined order, as can be seen in appendix C for the upper shell and appendix D for the lower shell. When the manual stacking of the shell is finished, the prepreg skin reinforcement is placed manually on the double curved mould.
Parallel to that the U and L-profiles need to be shaped. For this, the stringer reinforcements are placed on mandrels and transferred one by one to a press. When a mandrel is placed in the press, the press is lowered and the temperature is raised. Because a rise in temperature and pressure of the press it is possilble to deform the stringer reinforcements into U and L-profiles.
The mandrels with U and L-profiles are positioned next to each other and clamped. Now it is possible to rotate the mandrels 180° and lower them on the mould with the skin. The mould with skin and U and L-profiles including the mandrels can now be prepared for curing in the autoclave. To prepare for curing a layer of release film, breather and vacuum foil is used. The vacuum foil is sealed with tacky tape. The shells can be placed into the autoclave. The curing process cycle takes 9 hours in total and the temperature is raised to 180 ° Celsius.
After curing the shells are demoulded. The release film, breather, vacuum bag and tacky tape are removed. It is also important that excess resin is also deburred from the shells. The shells can now be CNC trimmed, because extra material at the edges between 5 and 25 mm is present. Afterwards, the shells go to the non-destructive testing (NDT) area, where different properties are checked. If the result is negative, the shells might need some rework and are sent back for repair.

3.3 Why automation?

The intention for the lead time reduction of the laminating part of the inboard flap by automation comes from an intitial process flow and manufacturing and cost breakdown. First an initial process flow of the entire production process is made. The production process of the inboard flap is divided into two main categories; the laminate build-up of the upper and lower shells of the IBF and second mechanical machining of the shells. Th process flow of the laminate build-up can be seen in figure 3.3, where the mechanical machining process flow of the IBF is shown in figure 3.4.

The next step was to define the processing times and costs of all these processing steps.

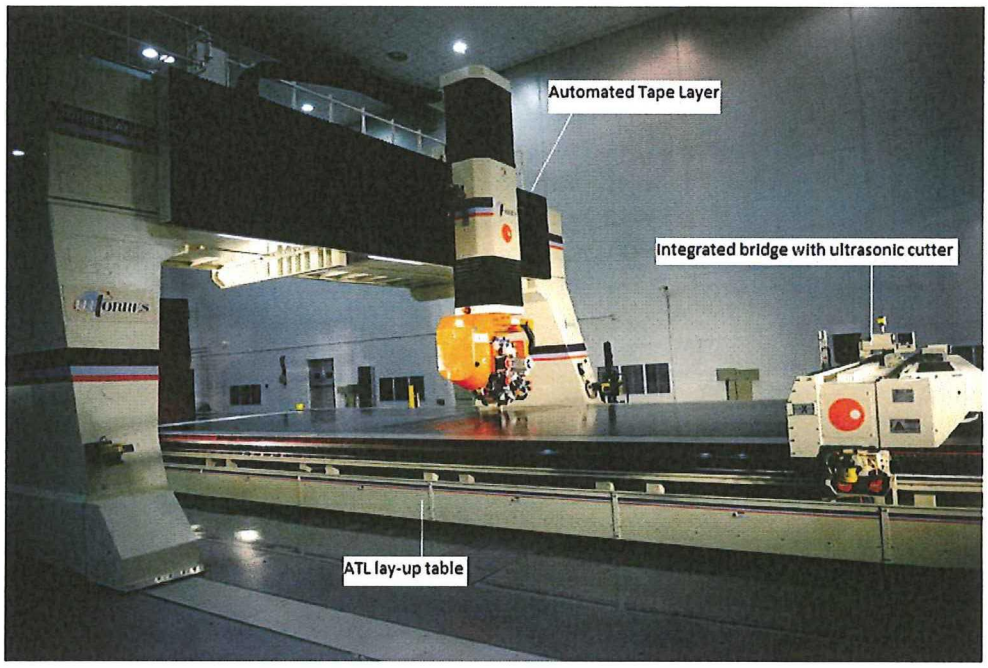

Figure 3.2: Automated tape layer on left hand side, including lay-up table and CNC cutter on the right hand side.

Figure 3.3: Process flow of laminate build-up of the inboard flap.

Figure 3.4: Process flow of mechanical machining of the inboard flap.

Table 3.1: Processing times and costs of the main processing steps for the production of the inboard flap shells.

Processing step	Processing time	Unit	Processing cost	Unit
ATL and cutter	350	IM	2432,74	Euros
laminating and autoclave build-up	1025	IM	1026,23	Euros
Cure in autoclave	168	IM	403,20	Euros
Demoulding and cleaning	401	IM	433,50	Euros
Machining and trimming	162	IM	186,53	Euros
Finishing	104	IM	121,28	Euros
Testing	563	IM	392,52	Euros
Apply filler	161	IM	328,35	Euros
Total IBF	3534	IM	4928,14	Euros

The information of the processing times for the steps is based on the cost centers provided in Systems applications Products audit (SAP) for each month. The detailed processing times for the main steps are shown in figure 3.5 and in table 3.1 a roundup of the processing steps and the processing costs of the steps are summarized.

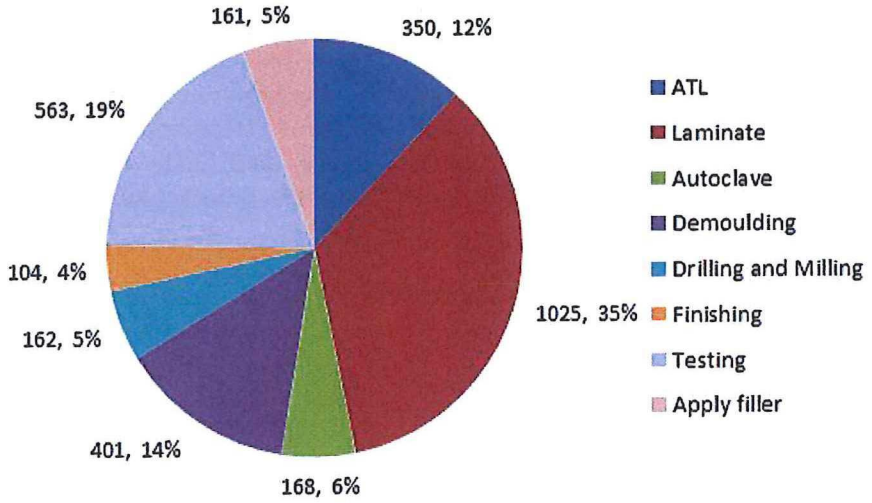

Figure 3.5: Process times of main processing steps for the production of the inboard flap shells.

From this analysis it was concluded that the laminating of the shells and the U and L profiles and the vacuum build-up are the largest contribution in the total processing time. Therefore they have the most potential for possible lead time reduction. Previous analysis showed that one of the technologies which can achieve this lead time reduction and showing high potential is the development of a robotic pick and place system, which can do manual lay-up of the skin, doublers and front and aft spar reinforcements. It is believed that the automation results in higher part quality and repeatability.

One may ask, why is an automated process in the aerospace industry wanted? This question may arise because of the relatively low production rate in the aerospace industry. The choice to automate a production process in the automotive industry is more obvious because of the higher production rate.
There are some simple reasons why the automation of a sub process in the aerospace industry is wanted. The automation of a sub process as already mentioned will result in lead time and cost reduction. Furthermore repetitive same quality parts will be produced with high accuracy.
For the aerospace industry the production rate is rather low. In the case of the Airbus A320 around 312 aircrafts are delivered on a yearly basis. This implies that the robotic system needs to handle only 1248 sets of skins, doublers and reinforcements every year. To ensure the economic viability relatively low investment cost is required and long lifetime of the robotic solution is needed. For the automation of production processes no standard solutions are present and therefore individual solutions are needed for each application. Finally it is important that the automation solution can be implemented in today's production line and no design changes to the IBF may be introduced.
In this research the focus lays on transferring the hand lay-up process into a 100% automated process. For this, the available single aisle (SA) infrastructure will be used.

3.4 Requirements analysis

In order to end with a succesful design a good requirement analysis for the pick and place robotic system is needed [31, 32, 33, 34]. The requirements to be fulfilled by the robotic system are listed in table E.1 in chapter E. The requirements are split into customer requirements, functional requirements, performance requirements, operational requirements, interface requirements, testing requirements and finally constraints. These requirements are later on transformed into the design of the robotic pick and place robotic system later on.

Chapter 4

Conceptual design phase

The aim of this research is to make a proof of concept for a robotic system, which is able to pick up prepregs of different dimensions from a cutting table and place them onto a flat lay-up table. It has to be assessed how the robotic cell lay-out should look like, which end-effector is most suitable to pick up the prepregs and what the method is to remove the backing paper.
Different end-effectors and end-effectors lay-outs are derived from existing dry carbon textile pick and place robotic systems. An attempt will be made to adapt this pick and place systems to a system which is able to pick and place prepregs and overcome its problems. All these systems and end-effectors have their advantages and disadvantages. Different concepts for the robotic cell, end-effectors, the handling of laminates of different dimensions and backing paper removal are evaluated in this chapter.
The different robotic cell lay-outs are discussed in section 4.1, different end-effectors and lay-outs to pick up these different dimensions are assessed in section 4.2 and section 4.3. Next to that different concepts for the backing paper removal are described in section 4.4. Finally all these concepts are evaluated with a trade-off and one robotic system will be selected in section 4.5.
It is relatively easy to come up with different concepts, however obtaining detailed information of the different concepts is more difficult, since most data available is rather qualitative instead of quantitative. In order to make sure that all the concepts fit in the requirement of a return of investment (ROI) in 2 years, most concepts are based on off-the shelf products to make sure that no high development costs are present and the robotic system will be economical viable.

4.1 Robotic cell

For the robotic cell, three different main set-ups are identified. The first one is an industrial robot, which can be fixed at a point. Second is an industrial robot which can be mounted on a track system on the ceiling or floor and finally a gantry system is possible.

4.1.1 Fixed point

One concept is an industrial robot which is mounted on a fixed place. The robot is able to turn 360 degrees from this point around it's z-axis, but it is not able to move along the x and y-axis. An example of an industrial robot, in this case an articulated robot can be seen in figure 4.1. In order to meet the work envelope, different robots can be installed to cover the required distance to move the prepregs from the cutting center to the laminating table. Which is shown in figure 4.2.

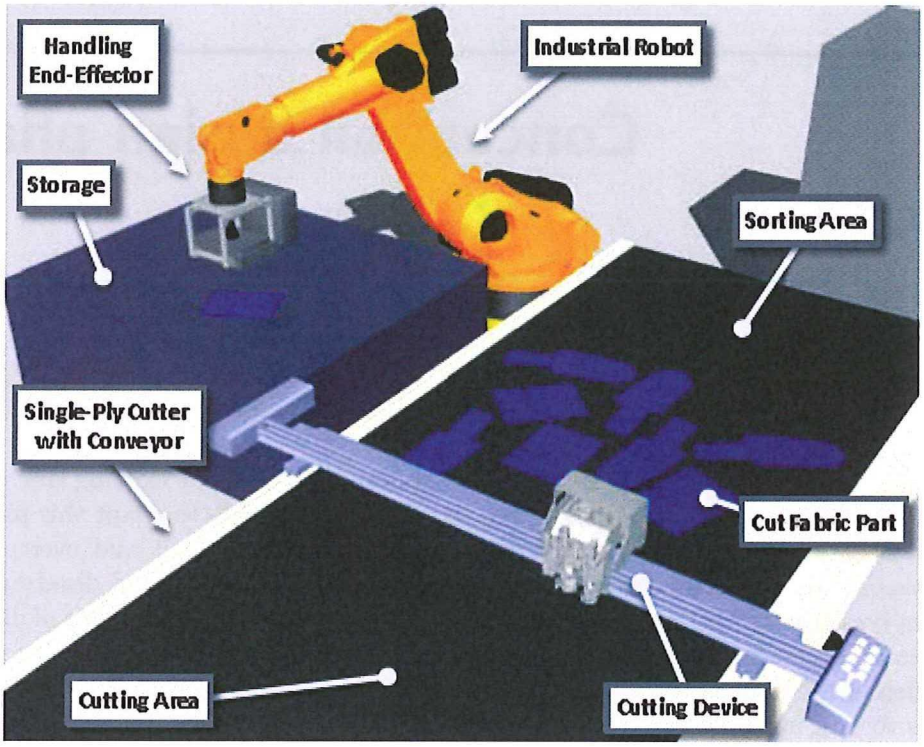

Figure 4.1: Robotic cell lay-out of an articulated robot at fixed place next to cutting table.

Advantages Mounting an industrial robot at a fixed position is a relatively simple solution which can be installed at different places. Furthermore the articulated robot has a high accuracy of around $\pm 0,06mm$, requirements state a placing of only $2,5mm$. In contrary to mounting the industrial robot on linear tracks or gantry systems, where the mounting on these systems will reduce the accuracy. Furthermore if multiple industrial robots are used in line, the prepreg ply can be exchanged between the industrial robots, in this way high travelling speed can be achieved. While the last robot is still placing the right prepreg ply on the lay-up table, the first and second robot can already start picking and transferring the next doubler or front or aft spar reinforcement.

Disadvantages The main disadvantages of industrial robots fixed at a certain position is the limited range of a robot. Typical ranges of articulated robots vary from maximum 0,7 to 4,2 meters. The shortcoming in range can be overcome by installing multiple robots

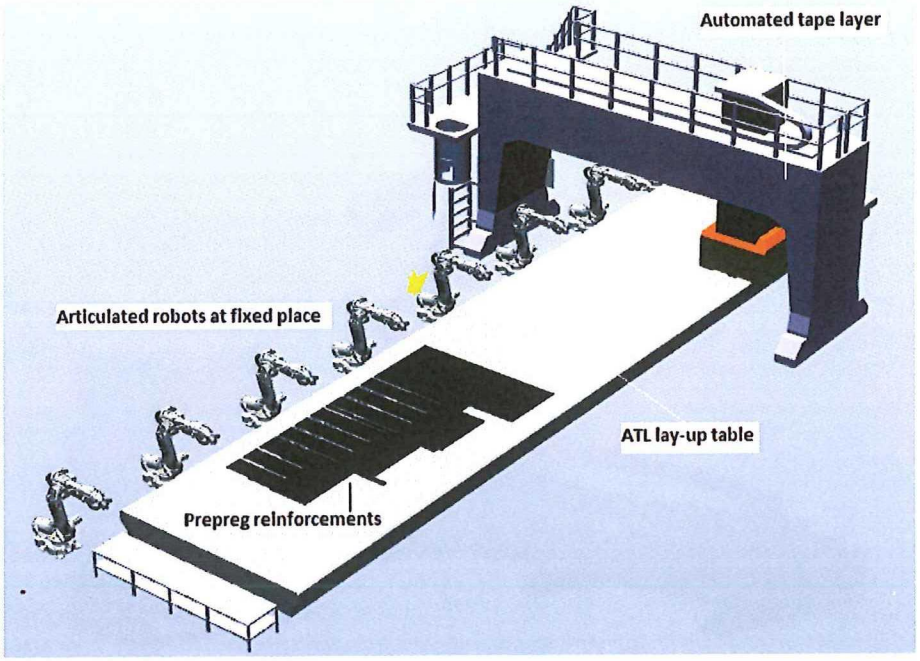

Figure 4.2: Multiple articulated robots at fixed place along the entire length of the ATL.

at fixed positions, however multiple end-effectors are needed in order for each robot to easily pick and place the prepreg material. The use of multiple end-effectors will come with high investment cost. The cost of a standard articulated robot to be used in this application will cost around 80,000 euros. In order to be able to cover the entire length of the ATL lay-up table 9 industrial robots need to be installed, resulting in an estimated robot cost of 720,000 euros without end-effector. Finally the use of multiple industrial robots will be more difficult to control and program. It has to be ensured that no collisions will occur and perfect collaboration between the industrial robots is present.

4.1.2 Robot track

An industrial robot can be mounted onto a linear unit, this linear unit ensures an increased workspace. The linear unit can be mounted on the floor as in figure 4.3 or one can install a system where a beam is mounted at a certain height as in figure 4.4.

Advantages The main advantage of the mounting of an industrial robot on a linear track on the floor or ceiling is the increased working range of the industrial robot. Linear track solutions are known for their simplicity, robustness and compactness. The industrial robot mounted on a linear track travels at high speeds, depending on the track unit between 1,45 and 2,35m/s. Furthermore linear track units have high accuracy, with a maximum deviation of $\pm$ 0,02mm. Mounting the industrial robot onto a linear track unit will make it less accurate compared to an industrial robot fixed at a point. From the requirements, the doublers and reinforcements can be stacked with an accuracy of $\pm$ 2,5mm, which is far from the accuracy of $\pm$ 0,08mm achieved with an industrial robot

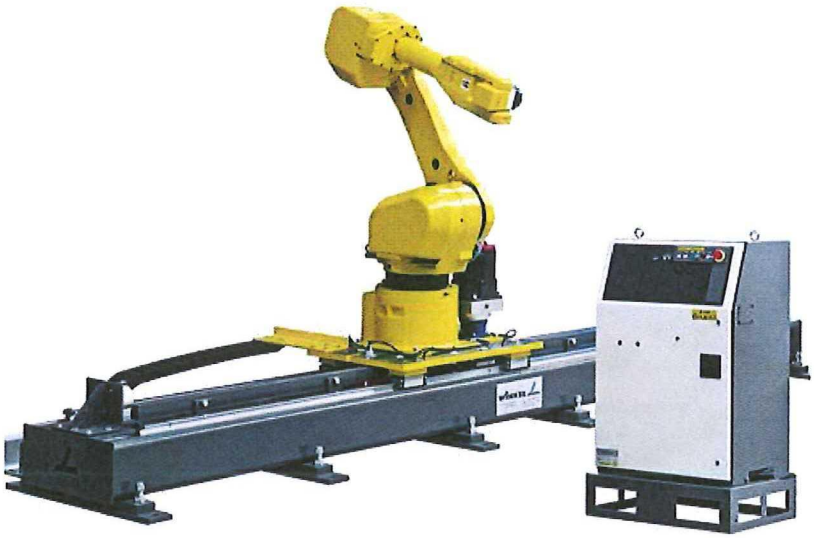

Figure 4.3: An articulated robot mounted on a linear track unit with a floor mounting.

Figure 4.4: An articulated robot mounted on a linear track unit with a ceiling mounting.

mounted on a linear track. The track can vary in length from 1 to 30 meters and have a width varying from 1 to 2,4 meters, depending on the maximum payload it can carry.

Disadvantages The main disadvantage of this setup, is the increased cost of the linear unit. The cost of a linear track of 30 meters is around 95,000 euros without installation costs. An industrial robot is also needed with an estimated cost of 80,000 euros. Resulting in a total cost of around 175,000 euros. The linear track is restricted to linear motions only. The linear track has to be installed along the entire length of the ATL lay-up table. Therefore there can't be any interference between the industrial robot, ATL and CNC cutter will occur. Finally the width of the ATL lay-up table is 5,5 meters. If it is assumed that the middle of the big laminate layed by the ATL never exceeds the middle of the ATL lay-up table, the industrial robot should have a minimum length of $3{,}635m$. Currently these lengths are at the edge of technology for industrial robots.

4.1.3 Gantry robot system

A portal or gantry system is a robotic system which has three elements of motion. The elements of motion are linear in x, y or z direction and perpendicular to each other. Therefore no rotational motions are possible, except when an industrial robot is mounted on the gantry system. Important for this concept is that the gantry system does not collide and interfere with the ATL at any time. Three main gantry system concepts are considered: (1) a long beam along the length of the ATL, (2) one along the width of the ATL and (3) two gantry robot systems, each equiped with an industrial robot. An example of a gantry robot system can be seen in figure 4.5.

Figure 4.5: Gantry robot system with 4 pillars and linear robot.

Advantages The gantry robot system offers the advantage that only linear motions are used, for this reason the solution is simplified and it is easy to calculate the exact positioning coordinates for for pick and placement. The second advantage of this system is that an articulated robot can be mounted on the gantry robot system. This way the system is more flexible, increasing the degrees of freedom. The system is versatile and large working envelopes are possible. Gantry systems with a length of $37{,}5m$ and a width and height of $8m$ are no exception. The gantry system has high accuracy, $\pm$ $0{,}05mm$ and the movements are relatively short and parts can be easily reached because of a high number of degrees of freedom when an industrial robot is mounted on the gantry system.

Disadvantages The main drawback for this concept is the relatively large structural framework that is needed. In order to be able to switch pick and placement from the left to right hand side and for the ATL to being able to pass the robot, only the solution with two gantry robot systems each equiped with an industrial robot is suitable. The concept with a beam of 30 meters length is simply not feasible and the one with the beam along the width of the ATL lay-up table makes it impossible for the ATL to pass and start the next program on the other side of the table. First of all the steel framework implies high investment and installation cost.

4.1.4 Integrated bridge

An integrated bridge is a system which covers the entire width of the lay-up table, just like the CNC cutter which can be seen in figure 3.2 and figure 4.1. This bridge is able to move along the entire length of the layup table by linear guidings. For the integrated bridge two lay-outs are available; (1) an industrial robot with end-effector placed on top of the bridge as in figure 4.6 and (2) an integrated end-effector in the bridge, as can be seen in figure 4.7.

Advantages The integrated bridge can be installed without any interference with the ATL or other equipment, as it is just an improved CNC cutter able to pick and place prepreg material. To move along the length of the table, the integrated bridge can use the linear guidings installed at the ATL lay-up table which are present today. Therefore the integrated bridge can be easily integrated in the current lay-out. Second the bridge can operate relatively fast, with a maximum travelling speed of 2 m/s. Finally because the CNC cutter is replaced by this integrated bridge, including cutter and end-effector, labeling of the different skins, doublers and reinforcements can be discarded. Labelling is present for the workers to show which doubler or reinforcement they have to place next. This elimination of labelling will reduce the lead time for the cutting with 25% or 37IM per ATL cycle.

Disadvantages Maybe the biggest disadvantage of this concept is the need for a new development of an integrated bridge with cutting and pick and place function. This development will come with a certain investment cost and is estimated around 350,000 euros. Next to that the linear track unit connected at the ATL lay-up table to carry the integrated bridge needs redesigning and extra strengthening to carry the extra weight of the end-effector. Today the linear tracks are not able to carry this extra weight.

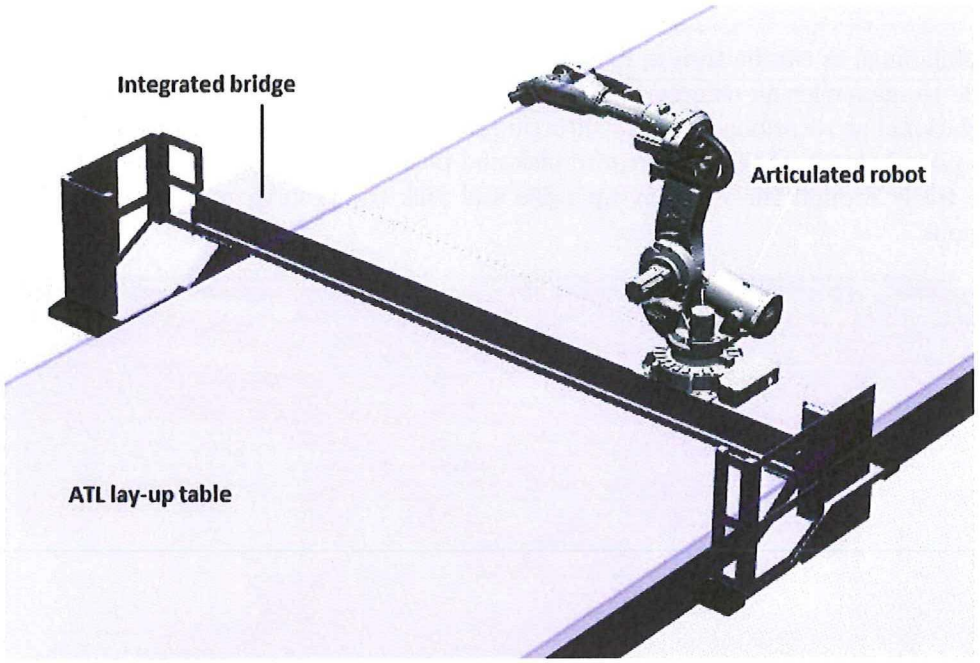

Figure 4.6: Integrated bridge attached to ATL lay-up table with articulated robot placed on top.

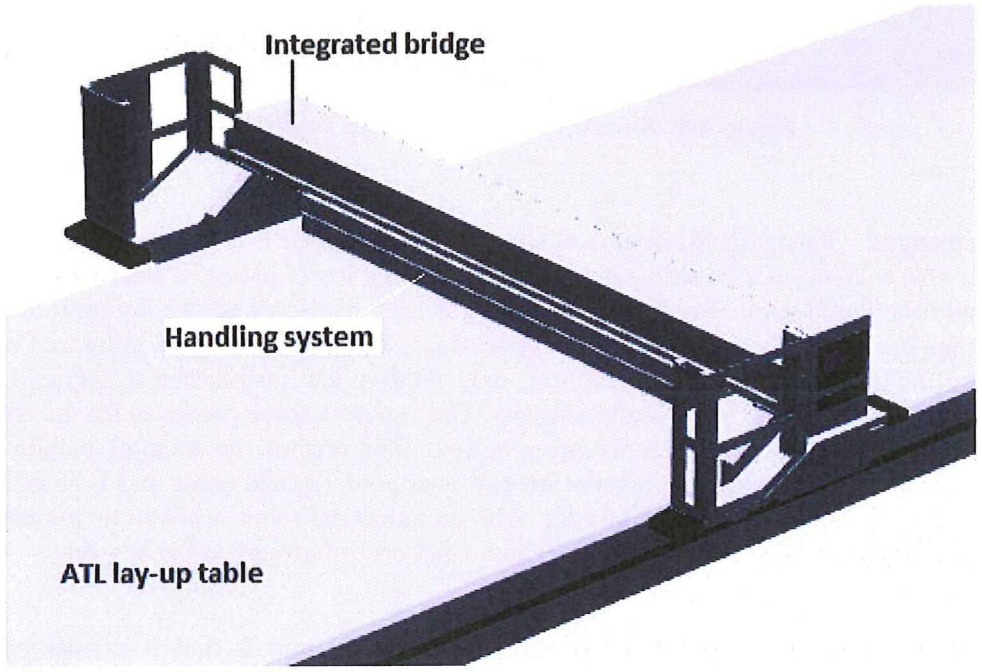

Figure 4.7: Integrated bridge attached to ATL lay-up table with integrated handling system.

4.1.5 Mobile unit

A mobile unit, as can be seen in figure 4.8, is a flexible mobile platform. The mobile unit is able to maneuver on command with sufficient accuracy. It is able to manoeuver both translational as rotational in every direction from stop position. An industrial robot can be mounted on top of this platform to pick and place the laminates. The mobile unit can move freely around the ATL lay-up table and pick the prepreg material from different positions.

Figure 4.8: Articulated robot placed onto a mobile unit.

Advantages The main advantages of the mobile unit is that it is a higly flexible system and is able to move in all possible directions, by making use of patented wheel technology. Because the mobile unit is able to move freely, it isn't restricted to one lay-up table and therefore can be deployed for different applications. Finally because the industrial robot can be mounted on the mobile platform, only relative low installation is required and therefore also relatively low installation cost. Only special anker points to fix the mobile unit during pick and place activity are required. The cost of the smallest mobile unit on the market today, without installation cost is around 120,000 euros and is considered positive compared to the other concepts. Also an industrial robot needs to be purchased, which is stated at 80,000 euros, to result in a total cost of around 200,000 euros.

Disadvantages The main disadvantages of the mobile unit is that it is rather slow, with a maximum speed of 0,8 m/s. Furthermore the smallest mobile unit available on the market has a length of 2,4 meters and a width of 1,7 meters. These dimensions make the system rather large and bulky and it may be difficult to manoeuver between the ATL

lay-up table and ATL. Finally the mobile unit is not autonomous. A worker is needed to navigate the mobile unit from point a to point b. Finally the accuracy of the mobile unit is low compared to the other concepts, an accuracy of $\pm 1mm$ can be achieved. This is still acceptable looking at the requirements, but lower compared to the other concepts.

4.1.6 Industrial robots

In order to carry the end-effector and move the prepreg material from place a to b, an industrial robot is required. Different industrial robot suppliers and industrial robots are available [7]. In total three main types of robots can be defined, each having their specialities and pros and cons. The different robot types distinguished are articulated robots, SCARA robots and parallel robots. Figure 4.9 shows an overview of the moving principle, kinematic structure and a photo of the robot. The three main types of industrial robots are briefly discussed in this section.

Articulated robot

The articulated robot uses rotary joints to rotate over different planes. An articulated robot can range from 1 to n joints, depending on the type and application. The robot is able to pitch, roll and yaw over its joints. The robot consists of different arms, which can differ in length and will influence the maximum range and maximum payload the robot can carry.
As mentioned articulated robots come in different types, they vary in ammount of degrees of freedom, maximum payload it can carry, maximum range, mounting position, etc. Articulated robots can be listed in four main payload classes; low, medium, high and heavy duty payload class. Some articulated robots can only be mounted on the floor, ceiling, wall or a combination of possible mounting positions are available. Next,the working envelope or the maximum range of the robot also differs depending on the type and mainly depends on the length of the robot arms.

Advantages The main advantage is that a large amount of different types of articulated robots can be purchased off the shelf. The heavy duty payload class is even able to carry high payloads up to 1300 kg. Next, the articulated robot is highly flexible because of its 6 degrees of freedom. Another advantage is the large arm some robots have, the maximum reach available on the market today is 4,2 meters. It can be seen that a large variation of articulated robots is avalaible and therefore a suitable robot fulfilling the customers need is available most of the time.

Disadvantages The main disadvantage of the articulated robot is that in order to carry high payloads counterbalance or large fundaments are needed to transfer the forces due to the high moment of inertia.

SCARA robot

A Selective Compliant Articulated robot arm or simply SCARA robot imitates the motion of a human arm. The SCARA robot is able to operate at high speed, effecient and has

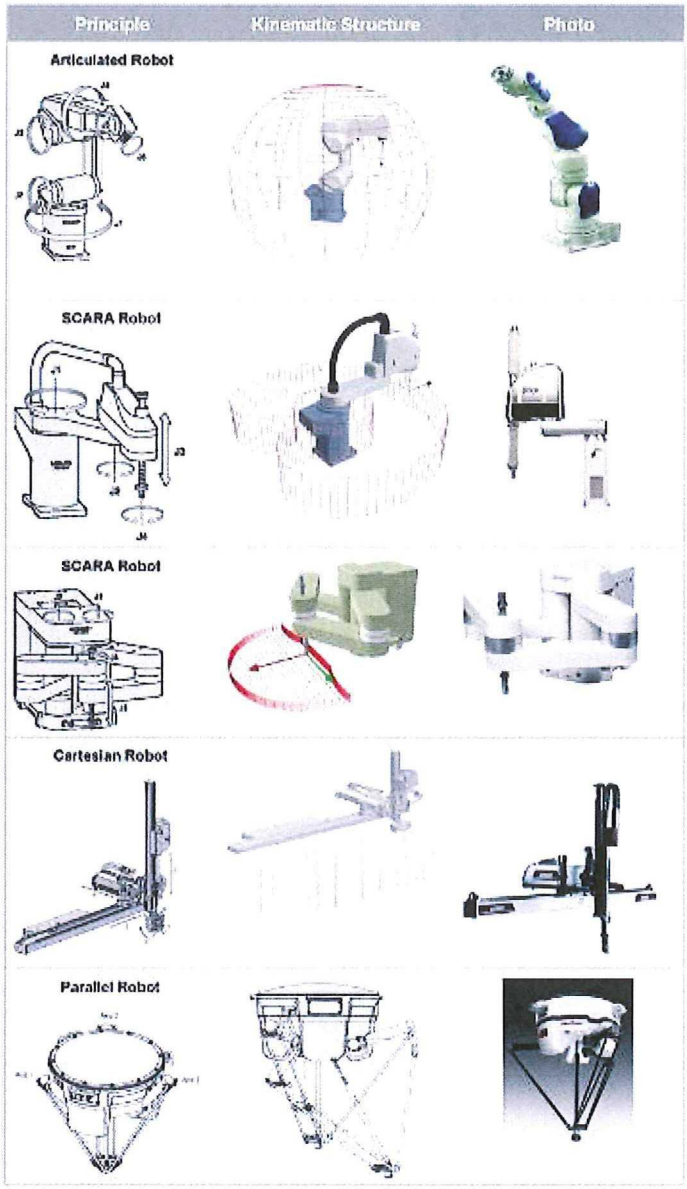

Figure 4.9: Overview of industrial robots principles and kinematic structure.

low investment cost. It is mainly used for assembly tasks which require high accuracy. The SCARA robot is a 4-axis robot and the arm is able to move in x, y and z-direction in a circular work envelope.

Advantages The main advantage of a SCARA robot is its high working speed, low mass and low cost. Its operating speed is maximum 11 m/s, has a mass of $50kg$ and a cost of around 5000 euros. It can repeatably pick and place objects with high positioning accuracy of $\pm 0,025mm$.

Disadvantages The main drawback for the usage of a SCARA robot is the limited workspace and possible movements, therefore it lacks in flexibility. The SCARA robot is only able to do circular motions and the length of the arms are limited to a length of $350mm$ each. Its maximum payload is also restricted to $10kg$. Besides this the work envelope of the robot tends to be difficult to control.

Parallel robot

The parallel or cartesian robot has three or more rotary axes. Which makes it possible to move the arms parallel to each other. Therefore the working range is flexible, but limited to linear motions of the arms. Parallel robots are mainly used in applications which require good stability, rigidity and accuracy.

Advantages Since the end-effector is supported in several places by a certain number of legs, high structural stiffness is ensured. The structure of the parallel robot is often a light construction, because only a number of legs are connected to a base. The use of linear movements of the arms makes a wide range of motions possible. The parallel robot can operate at high speed and accuracy, because of the light construction of the arms and actuators.

Disadvantages The workspace of the parellel robot is limited by the construction and length of the arms. Another disadvantage of the parallel robot is the relatively large footprint-to-workspace ratio.

4.2 End-effector

In this section different suitable end-effectors to pick and place composite materials are reviewed and discussed. The end-effector needs to handle carbon prepreg material and should take material properties, such as weight of the laminate, the thickness and the quality of the surface into account [10, 17].
There is a great variety of end-effectors available, each using different physical principles. The end-effectors found in literature are mainly to pick up dry carbon textiles and preforms [17], little research is available for prepreg composites. Figure 4.10 shows an overview of the end-effectors which will be reviewed in this section.

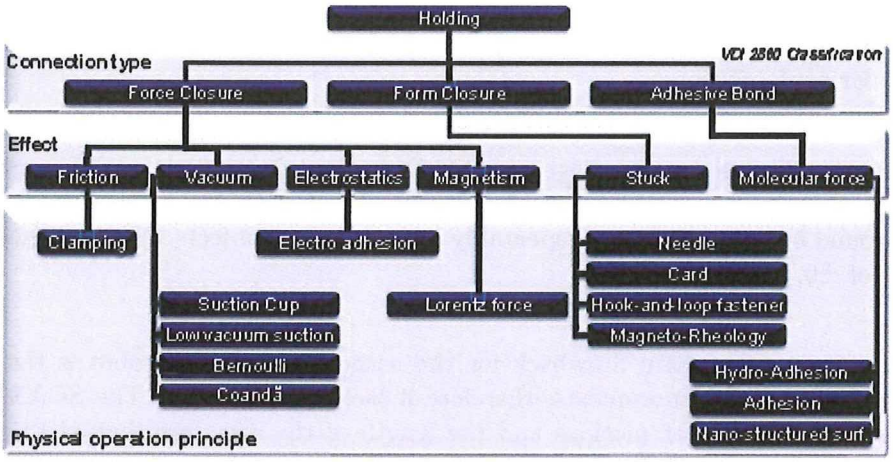

Figure 4.10: Overview of different end-effectors types.

4.2.1 Mechanical gripper

The mechanical gripper [18] is one of the simplest techniques and comes in different varieties, such as tension jacks, clamping of the laminate, flexible fingers, etc. The material is gripped with at least two clamps and due to the clamping pressure, the resulting friction prevents the material from slipping. The mechanical gripper can clamp the surface of the prepreg material or the side. The last option can only be used for stiff materials. An example of a mechanical gripper is shown in figure 4.11. Mechanical grippers, such as jaws, clamps and chucks are rarely used to grip prepreg material and are more often used for cured composites.

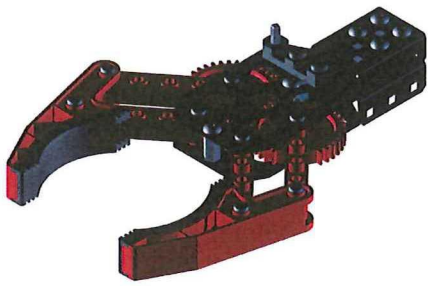

Figure 4.11: Example of a mechanical gripper.

Advantages Mechanical grippers show minimal consumption of air, electricity or other supplementary materials, therefore the gripper has low recurring cost. Because the material is clamped from the upper and lower side a good grip and therefore good grab reliability is achieved. Finally mechanical grippers are independent to ambient conditions, in this case the lay-up area temperature, humidity and presence of carbon fibre particles.

Disadvantages By clamping the material, sufficient holding force is needed to ensure that the prepreg material doens't drop on the floor. This high clamping force can cause ondolations and leaf marks on the prepreg material [17]. Another main drawback is that mechanical grippers need some fixture elements; these elements need to be placed at strategic locations and might be impossible for laminates [35, 36]. Last, the prepreg material should be reachable from underneath, as from above and the gripper is only capable of clamping the material at the edges.

4.2.2 Suction gripper

The second end-effector is a vacuum gripper [13, 15, 10, 11, 23, 18] here a suction cup in combination with vacuum is used to lift the laminate. The working principle is to apply a pressure difference between the ambient pressure and a low vacuum pressure chamber. The air entrapped in the suction cup and the material is evacuated and it can be gripped. Vacuum grippers are widely available on the market and differ in material, shape and cup profile. However most of the time the suction cup is made of Silicon rubber, Silicon rubber is used because of its flexibility and resistance against chemical attacks [19]. The cup profile may be either circular or have an irregular shape and is mostly planar to increase gripping flexibility and decrease the chance of possible imprints in the material. Vacuum grippers are widely used in automated pick and place systems and are a recommended method for the pick and placement of prepreg laminates [18].

Figure 4.12: Vacuum cups with variation in cup size.

Advantages The vacuum gripper is able to grip any smooth material, including prepreg reinforcements. Vacuum grippers are recommended as the most suitable gripper to pick and place prepreg materials. The airflow passing through the material is negligible small. Next, a large range of products is available, differing in size, shape and material, this way fulfilling the demands of the client. Finally the vacuum gripper is independent of the ambient conditions, such as the lay-up area temperature and humidity.

Disadvantages The main drawback of the suction gripper is that it is best used to lift airtight materials [20]. If porous materials are used a rise in airflow is required, increasing the energy consumption of the vacuum gripper even more. Besides the airtightness, the surface rougness influences the leakage of the vacuum cup. This leakage can be increased or reduced depending on the suction cup material and shape. But in general the higher the surface roughness, the more leakages will be present. Also deformations of the material can occur if the suction force is to high. The material can be sucked in the shape of the suction cup, however using a flat shape may solve the problem. There is no consession whether this suction cup imprint influences the mechanical behaviour of the laminate or not. Since the suction cup sucks the environmental air in, the vacuum suction might be contaminated with dust and small carbon fibre particles. Another drawback is that if the suction cup loses contact with the lifted material, the suction cup will act as a "short circuit". This will lead to an under pressure at the other suction cups. For this reason a mechanism should be built in, that if a suction cups loses contact, the suction cup is turned off. However this mechanism will lead to a heavier pick up system. Finally due to the continuous air flow the energy consumption of this end-effector is high, resulting in high recurring cost.

4.2.3 Bernoulli gripper

The Bernoulli gripper [13, 10, 24] is a contactless gripping system based on the law of Bernoulli. The Bernoulli law states that an increase of speed of a fluid results in a pressure drop. The bernoulli gripper creates a vacuum by inserting compressed air, the flow of compressed air passes the body of the gripper and creates a negative underpressure at the center of the gripper, as can be seen in figure 4.13. The gripper is positioned at the right distance from the laminate and will be able to lift the laminate without actual contact. However rubber pins are often installed to prevent the material from flowing around and to place the gripper at the right distance. From experiments it is concluded that reliable gripping is present if the gripper is placed between 0,5 and 2 mm from the prepreg material. The Bernoulli gripper consists of a nozzle which creates airflow, a deflector and a plate. At first if the distance between the air jet nozzle and the laminate is too big, the laminate will just be blown away, but at a certain point when the distance between the air jet nozzle and the laminate decreases a lifting force will be created. This lifting force increases when the distance is decreased.

Advantages The biggest advantage of the Bernoulli gripper is that it is a contactless gripper. Therefore there is no interference or influencing the prepreg material and for this reason it is a suitable method to pick and place prepreg material. Furthermore the Bernoulli gripper is independent of the ambient conditions, such as the lay-up area temperature, humidity and thepresence of carbon fibre particles. Finally the Bernoulli gripper is able to pick almost every material type.

Disadvantages The main drawback of the Bernoulli gripper is that, it still has a high energy consumer compared to the other end-effectors. Next, in the case of pressure loss and because no real contact between the gripper and prepreg material is present,

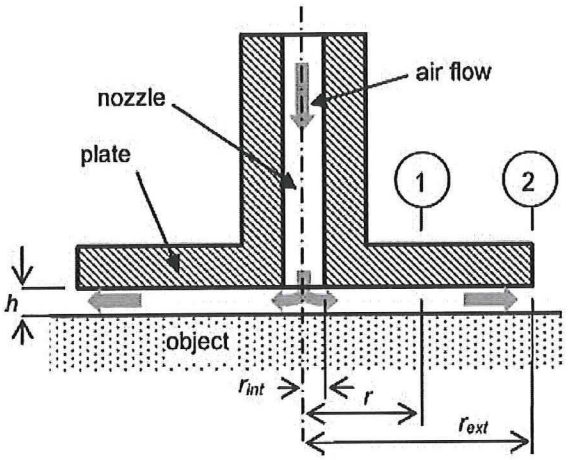

Figure 4.13: Working principle of Bernoulli gripper.

the material can drop easily on the floor. The Bernoulli gripper works as explained by creating an underpressure between the gripper and the material due to deflection of the compressed air. The phenomenon is very complex, due to the presence of turbulent air flow, supersonic regions and shock waves [24]. This comes with high noises between 80 and 90 dBA and workers close to the gripper need to wear ear protection for safety reasons. Finally the energy consumption is 40% higher compared to the vacuum gripper, leading to high operating cost.

4.2.4 Needle gripper

The needle gripper [13, 10, 15, 11, 18, 16] simply uses needles to penetrate and actually puncture the material under a certain angle. Needle grippers are often used to grip porous materials such as dry composite fabrics [18].

Advantages The needle gripper offers high grab reliability, because the needles penetrate the material under a certain angle and therefore a high quality grip is achieved. Next, the time to extend the needles into the material takes less then a second. The needle gripper is also independent of the ambient conditions and uses little electrical energy. Therefore the recurring cost of the needle gripper is low.

Disadvantages The main drawback of the needle gripper is believed to be the cause of damage to the carbon fibres. However no real consensus on whether needle gripper damages the material is present. Gripping UD prepreg materials can however cause relative motion of the fibres, which can lead to lower lay-up accuracy [17]. Also penetrating the material can result in voids in the laminate. This is unwanted, unless the needle gripper only grips the material at the edge of the material and is afterwards trimmed. Voids will reduce the interlaminar shear strength of the laminate. In terms of costs the needle gripper is 40% more expensive compared to the vacuum gripper.

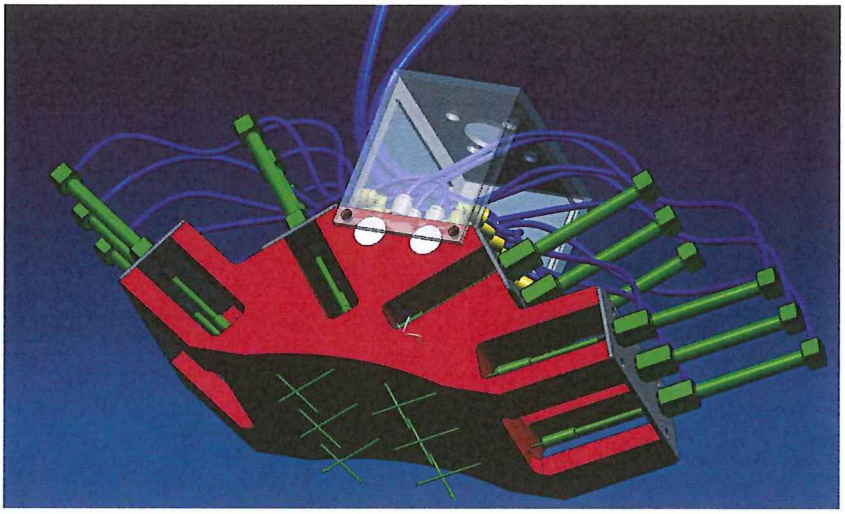

Figure 4.14: Working principle of needle Gripper with twelve needles.

4.2.5 Adhesive gripper

An Adhesive gripper [10, 11, 13, 35] uses an adhesive that sticks to the laminate and uses the adhesive force between the gripper and material to lift it. The achieved lifting force of the gripper is related to the applied pressure of the gripper on the gripped material [18].

Advantages The main advantage of an adhesive gripper is that the actual time to grip the material only takes several milliseconds, because it is only the pressing force that determines the holding force of the material. Next, the adhesive gripper has relatively low recurring cost. There is no need for electrical energy or pressurized energy, reducing the cost. The adhesive should be renewed from time to time to ensure proper gripping of the material. The solution works best if a full surface grip is possible.

Disadvantages In total two main drawbacks for the use of an adhesive gripper are defined [21]. First the adhesive force decreases over time and the gripper therefore will need maintenance. Secondly the adhesive is contaminating the laminate, which may be considered as unacceptable. Next, in contrary to other end-effectors where an action or mechanism is required to disconnect the gripper, there is no possibility to stop or switch off the adhesive force of the gripper [22]. Therefore it is possible that some adhesive may be left on the material and that fibres may be torn off during removal of the gripper.

4.2.6 Hydro adhesive gripper

A hydro adhesive gripper [13, 10, 15, 18] deposits a low amount of water vapour on the laminate and freezes it by means of a cooling or Peltier element with a temperature around -10 ° Celsius [17]. This way a contact surface between the end-effector and the laminate is created and the gripper is able to lift the laminate. The ice is liquefied again by using

compressed air and the reversed Peltier-element. The water dries and the laminate turns back into its initial state. The whole lifting operation takes around 0,1 ml of water and is finished within 1 second [15]. Hydro adhesive grippers can achieve high holding forces, however the high holding force is only achieved if non polished surfaces are gripped [17].

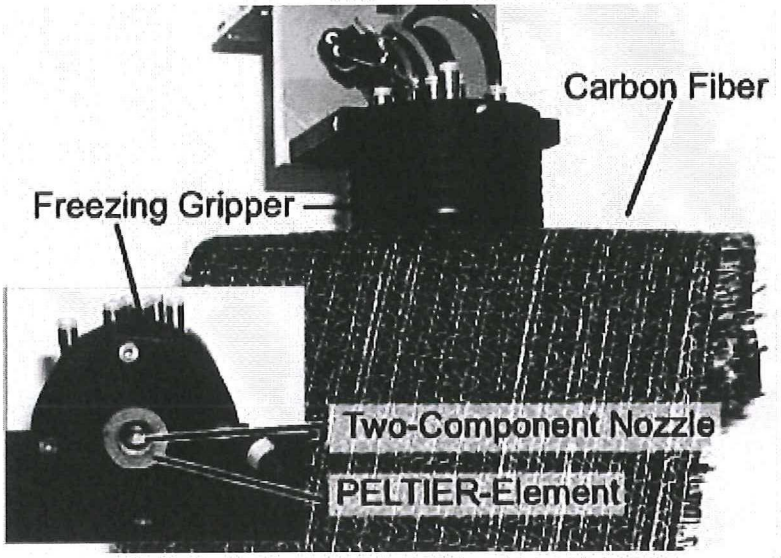

Figure 4.15: Hydro adhesive gripper with Peltier element.

Advantages The high grab reliability and the gripping time are the main advantages of the freezing gripper. First it takes just several tends of a second to freeze the water droplets and grip the material. Second, by freezing the water droplets high grab reliability is achieved. Due to the low amount of water needed and low energy consumption of the Peltier element the freezing gripper operates at low recurring cost.

Disadvantages The main drawback of the hydro adhesive gripper is the possible permeation of the water droplets into the material. From requirements the material shall not humidify and influence the material. Furthermore during heating the resin of the prepreg material can melt. Finally to remove the prepreg material from the gripper, the frozen water droplets needs to be heated by the Peltier element. This heating takes several seconds, increasing the total cycle time.

4.2.7 Electrostatic gripper

The electrostatic gripper [10, 15, 18, 37] is based on the physical mechanism, that materials with different charges attract each other. Therefore the gripper is able to pick up electrical conducting materials by making use of electromagnetic forces between the end-effector and the electrical conducting material. In order to achieve this a circuit board is covered with a dielectric material. After this, a high voltage is applied to this dielectric material. If the laminate is then brought into contact with the electrostatic gripper, it is

able to lift the laminate. For this concept no real contact between the laminate and the end-effector is needed to lift it, however contact is recommended to improve the gripping reliability.

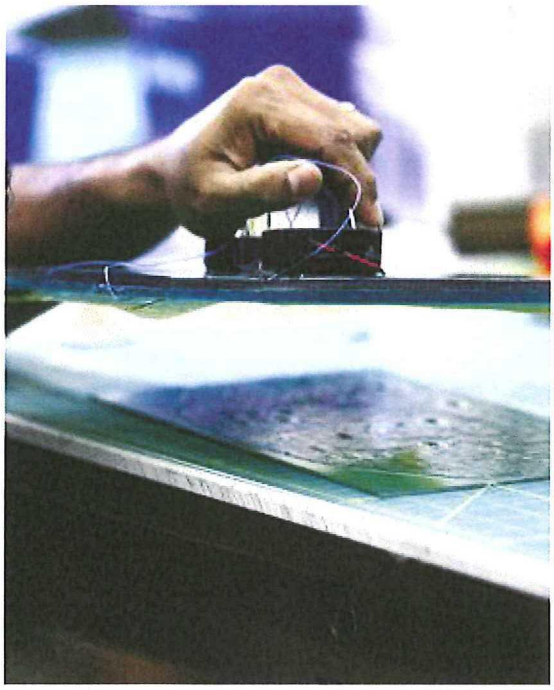

Figure 4.16: Electrostatic gripper in development stage.

Advantages The electrostatic gripper offers high grab reliability, reducing the chance of dropping the prepreg material. Furthermore the gripping time of the prepreg material by the gripper is around 60 milliseconds and is therefore considered as a fast gripper. The electrostatic gripper is easy to reconfigure and is a lightweight solution with a uniform distribution of the holding force. The low weight is due to because the circuit bord which only has a thickness of around $1mm$. Furthermore the recurring cost of the gripper is relatively low. This can be stated because the gripper has to be charged only once during pick up and immediately afterwards it can be turned off. After the charge is turned off, the prepreg material stays attached to the gripper during handling.

Disadvantages Maybe the biggest disadvantage of the electrostatic gripper is the development stage. So far no company managed to develope an electrostatic gripper which is able to grip prepreg materials with large dimensions. Also for the electrostatic gripper it is important that the electronic circuits are protected from dust at all time. From literature research it is also concluded that because of the high electrical potentials and charging voltages that are required, the electrostatic gripper is not the best option. Charging voltages are around 8000 Volts [37]. The combination of high electrical potentials and a work environment contaminated with small conducting carbon fibre particles may be considered as unacceptable [25].

4.2.8 Carden gripper

The carden gripper is a suitable end-effector for adhesive materials, such as prepregs. Carden grippers use the principle of retention force by interlocking a large number of carden teeth between the fibres of the laminate. The small fixed needles will pierce the material due to the movement of the gripper itself. In order for this retention force to work, tension between the two card grippers is needed. As can be seen in figure 4.17.

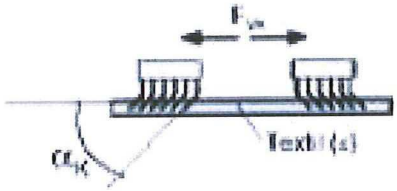

Figure 4.17: Working principle of carden gripper.

Advantages The carden gripper, like the needle gripper is able to have a reliable grip on the prepregs and is completely independent of the ambient conditions, such as lay-up area temperature, humidity and presence of carbon fibre particles. The carden gripper is a simple technology and has little energy consumption and therefore the recurring cost is low.

Disadvantages The main drawback of the carden gripper is believed to be the cause of damage to the carbon fibres. However no real consensus on whether the carden gripper damages the material is present. Gripping UD prepreg materials can however cause relative motion of the fibres, which can lead to lower lay-up accuracy [17]. Also penetrating the material can result in voids in the laminate. This is unwanted, unless the needle gripper only grips the material at the edge of the material and is trimmed afterwards. Voids will reduce the interlaminar shear strength of the laminate.

4.3 Handling system

In this section different concepts to handle prepreg material of different dimensions are discussed. The main question asked for this is; what should a flexible system look like in order to selectively grip prepreg material. In total, four different concepts are identified. First a multi-actuator system, second retractable bars, third a combination of the multi-actuator and retractable bars system and finally multiple end-effectors of fixed dimensions. The handling system should be able to pick and place prepreg material of different dimensions, thicknesses and weight. An overview of the different prepregs the handling system should be able to handle can be found in appendix G. Table G.1 shows the different dimensions, thicknesses and weight of the upper shell and table G.2 of the lower shell.

4.3.1 Multi actuators

The multi actuator system is a big construction with a large perforated plate with small holes in matrix form [14, 26]. All these holes can be individually opened and closed by actuators. The multi actuator system is a highly flexible system because of the individual actuation of holes and therefore it is possible to pick and place a large variation in dimension. It is able to pick the largest prepreg layer, in this case the skin with a length of $4380mm$ and a width of $618mm$. So if the system needs to pick a doubler or reinforcement, a preselected number of end-effectors are actuated and the system is able to lift the prepreg layer. The handling system can use different end-effectors and will depend on the most suitable end-effector to pick and place prepreg material, resulting from trade-off. An example of a multi actuator system using low vacuum suction can be seen in figure 4.18.

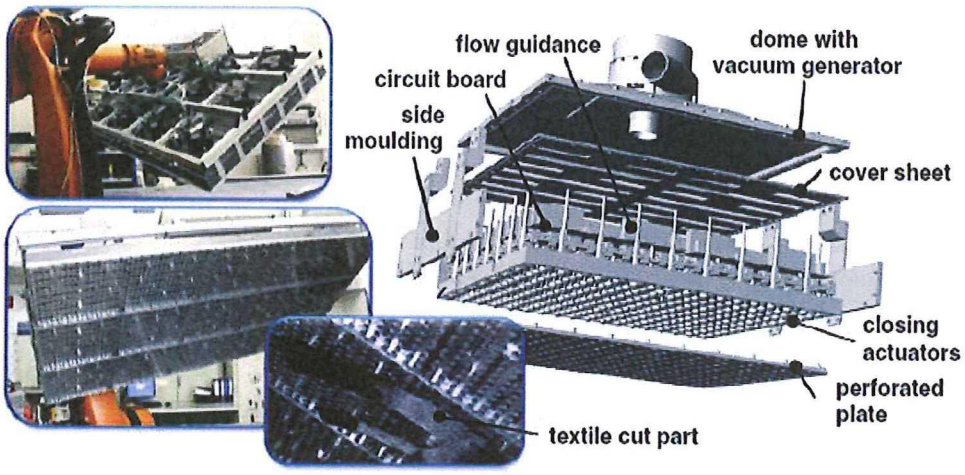

Figure 4.18: Multi acuator vacuum system.

Advantages The individual actuation of the end-effectors a highly flexible system is achieved. Therefore the system is able to handle a large variation of material, varying in dimensions. The system is not only restricted to one application, but can be utilized in different applications and not only for the pick and placement of the skin, doublers and reinforcement of the IBF of the A320. Also because a large number of end-effector will be used, in order of 3000 end-effectors, they are placed relatively close to each other. Therefore the prepreg layer is gripped over the entire surface, minimizing bending of the material. Also because multiple end-effectors are used, the chance of dropping the laminate is minimized. In contrary to when only few end-effectors are used and one of the end-effectors loses contact, faults during stacking may occur in this case. Finally, in case vacuum is used, only low vacuum suction is needed because of the high number of holes in the perforated plate, reducing the recurring cost of the system.

Disadvantages The large number of end-effectors and actuators used for the handling system, this results in a bulky and costly solution. It is logical that increasing the number

of actuators results in a higher total mass of the handling system. The total handling system will weigh around 600kg. The cost is increased in several ways, increasing the number of end-effectors increases the need for extra actuators. Because of this higher mass a more expensive industrial robot is required which can handle higher payloads. Also control cost is increased because of the more difficult steering of the multiple individual actuators. The total cost of the entire system is estimated at around 200,000 euros. Finally the multi actuator handling system can only be used with several end-effectors; the suction gripper, Bernoulli gripper, hydro adhesive gripper, electrostatic gripper, needle gripper or carden gripper. It can't be combined with the mechanical gripper or adhesive gripper, because they can't be actuated individually.

4.3.2 Retractable bars

The handling system consists of four arms and at the end of each of the arms, an end-effector is installed, as in figure 4.20 [27]. Each of these four arms can be deployed or extracted in a translational way. The total distance it can be deployed or extracted depends on the number of subbranches. The greater number of subbranches, the longer distance the end-effectors can travel. The working envelope of this gripping system is restricted by the length of the non-extended branch and a fully extended branch.

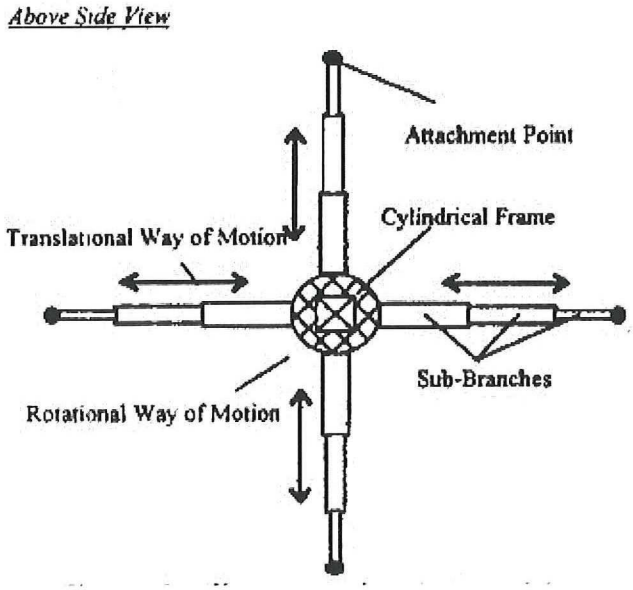

Figure 4.19: Gripper with retractable bars.

Advantages The main advantages of the retractable bars is that they are a relative simple solution. Only four arms are needed with four end-effectors. The solution is relatively light and will be easy to steer. Because of the four arms and four end-effectors the handling system will have low investment cost. The weight of the entire gripper is estimated at 50 kilograms and will cost around 50,000 euros.

Disadvantages The retractable bars handling system is equiped with four arms with an end-effector at the end of each arm. Therefore a prepreg layer can only be gripped at only four attachment points. As already mentioned, the largerst ply to be gripped is the skin and has a length of 4380 mm and a width of 618 mm. Therefore the arms needs to be two meters extended, therefore the arms have to be stiff to reduce bending of the relatively long arms. Next, the handling system only has four end-effectors, in case one of the end-effector loses contact the chance of dropping the laminate and faults during placement are increased. Finally the flexibility of the gripping system is low, it is restricted to a circular work envelope.

4.3.3 Multi actuator retractable bars

The multi actuator retractable bar gripping system is a combination of the multi actuator handling system and the retractable bars handling system. The end-effectors, which can be individually actuated, are installed in one line. These bars can be extracted and retracted, increasing or decreasing the length between the two lines of end-effectors, as in figure 4.20.

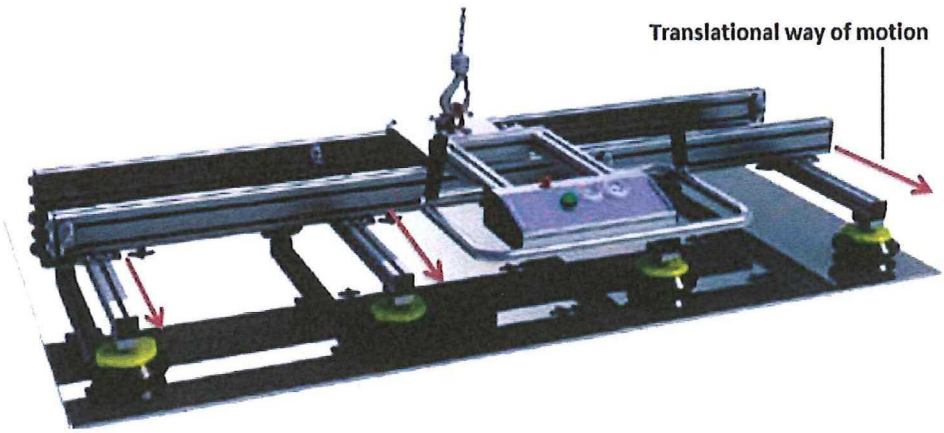

Figure 4.20: Gripper with retractable bars, where end-effectors can be individually actuated.

Advantages Being able to extend and retract the arms of the "H-shaped" multi actuator gripping system leads to a more flexible system compared to the retractable bars handling system. Laminates of different dimensions can be picked and placed. The gripping system has more end-effectors compared to the retractable bars gripping principle. Because of the increase in end-effectors a better and more reliable grip of the laminate is present and bending of the laminate during handling is decreased.

Disadvantages Compared to the rectractable bars system, the multi actuator retractable bars system is more bulky. This can be stated because more end-effectors will be present, which all can be actuated individually. Therefore the weight of the system is estimated

at 200 kilograms and a cost of 125,000 euros. Which is categorized in between the multi actuator gripping system and the retractable bars handling system. Also for this concept no mechanical and adhesive gripper can be used. Finally because the arms have to be deployed and extracted, adaption time between placement and next pick up is needed. This configuration change increases the total cycle time of the system.

4.3.4 Multiple gripping systems

The multiple gripping system concept is based on a fixed end-effector with an ideal size and configuration for all different prepregs. This solution implies that there is no need for a complex design, able to adapt to different configurations. Therefore the number of end-effectors and their inter-distance can be varied and optimized for each handling system. This means that 27 handling systems for the upper, as well the lower shells are required.

Advantages The main advantage of a multiple gripping system is that there is no need for complex design, which is able to change configuration in order to handle prepregs of different dimensions. Next, each gripper has an optimized number of end-effectors and inter-distance and therefore an ideal gripper for each prepreg ply is present.

Disadvantages In total two main disadvantages are defined. First the need for 27 multiple gripping systems comes with high investment cost. One gripper system is estimated at 75,000 euros, multiplying this by 27 different grippers results in an investment cost of 2,025,000 euros. Second after placement of one prepreg, the robot needs to store the handling system in a pre-determined storage place and connect to a new gripping system. This gripper exchange increases the cycling time of the system tremendously.

4.4 Backing paper removal

This section discusses different concepts of how to remove the backing paper from both sides of the prepreg material. The task of automated backing paper removal is identified as one of the main challenges to transfer from a manual to an automated process. Until today no solution for the automated removal exists. Therefore a proper solution to perform this backing paper removal task needs to be developed. Several questions arose during conceptual design of the automated backing paper removal. First, when should the backing paper be removed and second, how is the backing paper best removed? From literature it became clear that the backing paper removal problem can be divided into two parts, (1) peel initiation and (2) peel continuation [11]. Different concepts for the initial seperation and the peel continuation are discussed in this section.

4.4.1 Initial separation concepts

The first step in the backing paper removal problem is to find possible concepts for the peel initiation at a corner of the prepreg ply [38]. Today, the peel initiation step is also

performed manually by the workers. To initiate the backing paper removal they use a Stanley knife to initiate the removal between the prepreg ply and the backing paper, as can be seen in figure 4.25. Initial separation of the backing paper is enough for the continuation step to easily continue complete automated backing paper removal. In total three initial separation concepts are generated, namely injection with compressed air, second controlled mechanical bending and finally initiation by cooling spray.

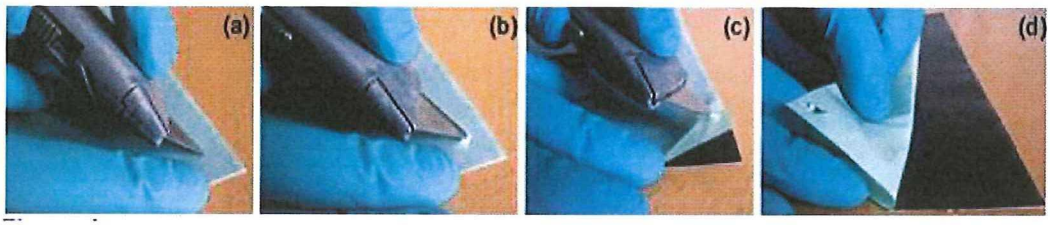

Figure 4.21: Principle of manual backing paper initiation using a Stanley knife.

Injection of compressed air

The injection of compressed air concept uses a small needle and compressed air. The injection needle punches a small needle into the backing paper and not into the prepreg ply. Therefore compressed air can be injected between the prepreg ply and the backing paper. In this way a separation between the prepreg and the backing paper is created. A foot can be used to guide the airflow in the wanted direction.

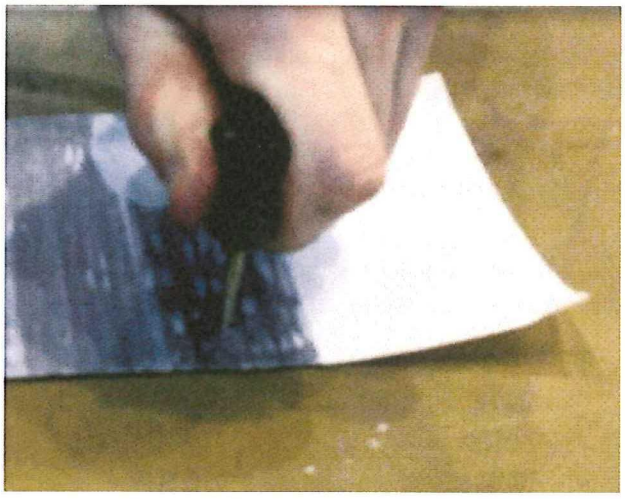

Figure 4.22: Principle of peel initiation by injecting compressed air with an injection needle between the backing paper and prepreg material.

Advantages The main advantage of the injection of compressed air is that there is no need for a free edge to create initiation. The injection needle can be easily integrated in the handling system. Especially with vacuum grippers combined with an air compressor. The compressed air can be used to inject the air.

Disadvantages The first disadvantage of the injection of compressed air concept is that the injected air has to be clean. Clean air has to be ensured to prevent contamination of the prepreg material. Another risk may be that the fibres get damaged if the needle for injection punches to deep and the fibres may shift. Finally if the metal injection needle gets damaged, metal may be introduced in the prepreg material, which is unacceptable.

Controlled mechanical bending

Controlled mechanical bending is based on human movements. The initial separation is achieved by seperating two layers, in this case the prepreg ply and backing paper, by flicking or bending a corner of the laminate. The concept is based on force bending. A lifting tool is needed to lift the laminate at a certain distance and a support presses the backing paper and prepreg down, as in figure 4.23. The two point bending system introduces shear forces between the prepreg ply and the backing paper. If the shear force is higher than the adhesive force, initial separation will occur.

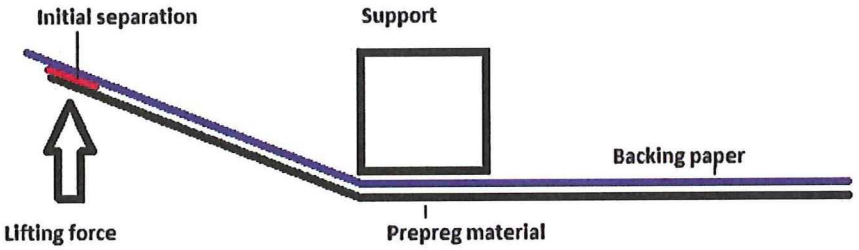

Figure 4.23: Principle of initial separation of backing paper by controlled mechanical bending.

Advantages Backing paper initiation by using controlled mechanical bending is a reliable method. An extra device can be used to lift and support can be integrated in an extra device, which can easily be integrated in the robotic cell.

Disadvantages To perform this mechanical bending mechanism, an extra device with a lifting and pressing tool needs to be designed. This tool requires that the bending mechanism tool has free access to one corner of the prepreg to initiate the backing paper removal. This might not always be the case, depending on the handling system. Finally, depending on the prepreg material and resin system, the shear force introduced by mechanical bending, might not be higher compared to the adhesive force and no initiation will be present. This has to be tested with this resin system and prepreg material.

Cooling spray

The third concept to introduce initial separation is by using a cooling spray. By spraying on the surface, the temperature is reduced and therefore the tack is reduced and it will

be easier to remove the backing paper. The freezing spray has a freezing point $< 42°$ Celsius. The adhesive force between the prepreg ply and backing paper is reduced and therefore the backing paper can be removed relatively easily.

Advantages The main advantage of the cooling spray is that it is a simple solution, only a small amount of liquid has to be sprayed on the surface. It is also easy to reproduce the initiation.

Disadvantages The cooling spray introduces a small amount of liquid onto the prepreg material, introducing a risk of condensation to the material. This is against the requirements set before. Finally the cooling spray and cooling head have to be clean. If this is not the case moisture may be introduced in the material.

4.4.2 Peel continuation concepts

The second step in the backing paper removal after initial separation is peel continuation. Once the backing paper is initiated, it should be peeled off over the entire length of the prepreg ply in the direction of the fibre. In total four peel continuation concepts are generated, first by using another industrial robot and end-effector, second by using the end-effector systems, third by making use of a spiked roller and finally by using vacuum of the ATL lay-up table.

Extra robot

The first peel continuation concept is a second installed extra robot continuation concept using a second industrial robot with an end-effector attached to it. This end-effector can be a suction cup or any other end-effector from section 4.2. The handling system has to hold the prepreg ply and has to stop at a predetermined position. The extra industrial robot then comes and grips the backing paper and removes it along the entire length of the prepreg ply by a peeling movement. For the removal of the upper side, the prepreg ply needs to be stacked on the lay-up table and the industrial robot comes to the lay-up table and peels the backing paper from the upper side.

Advantages The main advantage of using an extra industrial robot and end-effector is that it is able to peel the backing paper from the upper as well as the lower side of the prepreg material. The lower side can be removed if the end-effector holds the prepreg material and the robot grips the backing paper and continues the peeling motion. The backing paper on the upper side can be removed if the prepreg material is placed on the lay-up table. The second main advantage is that during placement of the prepreg ply on the lay-up table, the second robot can start removing the backing paper from the upper side. At the same time the industrial robot including handling system can travel back to get the next doubler or reinforcement. This will reduce the total cycle time of the system, compared to peel continuation concepts which are integrated in the handling system.

Disadvantages The main disasvantage of this solution is the high investment cost. Two extra industrial inclusiding end-effectors need to be purchased, installed and programmed. One industrial robot costs around 80000 euros and in total two are required. One on each side of the ATL lay-up table, resulting in an extra cost of 160,000 euros. This extra investment cost will make it hard to meet the stringent requirement of an ROI in 2 years. Furthermore depending on the handling system, additional space is needed for the industrial robot and end-effector to remove the backing paper.

Handling system

For this peel continuation concept the end-effectors from the robotic handling system are used. The end-effectors from the handling system have to grip the backing paper at the initated area and continue and remove the entire backing paper by a smooth peeling movement. This peeling momevement is guided by the industrial robot to which the handling system is attached.

Advantages The main advantage of this concept is that there is no need for extra investment. This is because the existing industrial robot and handling system are used to continue the backing paper removal from the prepreg ply.

Disadvantages The main downside of this concept, is that it is not able to remove the backing paper at the upper side of the prepreg ply. Therefore it can be considered as unacceptable or alternatively it has to be combined with an extra backing paper continuation concept, which is only able to remove the backing paper from the lower side. Finally, because the handling system has to remove the backing paper, the handling system is in use longer compared to using an extra robot, resulting in an increased cycle time.

Roller

The roller concept uses a roller as can be seen in figure 4.24. The cylindrical roller has small vacuum holes along the entire surface of the roller. The roller is attached to the frame of the handling system and therefore it is able to remove the backing paper from the upper and lower side of a prepreg ply. The roller is able to move 360° around its axis. Moving the roller along the length of the prepreg ply enables it able to get a grip on the backing paper and remove it. The roller can move along the handling system at the lower side of the prepreg ply. After placement the roller moves along the upper side of the prepreg ply.

Advantages The vacuum roller's main advantage is its capability of removing the backing paper from both sides of a prepreg ply. Because of predetermined heights of the industrial robot, the vacuum roller will be at perfect height for each laminate and subsequent removal of the backing paper.

Figure 4.24: Vacuum roller.

Disadvantages The main disadvantage of the vacuum roller is its extra weight and cost. The roller will add extra weight to the handling system and can result in industrial robots which need to handle higher payloads and increasing the total cost of the entire robotic system.The entire roller is estimated at a cost of 40,000 euros. Finally because the handling system has to remove the backing paper, the handling system is in use longer compared to using an extra robot, resulting in an increased cycle time.

Lay-up table vacuum

The last concept to remove the backing paper is by using the ATL lay-up table and its vacuum system. This concept can only remove it from the lower side of a prepreg ply and can be used in combination with the handling system concept to remove it from the upper side. The suction force at the lay-up table has to be lower than the lifting force of the handling system, but sufficient to remove the backing paper. The backing paper stays on the ATL lay-up table and the handling system transports the prepreg without backing paper at the lower side.

Advantages The main advantage of this concept is that there is no need for extra investment. The ATL lay-up table with vacuum along the entire surface is already present.

Disadvantages The main disadvantage of this concept, is that there is no possibility to initiate the separation. Therefore the question arises, will it be able to remove the backing paper without initation? Furthermore this concept is only able to remove the backing

paper from the lower side and it is required to remove it from both sides. This can be overcome by combining it with the handling system to remove the backing paper from the upper side. Finally vacuum has to be applied to the ATL lay-up table for a considerable time, this will result in higher energy cost. It is estimated that the vacuum needs to be applied for 1,5 hours for each set of skin, doublers and reinforcements resulting in high recurring cost.

4.5 Trade-off

In this section different concepts will be compared. The alternatives are compared, to see which concept best meets all criteria. In total 4 trade-offs are made, first different robotic cells are compared, after that the different end-effectors are compared. The third trade-off concerns the handling concepts to pick and place different dimensions. Finally different concepts to automatically remove the backing paper are traded.

4.5.1 Scoring system

For this trade-off a rough scoring system is used to assess the feasible candidates. A rough scoring system is chosen above a computed number system, because the research is still in preliminary design phase. Therefore no exact data about the performance of all concepts is available. Therefore the grading will be subjective and a three-state scoring system is used, where:

- "-": Unacceptable
- "0": Sufficient, acceptable
- "+": Excellent

In the case where a concept is rated unacceptable, the concept can either be eliminated immediately or one can look how to solve the problem. The rough scoring system is a good trade-off system because concepts which score unacceptable for one criteria can be eliminated immediately. If a weighted objectives method is used bad scoring criteria might be compensated by other outstanding performing criteria and this valuable information of an unacceptable performance might be lost. This could result in a concept still passing to the next stage even when possessing unacceptable criteria.

4.5.2 Professional advice trade-off

To get better insight in the different concepts, different companies in the field of pick and placement and automation were contacted before and during trade-off. Their expertise helped developing better insight into the shortcomings and advantages of the concepts. From the physical meetings several no-go's came clear and more importantly why they were a no-go. In total seven companies were contacted and several physical meetings were held. The companies met were Kuka robotics, ABB automation, Broetje Automation,

Schmalz, MTorres, MUK and Airbus. The contact details of the companies are summarized in appendix F and an overview of the different companies and there field of expertise is summarized here:

- *Kuka robotics* offers solutions for the automation of industrial processes. It is a leading company in the supply of robot technology.
- *ABB automation* is a leading company in automation technology and offers individual automation solutions. Furthermore they also supply a wide range of industrial robots.
- *Broetje automation* is specialized in production processes in the aerospace industry. They offer individual solutions for production processes.
- *Schmalz* has a wide range of vacuum components. They offer vacuum solutions that fit the customer's requirements.
- *MTorres* develops high complexity innovative solutions in industrial process automation. For this research they were consulted for their installed ATL machine at Airbus.
- *MUK* designs and manufactures customized solutions for inhouse material flow and production automation. At Airbus they offered several large-format cutting installations with ultrasonic knives, including the ATL lay-up table.
- *Airbus* is a leading aircraft manufacturer. Their expertise regarding the automation of production processes and methods was consulted at the Airbus Stade plant.

4.5.3 Robotic cell

To trade the different robotic cells, several trade-off criteria were used. Namely working envelope, repeatability/accuracy, implementability, speed and cost. The trade-off criteria are clarified first and after this the possible concepts are compared.

Working envelope The working envelope criteria includes the area the robotic cell needs to be able to cover. For this application the working envelope includes the entire ATL lay-up table, where the prepregs are picked, to the small lay-up tables at the side of the ATL, as can be seen in figure 4.2. Therefore the working envelope is 30 meters in length and 5,5 meters in width.

Repeatability/accuracy The repeatability and accuracy criteria are related to each other, since accuracy is the degree of proximity, and repeatability is the variation in placement or precission. It is an important criterion, since from requirement 3.4 in appendix E the positioning tolerance for the end of one prepreg ply shall not exceed the tolerance of $\pm$ 2,5 *mm* according to the technical drawing. Furthermore high repeatability and accuracy will increase the overall quality of the IBF shell. Improved quality may result in less rework and need for inspection. Table 4.1 summarizes the accuracies achieved with the different concepts.

Table 4.1: Achievable accuracy of robotic cell concepts.

	Fixed point	Linear track	Gantry system	Integrated bridge	Mobile unit
Accuracy $[\pm mm]$	0,06	0,08	0,1	0,5	1,06

Implementability The implementability criterion is created to check whether the different robotic cell concepts can be implemented in the current production lay-out. The criterion is created to fulfill requirement 1.7 in appendix E, that it must be ensured that the robotic system shall be able to be integrated in the current production lay-out without interference. The robotic system must not interfere with the ATL, ATL lay-up table and cutter. Furthermore for safety reasons, a minimum clearance of $600mm$ between the ATL and other automated equipment is required.

Speed The speed criterion is also an important parameter, because the faster the system can operate, the greater the reduction in total lead time that can be achieved. A greater reduction in lead time will result in better chance of a positive business case at the end. The speed of the different robotic cells is based on the speed it is able to achieve after pick up from the ATL lay-up table to the small lay-up tables at the sides for placement of the skin, doublers and reinforcements. The different maximum travelling speeds of the robotic cells are summarized in table 4.2.

Table 4.2: Maximum travelling speed of different robotic cell concepts.

	Fixed point	Linear track	Gantry system	Integrated bridge	Mobile unit
Speed $[m/s]$	3	2,35	2	2	0,7

Cost Finally also cost is one of the most important criterions. In order for Airbus to continue the project, a positive business case is needed. This requires the system has a return of investment of maximum two years, as in requirement 1.3 in appendix E. The cost criterion includes equipment, installation and programming cost. The cost for the different robotic cell concepts are summarized in table 4.3 and are determined by professional advice and are first estimations based on the current production cell lay-out and component costs. First estimations showed that with current production numbers of 312 A320 on yearly basis and a lead time reduction of 50% by automating the process the total system can only cost maximum 800,000 euros to achieve the return of investment in two years.

Table 4.3: Estimated cost of different robotic cell concepts.

	Fixed point	Linear track	Gantry system	Integrated bridge	Mobile unit
Cost in $[euro]$	720,000	175,000	-	350,000	200,000

Some concepts are discarded immediately, since they simply do not meet the requirements set in section 3.4.
First the concept of one or several industrial robots fixed at one place can be discarded. In this case there are two possible scenarios, the first one is just one fixed industrial robot. This solution is not able to cover the entire work envelope required to pick and place the prepregs. The second scenario, several fixed industrial robots at strategic places along the ATL lay-up table can be eliminated since the investment cost will certainly exceed the maximum total investment cost of 800,000 euros. The total cost of this concept is estimated at 720,000 euros without handling system and automated backing paper removal solution.
The second concept, the industrial robot installed at a linear track unit seems at first one of the most promising concepts. This is because it operates at relatively high speed, has a large working envelope, high repeatability/accuracy and finally low investment cost. However plant visits and expertise of the professionals, showed that the required minimum clearance between the ATL and linear track unit of $600mm$ to ensure safety can never be achieved. Furthermore there is not enough space for the linear track unit to be installed on the floor next to the ATL lay-up table. The linear track unit requires foundations to transfer the forces resulting from the long arm of the industrial robot. Currently between the ATL and ATL lay-up tables foundations for the ATL and vacuum pipes and cabling for the ATL lay-up table are already present. Therefore the linear track unit can't be installed and the concept is eliminated too.
The Gantry system can also be discarded immediately, also here the profesional expertise proved that it is never possible to meet the requirement of an ROI of two years. To cover the entire width and length of the ATL lay-up table a large gantry system is needed. The length of the gantry system will be 32 meters and the width 10 meters. Therefore a large steel construction is needed and this comes with high investment costs. The professionals agreed that the investment of the steel construction will easily exceed the maximum investment cost of 800,000 euros.
Therefore two possible concepts that meet the requirements remain, the integrated bridge and the mobile unit. The integrated bridge is a simple solution and covers the entire working envelope, this is also the case for the mobile unit. Since the mobile unit is able to drive where it wants, it is able to reach all the parts needed. For the repeatability/accuracy criterion the mobile unit has a lower accuracy compared to the integrated bridge, $1{,}06mm$ compared to $0{,}5mm$. The mobile unit also is much slower compared to the integrated bridge, $0{,}7m/s$ compared to $2m/s$. The mobile unit will also require extra time to exactly anker at the anker points, increasing cycle time and in process "down time" to transfer and secure at positions.
Even for the higher investment cost of the integrated bridge concept, it is concluded that the extra investment cost will be recovered due to the higher operating speed and the longer time the equipment will be implemented at Airbus. The results of the trade-off are summarised in table 4.4.

4.5.4 End-effector

To trade the different end-effectors, several trade-off criteria were used. The trade-off criteria are grab reliability, non-damage gripping, gripping time, suitability prepreg, maintainability, independency ambient conditions and finally accuracy. First the trade-off

Table 4.4: Final trade-off robotic cell concepts.

	Fixed point	Linear track	Gantry system	Integrated bridge	Mobile unit
Working envelope	0	+	+	+	+
Repeatability/accuracy	+	+	+	0	0
Implementability	0	-	0	0	0
Speed	+	+	+	+	0
Cost	-	0	-	0	+
Ranking	5	3	4	**1**	2

criteria are explained, after this the possible concepts are compared.

Grab reliability The grab reliability criterion is the ability of the robotic system's gripper to firmly grip the material, without losing grip over time. The criterion results from requirement 2.5 in appendix E, that the robotic system shall have sufficient holding force, being able to grip the prepreg material and handle it till placement, without dropping it. Dropping of the expensive prepreg material may result in unwanted damage and possible rework or scrapping of the part.

Non-damage gripping Non-damage gripping means that the end-effector may not cause damage to the prepreg during pick and placement. Requirement 2.1 states that the handling system, including end-effectors shall avoid any contaminations to the laminate during handling. Therefore the criterion can be a go or no-go for a concept and it is introduced.

Gripping time The Gripping time criterion covers the time needed after the end-effectors touches the prepreg and when it actually grips the laminate and is able to lift it. The criterion is important, since longer gripping time will increase the cycle time of gripping event and in its way the total cycle time of the lay-up of the skin, doublers and front and aft spar reinforcements of the IBF.

Maintainability The maintainability criterion is included to check whether the end-effectors needs special maintainability during its lifetime or that it can be operated without need for special inspection. Maintainability of an end-effector leads to extra work and more "down time". Maintainability can come in different forms, for example the change of parts in regular time, limited tool time, risk of production stop, etc.

Independency to ambient conditions The indepency to ambient conditions criterion is a soft criterion and is based on whether the end-effector can work within the required environmental conditions in the ATL lay-up area.

Table 4.5: Gripping time in seconds for the end-effector concepts.

	Mechanical gripper	Suction gripper	Bernoulli gripper	Needle gripper	Adhesive gripper	Hydro adhesive gripper	Electrostatic gripper	Carden gripper
gripping time per component in seconds	??	<0,5	<0,5	<1	<0,1	<1	<0,1	<1

Accuracy Finally the accuracy criterion is the degree of proximity wherein the end-effector can pick and place the prepreg. It is an important criterion, since high repeatability and accuracy will increase the overall quality of the IBF. This may result in less rework and need for inspection.

Cost Cost is also one of the most important criteria. In order for Airbus to continue the project, a positive business case is needed. A positive is the case if the system has a maximum return of investment of two years, as in requirement 1.3 in appendix E. The cost criterion includes equipment, installation and programming cost. The cost for the different end-effectors are summarized in table 4.6 and are gained by the professional advice and first estimations are based on standard components and a lead time reduction of 50%, so a total time of 175 IM. First estimations showed that with current production numbers of 312 A320 on yearly basis and a lead time reduction of 50% by automating the process the total system can only cost maximum 800,000 euros to achieve the return of investment in two years. The total number of end-effectors required and their individual cost will influence the total cost of the handling .

Table 4.6: Estimated Costs per end-effector concept.

	Mechanical gripper	Suction gripper	Bernoulli gripper	Needle gripper	Adhesive gripper	Hydro adhesive gripper	Electrostatic gripper	Carden gripper
RC per component in euro	0,64	0,47	49,61	0,64	9,63	123,19	162,00	0,64
NRC per component in euro	3,33	5,83	8,76	3,75	4,38	4,38	1,67	5,00

Also in this trade-off different concepts can be discarded, since they don't meet the requirements.
First the mechanical gripper can be discarded, it scores unacceptable on the suitability for prepregs criterion. It is graded unacceptable since a proper grip is needed to grip the prepreg material, using a mechanical gripper requires a free edge and being able to grip from the upper and lower side. For this application, it is physically impossible since the prepreg material on the ATL lay-up table is surrounded by other skin, doublers, front and aft spar reinforcements or scrap material as can be seen in figure B.1.
The needle and carden gripper have both needles penetrate the prepregs, the main difference is that for the needle gripper few needles pentrate the laminate under a certain angle and for the carden gripper multiple small needles just grip the laminate. From literature no real consensus is present whether the needles damage the fibres or not. It is judged that the needles won't damage the fibres, but will shift them. Shifting them will influence the mechanical properties of the material and is considered unacceptable and in contrary to requirements where it is stated that the prepreg material shall not be damaged during handling.
The adhesive gripper concept is eliminated for two reasons, first because the adhesive gripper may influence the prepreg material. This is possible because some adhesive may be left on the laminate and fibres can be torn off because the adhesive force can't be turned off. Requirement 2.1 states that the handling system, including end-effector, shall not contaminate the prepreg material and therefore it scores unacceptable on this criterion. Secondly, it scores unacceptable on the maintainability criterion. The adhesive force will decrease over time and the end-effector will therefore need maintenance. Lack of proper maintenance will reduce the grab reliability and so increase the risk of dropping the prepreg material during handling.
The hydro adhesive gripper concept is dismissed because it is considered unacceptable to use as end-effector for prepreg materials. As for the adhesive gripper, the hydro adhesive gripper will contaminate the prepreg material. Water droplets may permeate and influence the laminate, also during heating of the frozen water droplets the resin can melt a bit. This may influence the quality of the prepreg laminate.
Finally the electrostatic gripper concept is also eliminated. It is rated unacceptable on maintainability and independency to ambient conditions. The electrostatic gripper needs maintenance to keep the surface dust free. This surface cleaning is needed and will lead to more "down time" of the robotic system. Next to that, high electrical potentials are needed, with charging voltages up to 8000 Volts. Such high charging voltages in combination with a lay-up area contaminated with small conducting carbon fibre particles is considered as unacceptable. The electrostatic gripper shows high potential because of its extremely low weight. However, it is still in the development stage and can be a good solution in several years.
This result in two suitable end-effector, the suction gripper and the Bernoulli gripper. Due to the non-contact gripping the Bernoulli gripper scores less on the grab reliability criterion. However because of the non-contactless gripping it scores better on non-damage gripping. If suction cups are used the prepreg material deforms a little bit because it is slightly sucked into the vacuum cup. However studies at Airbus showed that the material deformations do not influence the mechanical behaviour of the final product and the deformations are invisible after autoclave. Because of the lower operating cost and higher grab reliability the vacuum gripper is chosen as the most suitable end-effector for this

application.

Table 4.7: Final trade-off concepts for end-effectors.

	Mechanical gripper	Suction gripper	Bernoulli gripper	Needle gripper	Adhesive gripper	Hydro adhesive gripper	Electrostatic gripper	Carden gripper
Grab reliability	+	+	0	0	0	+	+	0
Non-damage gripping	0	0	+	?	-	-	?	?
Holding force	0	0	0	0	0	+	0	0
Holding time	0	0	0	+	+	+	+	0
Maintainability	0	0	0	0	-	0	-	0
Independence ambient conditions	+	+	+	+	0	0	0	+
Accuracy	0	0	-	0	0	0	0	0
Costs	+	+	0	+	0	0	0	+
Ranking	4	**1**	2	5	8	3	6	7

4.5.5 Handling different dimensions

To trade the different handling systems, five trade-off criteria were used to trade the various handling system concepts. The trade-off criteria used are weight, work envelope, adaptation time, implementability and cost. In total 4 concepts are traded, a multi actuator system, retractable bars, a combination of retractable bars and multi actuator system and finally multiple grippers. First the trade-off criteria are clarified, after that the possible concepts are compared.

Weight The weight criterion says something about the total weight of the handling system. A lower weight can result in the use of an industrial robot from a lower payload range. An industrial robot of lower payload range, means lower investment cost. The weights of the handling systems are summarized in table 4.8.

Work envelope The work envelope criterion is the area of the handling system that is able to pick and place the prepreg material. If a large area can be created, it implies that a highly flexible system is created. This is beneficial since a large variation of prepregs needs to be picked and placed. The handling system should be able to handle the skin with a length of $4380mm$ and a width of $618mm$ as well as some small doublers, where the smallest dimension is $403mm$ of length and $41mm$ of width.

Table 4.8: Estimated weight of different handling system concepts.

	Multi actuator	Retractable bars	Combination	Multiple grippers
Weight in kg	600	200	400	variable between 20 and 150

Adaptation time The adaptation time criterion is an indication of how fast the handling system can change its configuration to pick the next prepreg ply of different dimensions. The longer the adaption time to change configuration takes, the longer the cycle time of the system. Longer cycle time means that the benefits compared to manual lay-up are reduced and eventually this can result in a negative business case. The adaption times of different handling concepts are summarized in table 4.9.

Table 4.9: Adaption times of different handling system concepts.

	Multi actuator	Retractable bars	Combination	Multiple grippers
Adaption time in s	<0,1	<10	<10	<300

Implementability The implementability applies to how easy the system can be implemented in current production lay-out. This criterion results from requirement 1.7; the robotic system shall be able to be integrated in current production lay-out without interference. From this criterion it can be seen whether reconfiguration of current production process is required or if it's possible that the handling device can be added to the current lay-out without further implications.

Repeatability/Accuracy The accuracy criterion is the degree of proximity the end-effector can pick and place the prepregs. The repeatability and accuracy criteria are related to each other. Accuracy is the degree of proximity, whereas repeatability is the variation in placement or precision. It is an important criterion, since from requirement 3.4 in appendix E the positioning tolerance for the end of one prepreg ply shall not exceed the tolerance of $\pm$ 2,5 mm according to the technical drawing. Furthermore high repeatability and accuracy will increase the overall quality of the IBF shell. Improved quality may result in less rework and need for inspection. Table 4.1 summarizes the accuracies achieved with the different concepts.

Table 4.10: Achieved accuracy of handling system concepts.

	Multi actuator	Retractable bars	Combination	Multiple grippers
Accuracy in mm	0,1	0,5	0,5	0,1

Cost Finally, the cost criterion says something about the investment cost of the handling system and whether it fits within the estimated budget. The cost criterion results from the killer requirement that the robotic system shall have a return of investement of maximum two years. If this is the case it will result in a positive business case and the project can continue and be implemented. The estimated costs of all handling systems obtained from the contacted companies are summarized in table 4.11.

Table 4.11: Estimated cost handling system concepts.

	Multi actuator	Retractable bars	Combination	Multiple grippers
Cost in *euro*	250,000	50,000	125,000	2,025,000

The handling system concepts are traded and some concepts can be discarded immediately, since they don't meet the requirements.
First the retractable bars handling system has been discarded, since the work envelope is insufficient. A large variation of prepregs that need to be picked and placed is present. The handling system, only has four retractable arms, which are relatively long to pick the front and aft spar reinforcements with a width of $55mm$ and a length of $2990mm$. Because of the long length of this reinforcement and the presence of only two attachment points between the prepreg and the handling system, the concept is rendered unacceptable. Due to the two attachment points, if one end-effector loses contact, the prepreg ply will drop on the floor or lay-up table. Next bending of the prepreg ply will be present due to only two attachment points. Therefore the accuracy of placement on the lay-up table can be influenced.
Next, the multiple grippers concept is discarded since the cost of the solution is unacceptable. The ROI of multiple grippers exceeds the estimated cost of the system, to achieve the requirement of an ROI in 2 years. To achieve this goal, the total system cost may not exceed 800,000 euros. The estimated investment cost of the different grippers is already estimated at 2,025,000 euros. Next due to the multiple handling systems, to change for each prepreg ply. This results in an increase in cycle time and the need for large storage space. It is considered unwanted and therefore the multiple grippers concepts is discarded.
In total two suitable concepts are acceptable to fulfil the requirements: the multi-actuator system and the multi-actuator retractable bars system. They are discussed and compared in more detail. The multi-actuator handling system is a large perforated plate with actuators to individually open and close vacuum holes. Because of the numerous actuators the total weight of the system is heavier compared to the multi-actuator retractable bars handling system. For the latter, less actuators are needed and only a retractable bars system is needed. Therefore the multi-actuator system will weigh around $200kg$ heavier compared to the multi-actuator retractable bars system. The higher weight of the multi-actuator handling system may imply that heavier and so more expensive robot is necessary.
Next, the multi-actuator system is able to pick and place prepregs which can differ largely in dimensions. According to requirement 1.5, as can be seen in appendix E, where it is stated that the system shall be universal and that it can be easily implemented for other pick and place activities at Airbus. Although handling systems are often individual solutions, the multi-actuator handling system is more flexible and can be more easily

implemented for different applications within Airbus. Because of the high flexibility, the concept is graded excellent. The multi-actuator retractable bars concept is also a flexible system, but less flexible compared to the multi-actuator handling system since the work envelope is restricted by the minimum length of the arms. Therefore the concept is graded as sufficient.
The adaption times of the handling systems are also compared. The adaption time of the multi-actuator handling system only takes less than 0,1 milliseconds to adapt its configuration. The only adaption required is the actuation of the holes. For the multi-actuator retractable bars handling system the adaption time is longer. The individual actuation of the end-effectors only takes less than 0,1 milliseconds, nut the elongation and retraction of the arms takes up to 10 seconds. Therefore the latter is rated acceptable and the multi-actuator handling system is graded excellent.
The handling system can be easily integrated into the industrial robot for the multi-actuator system, as well as the multi-actuator retractable bars system. Only one attention point is present, it has to be made sure that there is no danger of collision during the entire pick and placement activity. Both concepts are graded excellent because of the good implementability in current production lay-out.
The multi-actuator has higher accuracy compared to the multi-actuator retractable bars handling system concept. The accuracy of the multi-actuator only depends on the accuracy of the robotic cell. The accuracy of the multi-actuator retractable bars is less accurate because of the retractable bars. The accuracy is less but still sufficient to meet the position tolerance requirement that may not exceed 2,5mm according to the technical drawings. Therefore the first concept is rated excellent and the retractable bars concept as sufficient.
Finally, in terms of costs the multi-actuator is twice as expensive as the multi-actuator retractable bars handling system. 250,000 euros, instead of 125,000 euros. This is a reasonably large amount of the total estimated budget of 800,000 euros to achieve an ROI of maximum two years. Therefore they are both considered sufficient, but still not unacceptable.
Even though the investment cost is higher, the multi-actuator handling system still offers a larger work envelope. Therefore no expensive development cost to implement the gripper in other applications is needed. Next to that the adaption time takes only milliseconds, therefore reduced cycle time will result and the extra investment will be earned back in the long run. The results of the trade-off is summarised in table 4.12.

Table 4.12: Final trade-off handling system concepts.

	Multi actuator	Retractable bars	Combination	Multiple grippers
Weight	0	+	0	+
Work envelope	+	-	0	0
Adaptation time	+	0	0	-
Implementability	+	+	+	0
Accuracy	+	0	0	+
Cost	0	+	0	-
Ranking	**1**	3	2	4

4.5.6 Backing paper removal

The backing paper removal trade-off is divided in a trade-off for intial separation concepts of the backing paper and peeling continuation concepts. First the different trade-off criteria are briefly elaborated. Afterwards the different concepts are traded for initial separation and peel continuation.

Reliability The reliability criterion is the ability of the concept of the initial backing paper separation and peel continuation to remove the backing paper without leaving it on the prepreg material. The reliability criterion is important, since presence of backing paper on the prepreg material after removal is unacceptable. It results in either scrapping of the part or extra manual work to remove the backing paper left on the material.

Implementability The implementability criterion is created to check whether the initial separation and peel continuation concepts can be integrated in current production lay-out and with the handling system. The concepts may not interfere with the handling system, ATL and cutter. This is according to requirement 1.7, which states that the system shall be able to be integrated in current production lay-out without interference.

Non-damaging Non-damage means that the initial seperation concept may not cause damage to the prepreg. This is according to requirement 3.2. The backing paper shall be removed with great care. As to not detach strands, altering their alignment or producing damages.

Suitability prepreg The suitability prepreg criterion is present to check whether the concepts are able to initiate and continue the peeling of the backing paper from the prepregs from both sides of the material.

Cost Finally also cost is an important criterion. According to requirement 1.3, the system shall have an ROI of two years. The costs include equipment, installation and programming costs. Table 4.13 summarizes the costs of the initiation and continuation concepts.

Initial separation

In total three different peel initiation concepts are traded. First initial separation by injecting air between the backing paper and the backing paper, second by mechanical bending and finally by using cooling spray.
First the cooling spray concept is eliminated since it violates requirement 2.1. It is unacceptable that the handling system contaminates the prepreg material. Cooling spray

Table 4.13: Estimated cost peel initiation and peel continuation concepts.

Initial separation				
	Inection	Mechanical bending	Cooling spray	
Cost in *euro*	10,000	20,000	Variable	
Peel continuation				
	Extra robot	Handling system	Roller	Vacuum table
Cost in *euro*	80,000	0	16,000	0

introduces small water vapours on the material and may influence the material. Therefore the concept is graded unacceptable to use with prepreg materials and consequently is eliminated.
Next, the mechanical bending concept is eliminated for two reasons. First, it is graded unacceptable on the implementability criterion. The mechanical bending concept needs a free corner of the prepreg material, that needs to be fed into a machine and is forced to bend. On the ATL lay-up table, as well as being gripped by the multi-actuator handling system, there is no free edge available. Therefore the mechanical bending mechanism is graded unaccepatable. Second of all a small trial with small prepreg covered with backing paper have been organised. For this trial, a small set-up, shown in figure 4.23, has been constructed. Lifting the laminate several times and increasing and decreasing the distance between the lifing element and the support unit had no influence on initial separation. No separation occured, therefore the concept is discarded. The adhesive force of the resin system is concluded to be higher than the shear force created by the mechanical bending. Therefore it is concluded that the concept may work for different fibre and resin systems. Finally that leaves us with the winning concept, injected air. It scores excellent or sufficient on all trade-off criteria. It scores excellent on the implementability criterion, because it can simply be attached to the handling system and can be connected on the already existing pressured air widely available at the production hall. Furthermore a small trial has been performed to evaluate the concept. For this trial a pressurized gun with a small needle is used to manually puncture the backing paper, as can be seen in figure 4.22. It was concluded that it was easy to initially separate the backing paper from the prepreg material. A before and after picture of the experiment can be seen in figure 4.25. It was concluded that from the moment that the air bulb reaches the side, the initiation area doesn't grow anymore. Therefore a foot can be used to guide the bulb in the wanted direction. The results of the trade-off are summarised in table 4.14.

peel continuation

To trade the peel continuation concepts, the same trade-off criteria as for the initial separation concepts are used. In total four peel continuation concepts are traded, first by using an extra industrial robot and end-effector, second by using the end-effector of the gripping system, next a vacuum roller and finally by using the vacuum that can be applied by the lay-up table of the ATL.

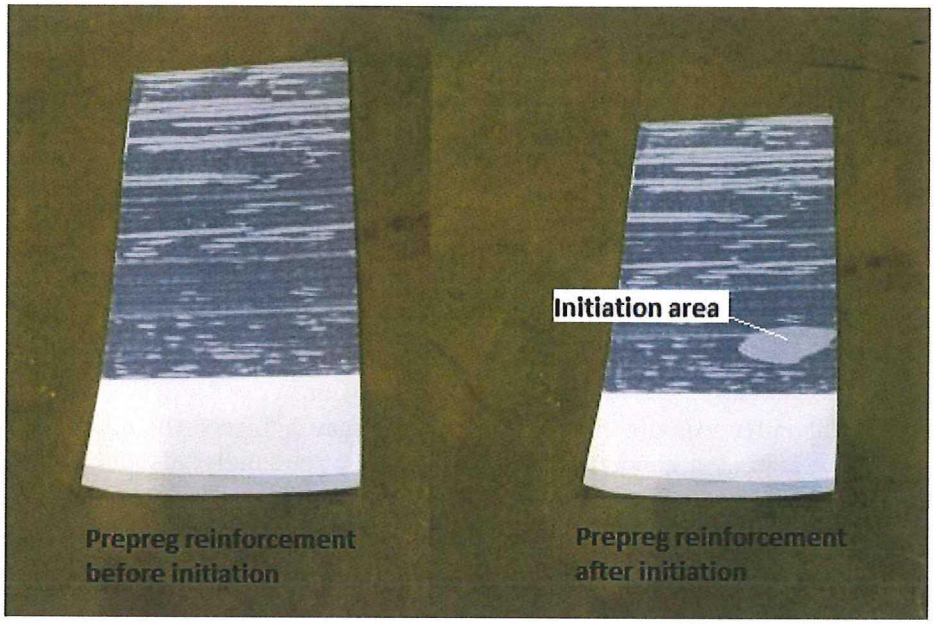

Figure 4.25: Small experiment performed to proof peel initiation concept. With test sample before peel initiation area on left hand side and initiated area on right hand side.

Table 4.14: Final trade-off peel initiation concepts.

	Injected air	Mechanical bending	Cooling spray
Reliability	0	+	0
Implementability	+	-	0
Non-damaging	0	0	0
Suitability prepregs	0	-	-
Cost	0	0	0
Ranking	**1**	2	3

The first concept, the extra industrial robot with end-effector is discarded. The solution is simply too expensive. Two industrial robots are needed, one at each side of the ATL lay-up table. The total cost of this is estimated at 200,000 euros. Requirement 1.3 states that the entire system shall have an ROI in two years. The investment cost of the industrial robots and end-effector is 25% of the total investment cost to achieve the ROI in two years.
The end-effector and ATL vacuum lay-up table concepts are eliminated for the same reason. The extra industrial robot with end-effector and the vacuum from the ATL lay-up table concepts are only able to peel the backing paper from either only the upper or lower side of the prepreg material. An option can be to combine them to remove from the upper and lower side, because the investment cost is 0 euros. However it is not possible to initiate the backing paper at the lower side. Therefore the concepts are eliminated.
Therefore only one possible peel continuation concept results, the roller concept. The

vacuum roller is suitable to use with prepregs and the material will not get damaged. Furthermore it scores acceptable on the other criteria and will therefore be used to remove the backing paper from the material. The results of the trade-off are summarised in table 4.15.

Table 4.15: Final trade-off peel continuation concepts.

	Different end-effectors	End-effector gripping system	Vacuum roller	Lay-up table vacuum
Implementability	0	0	0	+
Non-damaging	0	0	0	0
Suitability prepregs	+	-	+	-
Cost	-	0	0	+
Ranking	4	3	**1**	2

4.6 Conclusion

The goal of this chapter was to identify different concepts for the robotic system, in order to handle prepregs from the ATL lay-up table to a flat side lay-up table. In order to have a full proof of concepts, different concepts for the robotic cell, end-effectors, handling of different dimensions and backing paper removal are come up with and evaluated.
It can be concluded that automation of a process does not evolve from standard off the shelf solutions. Individual solutions within the predetermined requirements are needed. This statement is supported by the trade-off made in this chapter. Promising concepts are discarded because they do not meet the requirements. Because of high investment cost, non implementability possibilities in current production lay-out or contaminating/damaging the prepreg material.
Therefore a complete solution results that meets best all requirements. An integrated bridge will be used to travel along the entire length of the ATL lay-up table. The integrated bridge will be equiped with a multi-actuator handling system which can individually open and close the vacuum cups in order to handle a large variety of dimensions. To initiate backing paper removal, compressed air will be injected between the backing paper and prepreg material. Finally a vacuum roller will continue the peeling movement. The robotic handling system is designed in more detail in chapter 5.

Chapter 5

The robotic cell

This chapter describes the final lay-out of the robotic cell in more detail. In chapter 4 it was concluded that an integrated bridge in the ATL lay-up table with a multi-actuator low vacuum handling system is the most promising concept to handle prepregs from the ATL lay-up table to the side lay-up table. This chapter first describes the entire robotic cell lay-out in section 5.1. The future process steps are described in section 5.2. Next the components of the robotic cell are described in more detail in section 5.3. After that, section 5.4 dives into special attention points concerning the robotic system. Finally an economic analysis of the robotic system is carried out in section 5.5 and a conclusion of this system is made in section 5.6.

5.1 Robotic cell lay-out

This section shows the final robotic cell lay-out in more detail. In the automated cell six main components can be defined: the ATL, the ATL lay-up table, the integrated bridge, the handling system, backing paper remover and finally the side lay-up table and disposal container. An overview of the entire robotic cell lay-out and the main components can be seen in figure H.4. More impressions of the entire cell lay-out can be seen in appendix H. First, the automated tape layer [9] is an automated computer controlled machine tool which places UD prepreg tape on a flat tooling surface, the ATL lay-up table. The tapes have a width of 300 mm and are laid in different layers and orientations on top of each other, creating a big prepreg laminate. In appendix B, figure B.1 shows the big prepreg laminate for the upper shells and figure B.2 shows the laminate for the lower shells. The ATL is placed on a rail system and is therefore able to run along the entire length of the ATL lay-up table.
The second main component is the ATL lay-up table, it is a vacuum table with a length of 27 meters and a width of 5,5 meters. Because of the large dimensions, it allows the ATL to lay a big prepreg laminate on either the left or right side of the vacuum table. One lay-up cycle of the ATL included three sets of skins, doublers and front and aft spar reinforcements from which the shells are constructed. As mentioned before, such a set can be UR, UL, LR or LL. Because of the large dimensions it is possible to cut out the

reinforcements from the big prepreg laminate laid by the ATL on one side and start a new lay-up cycle of the ATL at the same time. Vacuum is integrated along the entire surface of the table to fix the prepreg tapes on the lay-up table and to ease cutting.
Next, the integrated bridge covers the entire width of the ATL lay-up table and is attached to the table. The cutter needed to cut the prepregs and the multi-actuator handling system are attached to the integrated bridge. Because of the longitudinal movement of the integrated bridge along the ATL lay-up table and the movement along the length of the integrated bridge, the cutting gantry is able to move in x and y direction and cut the required prepregs. The cutter is able to cut through the prepreg material by applying a high frequency to the knife, therefore the cutting knife vibrates vertically and cuts through the material.
The handling system is an important component of the robotic pick and place system and is attached to the integrated bridge. The handling system is present to pick the prepregs from the ATL lay-up table and place them on the lay-up table. In order to be able to pick and place all reinforcements at the right position and orientation, the handling system should be able to rotate 90 degrees and move along the width of the ATL lay-up table. Next at the handling system, the backing paper peel initiator and peeling continuator are attached. The peel initiator is able to move along the length of the handling system and to rotate 180 degrees in order to inject the compressed air on both sides of the prepregs. The peel continuator, in this case the vacuum roll is also able to move along the length of the handling system and is attached to it.
Finally, on both sides of the vacuum table, a disposal container and lay-up table are placed. The disposal container is present to gather the peeled-off backing paper whereas the lay-up table is present to stack the skin, doublers and front and aft spar reinforcements according to the technical drawings. Both the lay-up table and disposal containers have a length of 6 meters and a width of 0,75 meters and are placed at a minimum clearance distance of 0,6 meters. They are placed in the same direction as the length of the lay-up table. This configuration is needed for the handling system to be able to place the prepregs at the right position. In the other position, this would not be possible.

5.2 Process steps

Section 3.2 shows the current production steps to produce the entire IBF shells. One of the steps is the laminating of skin, doublers and front and aft spar reinforcements. To perform this task, after the prepregs are layed by the ATL and cut by the cutter, they are stored in special storage units. So to start the laminating processing step, a worker takes the required prepreg and removes the backing paper indicated with a label. Next the worker has to flip the prepreg and stack them at the correct position, according to the technical drawings. After that, the worker has to remove the backing paper manually on the upper side. The worker has to repeat this step and follow the technical drawings to stack the required reinforcements in the right order, at the right position to create the shells.
Since the robotic system will replace this manual processing step, the automated processing steps replacing it are summarized here.

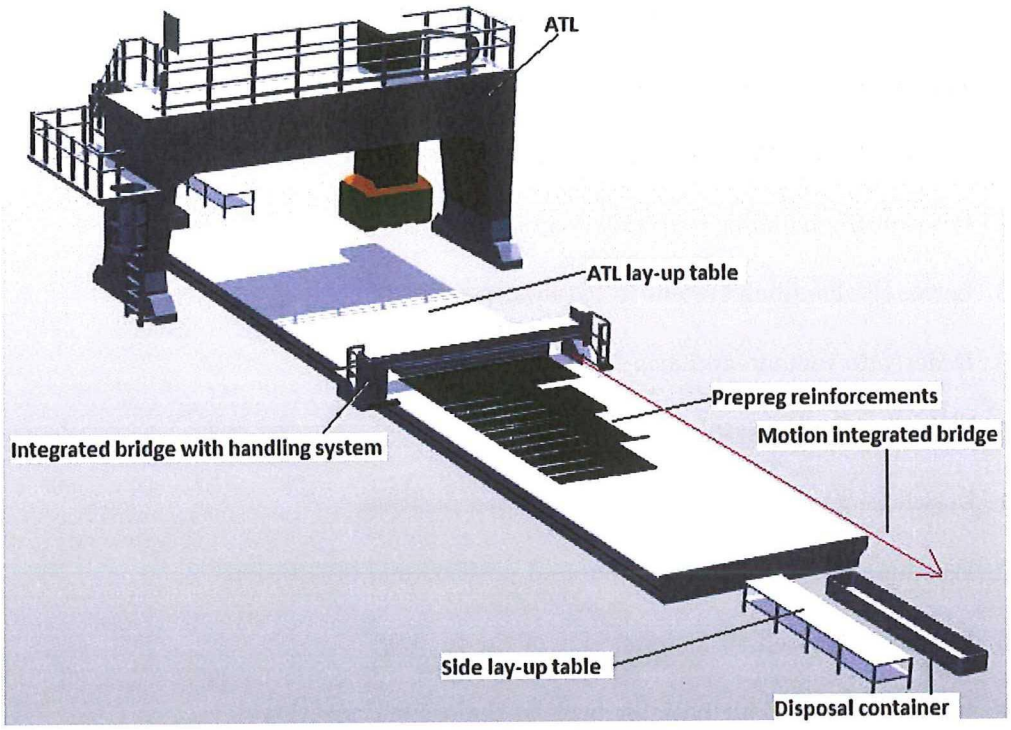

Figure 5.1: Overview of the robotic cell lay-out with ATL, ATL lay-up table, integrated bridge and lay-up table.

Process steps:

1. Position the integrated bridge to the required position.
2. Position handling system to the required position and orientation.
3. Lower the handling system to required position.
4. Activate vacuum and grip the prepreg.
5. Lift the handling system.
6. Position the integrated bridge to the disposal container.
7. Position handling system to the required orientation.
8. Move compressed air initiator to the edge of prepreg and rotate it 180 degrees.
9. Inject compressed air at lower side of the prepreg.
10. Move compressed air initiator back to the original position.
11. Activate vacuum of vacuum roll.
12. Move vacuum roll along the entire length of the prepreg.
13. Deactivate vacuum of vacuum roll.

14. Deposit backing paper into the disposal container.
15. Visual inspection for complete removal of backing paper.
16. Position the integrated bridge to the required position.
17. Position the handling system to required position.
18. Lower the handling system to required position.
19. Deactivate vacuum and grip the prepreg.
20. Lift the handling system.
21. Position integrated bridge to the required position.
22. Position handling system to required position and orientation.
23. Inject compressed air at lower side of the prepreg.
24. Move compressed air initiator back to the original position.
25. Activate vacuum of vacuum roll.
26. Move vacuum roll along the entire length of the prepreg.
27. Deactivate vacuum of vacuum roll.
28. Position the integrated bridge to the disposal container.
29. Position handling system to the required orientation.
30. Deposit backing paper into the disposal container.
31. Visual inspection for complete removal of backing paper.
32. Repeat step 1.

5.3 Robotic cell components

This section discusses the robotic cell components in more detail. The components discussed in this section are the ATL lay-up table, integrated bridge, handling system, backing paper removal system, side lay-up table and disposal container, controller and finally the sensors.

5.3.1 Automated tape layer lay-up table

The ATL lay-up table is developed and manufactured by MUK, a company specialized in production automation. The lay-up table is used to lay the prepreg tapes from the ATL and later on cut the required dimensions. The lay-up table or vacuum table is equipped with a vacuum surface. The vacuum holes have a diameter of 2,5mm and are positioned in matrix form at a distance of 25mm. Applying vacuum ensures that the backing paper and prepreg material are sealed to the surface of the lay-up table. Because of the sealing, no shifting of the prepreg and backing paper or individual movement of the fibres will be present during cutting. To achieve this vacuum force a vacuum pressure of 0,2 is applied, which can be turned on and off manually. The ATL lay-up table has a surface area of $27x5,5m^2$ and is placed centrally in the production hall. At the side of the table linear guidings are integrated at each side. These lineare guidings make it possible for the integrated bridge to move along the entire length of the lay-up table, including the side lay-up table and disposal container. Because the weight of the current integrated bridge will increase due to the multi-actuator handling system, current linear guidings are not able to handle the extra forces acting on it. Therefore redesign of the bearings and linear guiding is needed. Furthermore the linear guidings have to be elongated on both sides of the ATL lay-up table to ensure the integrated bridge to achieve the required range. Figure 5.2 shows the integrated bridge on the linear guidings.

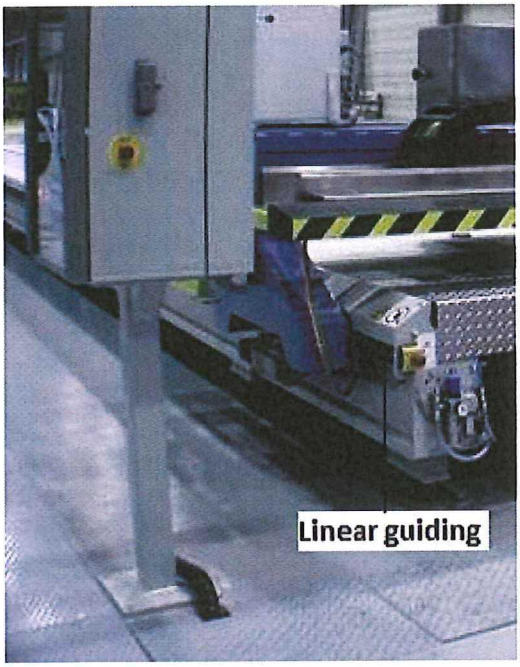

Figure 5.2: Linear guiding of integrated bridge, integrated in the ATL lay-up table.

5.3.2 Integrated bridge

The integrated bridge is present to reach the required range to pick and place the prepregs. Apart from this, the cutter is attached to it, to cut the required prepregs laid by the ATL.

To be able to perform this task, the current integrated bridge with attached cutter needs to be redeveloped for this project. The integrated bridge will be equipped with an ultrasonic cutter and handling system. The ultrasonic cutter is able to travel along the entire width of the integrated bridge and is therefore able to cut the required contours. The handling system allows to handle prepregs, which vary in dimensions. During handling no neighbour material is influenced.
As mentioned before, the ultrasonic cutter is able to move along the entire length of the integrated bridge. The ultrasonic knife itself, is able to turn around its axis. The combination of movement of the integrated bridge, ultrasonic cutter and the rotation of the ultrasonic knife make is possible to cut straight lines, circles and splines. To control the movements of these parts, special software is used in order to cut the desired contours. The ultrasonic knife consists of a transducer and an oscillator, creating a vibrating blade which is capable of cutting the prepreg material. The transducer generates the vibration and the oscillator drives the transducer. To generate the vibration, the transducer is equipped with a piezoelectric element. When a voltage is applied to the piezoelectric element, the transducer displaces a few micrometers. Periodically applying voltage creates a vibrating moment that resonates the cutting blade. The vibrating motion goes from the transducer to the blade tip, generating a vertical displacement at the tip. The vibration generally exceeds a frequency of $20kHz$.
Next, the handling system, in this case a multi-actuator handling system is mounted on the integrated bridge with a robotic tool changer. The tool changer is a universal part and allows easy swithing of the handling system. It consists of two parts; the master side and the tool side. Therefore the handling system can be locked automatically to the integrated bridge, allowing pneumatic supply and electrical signals to be guided from the handling system to the integrated bridge. For this application the robotic tool changer is able to rotate 90°, this rotation enables the handling system to pick and place the prepregs at the right position and orientation. No rotation means that some reinforcements cannot be positioned correctly on the lay-up table. In order to lift, sink and move the handling system along the length of the integrated bridge, linear guidings can be used. To rotate the universal robotic cool, rack and pinion gear system can be used.

5.3.3 Handling system

The multi-actuator handling system is used to grip the prepregs from the ATL lay-up table and move them to the side lay-up table. The handling system needs to ensure that no damage, shifting of individual fibres or contamination occurs to the prepreg material during this handling. Maintaining the quality of the prepregs ensures the required and calculated mechanical properties of the IBF shell and therefore guarantees high part quality.
The handling system needs to handle a large variation in prepreg dimensions, therefore continuous adjustment of the handling system is required. The adjustment is achieved by opening and closing specific holes in the perforated plate of the handling system. This opening and closing is achieved by using multiple bi-stable solenoid actuators. In figure 5.3 the bi-stable solenoid actuator principle is shown. To control the actuation of the solenoids into different configurations, appropriate programming is needed. For the upper shells 28 different configurations are required, whereas the lower shells 26 require different configurations are needed.

The perforated plate is completely flat in order to handle the flat prepregs. The perforated plate can be covered with a special coating or foam to protect the prepregs. Due to the flat shape and low inner volume of the vacuum box, the box can be evacuated quickly. Therefore it is possible to grip prepregs in a short amount of time.
The following paragraph will describe a selection process to determine the exact dimensions of the handling system, vacuum generator selection and finally the valves.

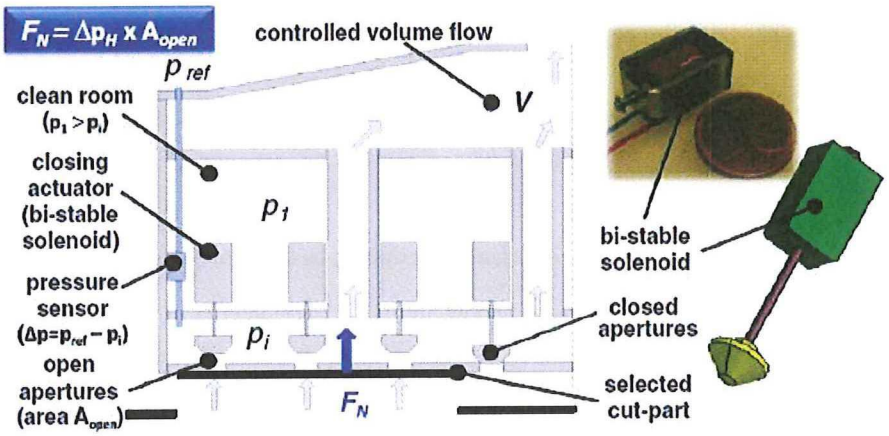

Figure 5.3: Concept of the selective gripping technology.

Dimensioning of handling system The handling system needs proper dimensioning. What are the dimensions of the handling system itself? How many holes will be present in the perforated plate and what is their spacing? These topics will be discussed in this paragraph.
In order to do this, first the required holding force needs to be determined. The calculated holding force will ensure that the gripper can safely grip the prepregs during handling without dropping them. To determine the required holding force, one needs to know the lift case. In total two main lift cases exist. The first lift case is horizontal lifting of the material and the second lift case is a vertically placed gripper and the material perpendicular to the gripper. The two lift cases can be seen in figure 5.4. For both lift cases the gripper itself is able to move as well horizontally and vertically.

To determine the required holding force, it is important to know that the gripper should not only be able to carry the weight of the prepregs, but it is should also be able to withstand the accelartion forces introduced by the movements of the integrated bridge. For this application the maximum acceleration is limited by the maximum acceleration of the bridge and is $2m/s^2$. Furthermore in this application the handling system and the prepreg handled are in horizontal position at all times. Therefore the second loadcase should not be considered and the required holding force can be determined with the first load case. Equation 5.1 shows the required holding force for a horizontal load case. Where m is the mass of the prepreg, g is the gravitational acceleration, a is the maximum acceleration of the integrated bridge and S is the safety factor. As an example, the skin is used to calculate the required holding force. The skin is the largest and heaviest reinforcement. The reinforcements have smooth surface finish.

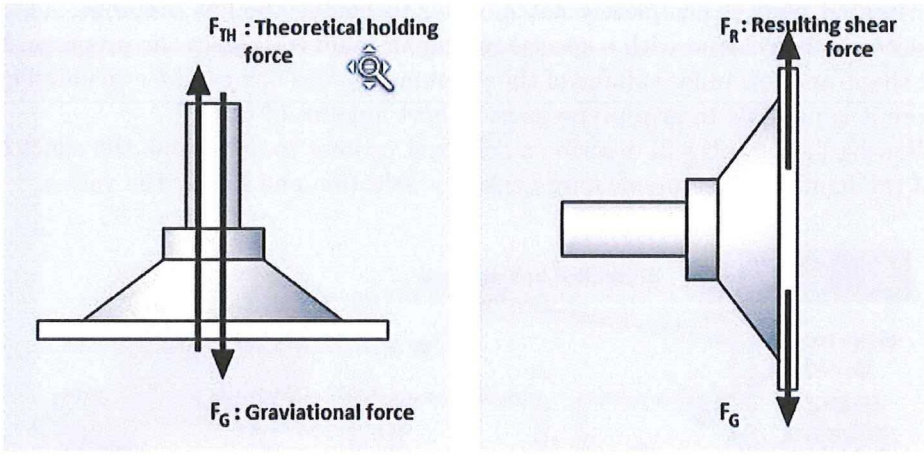

Figure 5.4: Two lifting cases for gripping by vacuum suction.

$$F_{TH} = m * (g + a) * S \tag{5.1}$$

During the calculations a safety factor of 1,5 is used. The value is chosen because the accident prevention regulation prescribes that a minimum safety factor of 1,5 needs to be used. Knowing all data of the skin reinforcement and maximum acceleration, the required holding force can be determined.

$$F_{TH} = 4263,27 * (9,81 + 2) * 1,5 = 75,52N \tag{5.2}$$

Now the required holding force is known, one can determine the number of vacuum holes and their dimension. Together with this, the required vacuum pressure can be determined. The paramaters are linked to each other and the relation can be seen in equation 5.3. Where d is the hole diameter, P_u is the applied vacuum pressure and n is the amount of holes. All these parameters are related in this equation.

$$d = 1,12 * \sqrt{\frac{m * S}{P_u * n}} \tag{5.3}$$

From Airbus, one of the requirements is that a highly flexible end-effector needs to be designed, which can later be implemented for automated handling processes at the plant. There are two possible configurations; the first being the holes in the perforated plate organized in such a way that it is optimal to grip all prepreg for the IBF. The configuration of this lay-out is provided by the company Schmalz and can be seen in figure 5.5. The second one is a largely perforated plate with all holes in matrix form with a small distance separating them making it possible to grip an even larger variety of reinforcements. Because of the requirement that the handling system can later on be implemented for other automated handling processes and reducing the development costs, the highly flexible perforated plate with small holes in matrix form is opted for. Now to determine the hole diameter, the number of holes and the required vacuum pressure some choices

have to be made. First, the smallest bi-solenoid actuators available on the market have a diameter of $10mm$. In literature it was found that the hole diameter for a similar system had a diameter of $8m$, for this reason $10mm$ is a good value. Next, because UD prepreg is anisotropic, they have a low bending stiffness upright to the fibre orientation. Because of this reason a small aperture is opted for. Combining small hole diameter with small aperture results in a highly flexible handling system. As found in literature an aperture of $50mm$ is chosen. Implementing this in the handling system results in a system with a length of $4375mm$, a width of $650mm$ and a height of $200mm$. The perforated plate will consist of 80 holes over the entire length and 8 holes over the width. This results in a total amount of 640 holes and actuators for the system.

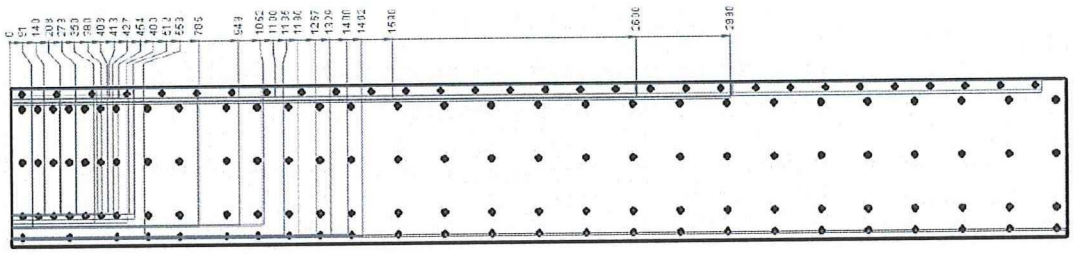

Figure 5.5: Configuration of handling system adapted to handle only prepregs for the IBF.

Equation 5.3 can now be rewritten to determine the required vacuum pressure. Equation 5.4 relates the vacuum pressure P_u to the mass of the prepreg m, the hole diameter d and the amount of holes n.

$$P_u = \frac{1,12^2 * m * S}{d^2 * n} \tag{5.4}$$

Implementing the values then gives us:

$$P_u = \frac{1,12^2 * 4273,27 * 1,5}{10^2 * 640} = 0,1256bar \tag{5.5}$$

For the skin reinforcement an underpressure of 0,1256 bars is enough to generate the required suction force to handle the reinforcement. In figure 5.6 the relation between the required holding pressure and number of holes is shown for the skin reinforcement and a hole diameter of $10mm$.

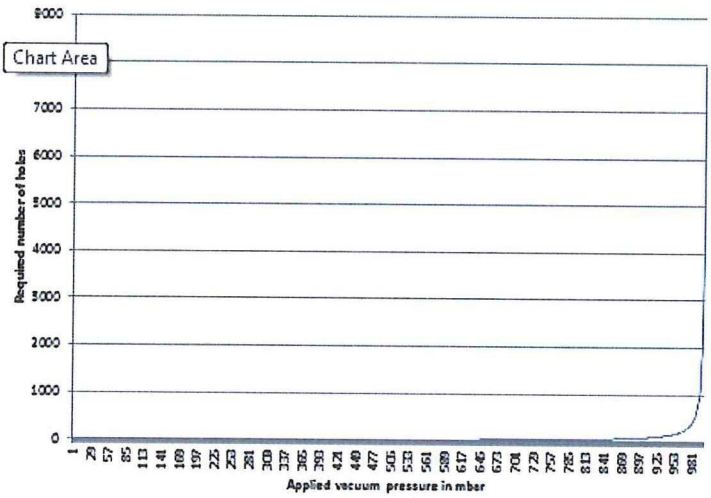

Figure 5.6: Relation between applied vacuum pressure and required amount of holes.

Volume flow Besides the dimensioning of the handling system and the required holding force, the required suction rate or volume flow is an important factor. The volume flow is mainly determined by the material being handled. If a non-airtight material is picked by a gripper, higher volume flow is required compared to complete air-tight material. Table 5.1 summarizes typical volume flow values for smooth air-tight surfaces.

Table 5.1: Volume flow depending on the diameter of suction pad for smooth, air-tight surfaces.

Suction cup diameter	Suction cup area	Volumeflow	Volumeflow
up to $60mm$	$28[cm^2]$	$0{,}5[m^3/h]$	$8{,}3[l/min]$
up to $120mm$	$113[cm^2]$	$1{,}0[m^3/h]$	$16{,}6[l/min]$
up to $215mm$	$363[cm^2]$	$2{,}0[m^3/h]$	$33{,}3[l/min]$
up to $60mm$	$28[cm^2]$	$0{,}5[m^3/h]$	$8{,}3[l/min]$

To determine the required suction rate for the Hexcel Hexply 6376 prepreg material covered with E3760 white backing paper, small suction trials have been carried out to validate the required suction rate and to ensure that the material behaves as an air-tight material. For the trial 3 layers of prepreg material were used in a $[0, 0 + 45]$ orientation. To suck the prepreg material, a Schmalz SGPN-20 suction cup is used. This suction cup has a flat shape and is specially designed to handle composite materials and foils. The cup has a flat sealing lip and inner support, therefore no "pulling in" of the prepreg will occur. Apart from the vacuum cup a pneumatic ejector is used to create vacuum pressure. The pneumatic ejector used is a Schmalz SBP-05 ejector. The set-up of this trial is shown in figure 5.7.

Performing this trial, it can be seen that when a pressure of $5bar$ was created with the pneumatic ejector, a vacuum underpressure of $850mbar$ could be achieved. With an applied pressure of $3bar$, a vacuum underpressure of $600mbar$ could still be created. From these results, it is concluded that the prepreg material, including backing paper,

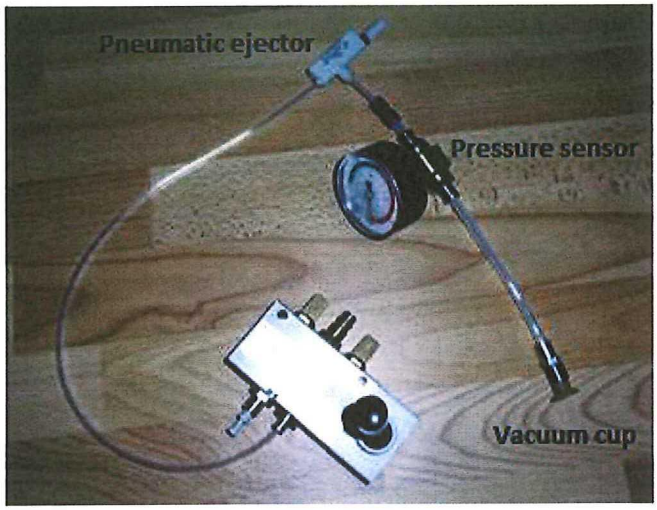

Figure 5.7: Trial set-up of ejector and vacuum cup.

are considered as air-tight. Figure 5.8 shows a relation between the applied pressure and the achieved vacuum pressure for air-tight materials. It shows that the values from the experiment correspond with the graph. Following the relation in table 4.1, a suction rate or suction capacity of $0{,}0833m^3/h$ or $1{,}3833l/min$ when a hole diameter of $10mm$ is used.

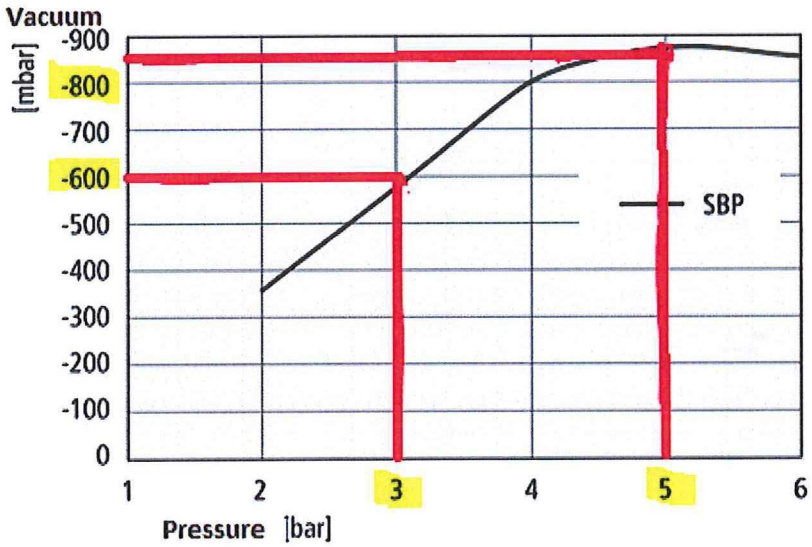

Figure 5.8: Relation applied pressure and generated vacuum pressure for air-tight materials.

Next, an interesting finding could be observed during the experiments. In this case, a non-flat suction cup is used to test the air-tightness of the material. Initial separation of the backing paper is promoted and the backing paper is locally detached from the prepreg material. Figure 5.9 shows this affected area.

Figure 5.9: Affected initiation area by using non-flat and flat suction cup.

Vacuum generator selection The next step is to select a vacuum generator, a suitable vacuum generator depends on different factors. The first factor is the type of material being handled, is the material air-tight or porous? Next, how is energy supplied? Is it supplied by electricity or compressed air? Also what is the cycle time of the gripper, are short cycle times enough or does the handling system need to travel long distances? Table 5.2 summarizes the three main types of vacuum generators; pneumatic ejector, vacuum pump and vacuum blower and the factors for which the vacuum generators are most suitable.

Table 5.2: Different vacuum generators and selection criteria.

	Porous	Air tight	Compressed air supply	Electricity supply	Short cycle time	Long cycle time
Ejector		X	X		X	
Pump		X		X		X
Blower	X			X		X

From paragraph 5.3.3 it can be seen that the prepreg material behaves as an air-tight material. For this reason the vacuum blower can be discarded from the beginning, since it is advised to be used when porous materials need to be handled. Next, for this project there is a need to cover a large range from the ATL lay-up table to the disposal container and lay-up table and back. Because of the large handling distances, the pneumatic ejector is discarded too. This leaves one suitable vacuum generator, the vacuum pump.
To determine which vacuum pump is required, one needs to calculate the suction rate that the vacuum generator has to apply. The total suction rate required by the vacuum pump is calculated by using equation 5.7. Where V is the volume flow, n is the number of holes and V_s is the required suction rate per suction cup.

$$V = n * V_s \tag{5.6}$$

This gives for this case:

$$V = 640 * 1,3833 = 885,312 \frac{l}{min} \tag{5.7}$$

Table 5.3: Technical data of the Schamz EMV-2 solenoid valve.

Diameter $[mm]$	Working principle	Volume flow $[m^3/h]$	Volume flow $[l/min]$	Input DC $[W]$	Position change $[ms]$	Weight $[kg]$
2	Without current: closed	1	17	2,5	10	0,150

In this case, the cheapest option is to purchase twenty vacuum pumps with a maximum suction rate of $165l/min$. The total suction capacity of the six vacuum pumps is $990l/min$ which is slightly more than required and sufficient. An example of this vacuum pump is the EVE-OG 165 AC3 vacuum pump from Schmalz with a unit cost of 4,312 euro.

Valve technology To open and close the vacuum holes individually, small bi-stable solenoid valves are used to "turn the vacuum on and off". The bi-stable solenoid valve has two stable positions, to get into these two stable positions the valve uses a spring or a permanent magnet. The position of the solenoid can be changed by applying a certain voltage for several milliseconds. By applying this voltage to predetermined individual solenoids, it is possible to open and close them in a short period of time. Because of small voltages are applied for such a short amount of time, the solenoids consume a small amount of energy. It is also important to know that the nominal flow of the solenoid valve may not be less than the suction rate of the vacuum generator. An example of a suitable solenoid valve is the Schmalz EMV-2 with a unit price of 51,60 euro. Table 5.3 summarizes the technical data of this valve.

5.3.4 Backing paper removal

The backing paper removal solution is directly integrated in the multi-actuator handling system and the integrated bridge. As mentioned in chapter 4 an injection needle will be used to initiate the backing paper initiation and a vacuum roller continues the peeling movement of the backing paper.

Peel initiation To initiate peeling, the injection needle penetrates the backing paper. The injection needle itself is connected to an air hose and injects cold compressed air between the backing paper and prepreg material. This compressed air has a standard pressure of 5 bars and is provided on the shop floor. Moreover, this cold compressed air reduces the tack of the prepreg, backing paper combination and initiates peeling by uncoupling the two layers at the edge of the material. In the previous chapter, the needle gripper was discarded, since it was considered unacceptable because it is believed that the needles influence the mechanical behaviour of the prepreg material by shifting fibres. For the injection needle, the needle only go through the backing paper and will not punch throught the entire prepreg. If the needle does punch through the prepreg material, the injection occurs at the edge of the material. This edge is trimmed later on, so possible contamination or damaging of the prepreg material is removed. The injection needle is installed at the edge of the handling system and is able to move along the entire length.

Because of this longitudinal movement, it is possible to initiate all the prepregs. No matter the position of the handling system, they are picked.
To be able to continue peeling the backing paper should be initiated on the upper, as well as the lower side. The injection needle is able to rotate 180 degrees, enabling it to reach the lower side of the prepreg during handling above the disposal container. The upper side of the material can be initiated after placement on the lay-up table. Finally to be sure the initiation area is controlled, a foot can be used. This foot is present for two reasons, first of all it prevents the needle from penetrating too deep into the material and damaging the carbon prepreg. Second, the foot is used to guide the air flow in the wanted direction, as can be seen in figure 5.10. It prevents the air flow from reaching the edges and stop growing because the air escapes at the edge.

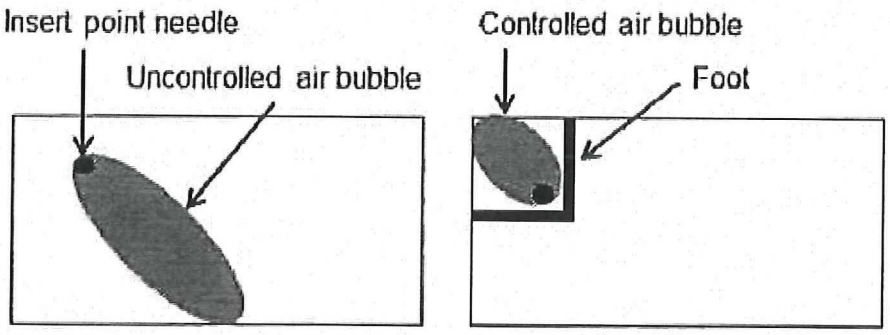

Figure 5.10: Peel initiation with and without using a foot to guide the airflow.

Peel continuation After initiation, the vacuum roller will be used to peel the backing paper. The vacuum roll is attached to the handling system and is able to move along the entire length of the handling system by using linear guidings. The backing paper at the lower side can be removed after pick up, above the disposal container. For the upper side, the robotic system first needs to lay the prepreg on the small side lay-up table. After placement, the vacuum roll rolls over the prepreg, removing the backing paper from the upper side of the prepreg material.
Buckingham has some advice about how to best peel backing paper [11]. For this reason his experiences are used as a guidline. First the prepreg must be held down, the down force must be greater than the normal component of the peel force to stop the prepreg lifting from the lower surface. Peeling is best initiated at a corner of the profile. Once initiated, peeling should preferably follow a direction that minimizes the width of the peel front. Because UD material is used, the peeling motion should be along the direction of the fibres. The backing paper is best peeled at an angle between 90 and 135 degrees and with a speed of $0{,}1m/s$ [11].

Vacuum roll The vacuum roll is an aluminium shell with a large number of holes. The holes are drilled in the aluminium shell to allow air to pass. The shell is attached to a centre tube, the centre tube is used to rotate the shell around the centre and to apply vacuum to the aluminium shell. An example of an aluminium vacuum roll can be seen

in figure 5.11. The aluminium roll may be covered with a special coating or covering to protect the material.

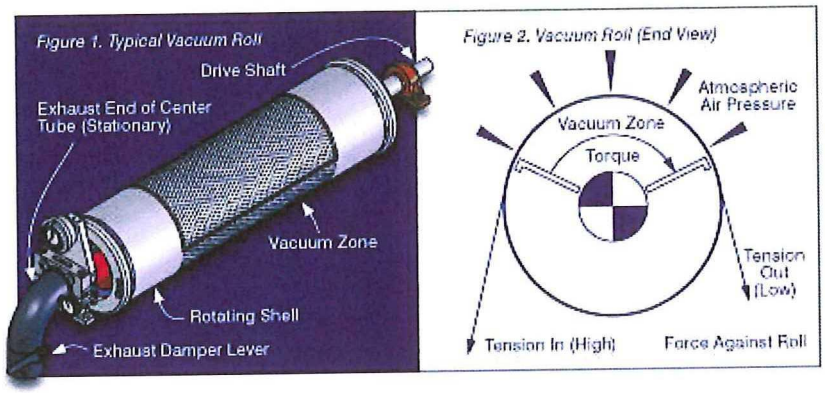

Figure 5.11: Lay-out of vacuum roll.

In the vacuum roll a vacuum zone is created, a blower is installed to remove air from the vacuum roll. In order to regulate the vacuum zone, a special barrier system is built into the roll. The barriers are able to move along the width of the vacuum roll and vary the vacuum zone.
There are two important factors in a vacuum roll. First the vacuum level and second the escape path. The vacuum level inside the vacuum roll is important. Because of the bigger pressure difference between the atmospheric conditions and the vacuum pressure inside the vacuum roll, it is more likely that air will be sucked into the interior of the vacuum roll. Second, the escape path, the escape path is necessary to remove air from the vacuum roll. The biggest part of this escape path is the holes. The higher number of holes in the vacuum roll, the shorter the escape route.
For the vacuum roll, no standard off the shelf solutions are available. For this reason some design tips are included:

- The web of the vacuum roll should only touch the backing paper on one side.
- Large normal forces are introduced by high pressure differences between the atmospheric environment and the vacuum pressure inside the vacuum roll. Higher pressure difference and so normal force will increase the friction between backing paper and roll. The normal force is produced by the backing paper tension and secondly by the pressure difference.
- To handle lightweight backing paper, a mesh surface covering can be used. This mesh will prevent the backing paper to deform by the vacuum holes and eventually get ripped.
- For proper design, one has to provide maximum and minimum backing paper width, wrap angle, Substrate types and thicknesses, line speed, tension and tension differential ranges, orientation of the centre of the vacuum zone and operating environment.

Removal strategy In order to be able to remove the backing paper from both the upper and lower side of the prepreg, proper removal strategy is required.
To remove the backing paper from the lower side of the prepreg, the integrated bridge and handling system are positioned on top of the disposal container. After peel initiation, the vacuum roll rolls over the lower side of the prepreg and removes the backing paper, while the handling system keeps holding the reinforcement. It is important that the suction force of the handling system is greater then the suction force of the vacuum roll. Figure 5.12 shows the strategy to remove the backing paper from the lower side and the disposal of it in the disposal container.

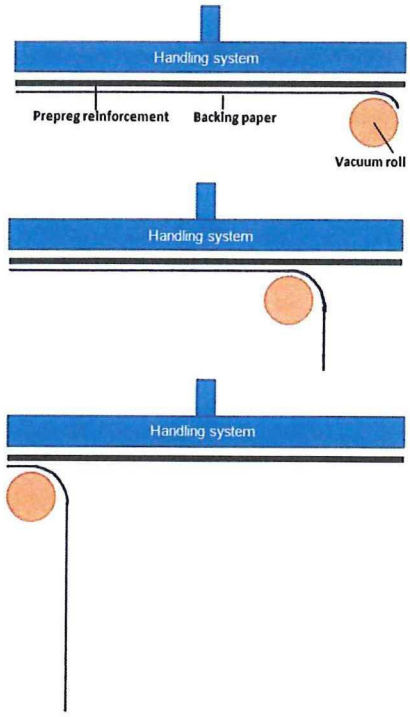

Figure 5.12: Removal strategy of backing paper from lower side of prepreg.

To remove the backing paper from the upper side of the prepreg. The reinforcement first needs to be stacked on the side lay-up table. After, the backing paper can be initiated and the vacuum roll can remove the backing paper from the upper side. Now the backing paper is wrapped around the vacuum roll. To be able to put the backing paper into the disposal container, the vacuum of the handling system is activated. Rolling back the vacuum roll will attach the vacuum foil on the handling system and unreel it from the vacuum roll. The integrated bridge and handling system now has to position on top of the disposal container. Deactivating the vacuum pressure of the handling system assures the backing paper will fall into the disposal container. Figure 5.13 shows the peeling strategy to remove the backing paper from the upper side of a prepreg.

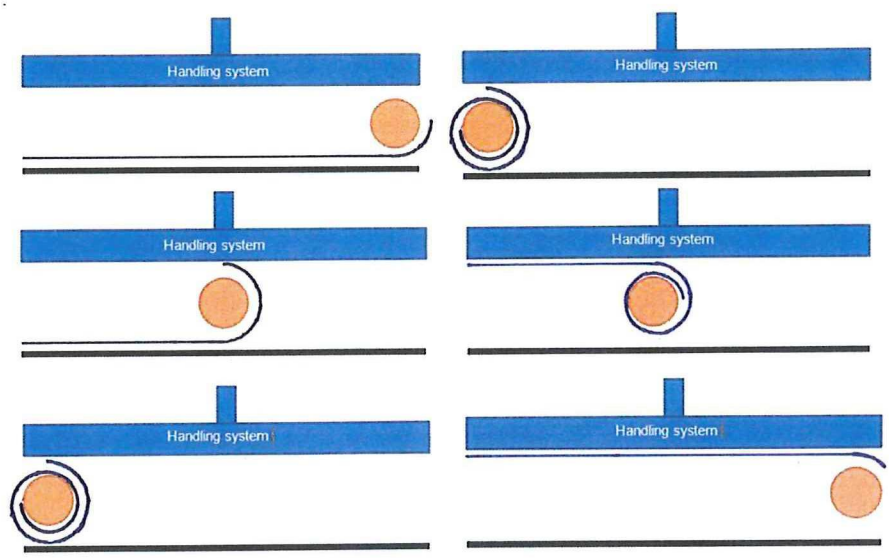

Figure 5.13: Removal strategy of backing paper from upper side of prepreg.

5.3.5 Side lay-up table and disposal container

Next to the ATL lay-up table, the side lay-up table and disposal container are placed. Both the lay-up table and the disposal container are placed in the same direction as the ATL lay-up table. This set-up is required because only in this set-up it is possible for the integrated bridge and handling system to place all prepregs at the required positions, according to the technical drawings.
The side lay-up table is the same table used today by the workers to manually stack the prepregs. The table is equipped with a vacuum surface, fixing the prepregs after placement. Next, vacuum is required to generate a higher suction force then the vacuum roll. In this way the prepregs stay attached to the lay-up table during peeling of the backing paper.
The disposal container is an aluminium construction with the same dimensions as the side lay-up table. A scale is integrated in the disposal container to weigh the backing paper thrown away by the handling system. If the backing paper added to the disposal container matches the weight of the backing paper removed by the robotic system, the system can continue its cycle. If the weight does not match, the system knows it failed removing all backing paper at one side and a worker should remove the backing paper that is left on the prepreg before the system can continue it cycle.

5.3.6 Controller

To control the entire robotic system, a digital system is required. For today's processes a Siemens NC 840D is used to control the ATL and cutter. For this reason, the same control unit will be used. The control unit is shown in figure 5.14. Using the same control unit means that there is no need to invest in a new control unit, only reprogramming of the control unit is needed.

The first things to be controlled are the coordinates, so the integrated bridge and handling system know where the prepregs are layed on the ATL lay-up table. The reference points and zero point of the laid out materials of the ATL is automatically exchanged with the integrated bridge. The ATL starting point is manually determined by the worker. When the ATL program is ready, the starting point and the corresponding coordinates are communicated with the controller of the integrated bridge. The bridge in its turn is now able to cut the prepreg material in the required contours. Now that the coordinates are known the integrated bridge knows where to grip the prepreg reinforcements and can start handling them and start stacking them at the nearest side lay-up table. During on ATL program, three sets of skins, doublers and front and aft spar reinforcements are laid down. To be able to place the prepregs at both sides of the ATL lay-up table, in total 24 different programs need to be programmed and controlled. The 24 programs result from 3 sets of skins, doublers and reinforcements, for the UL, UR, LL and LR shells on both sides of the ATL lay-up table. For the cutting program, only 4 programs have to be programmed and controlled; UL, UR, LL and LR.

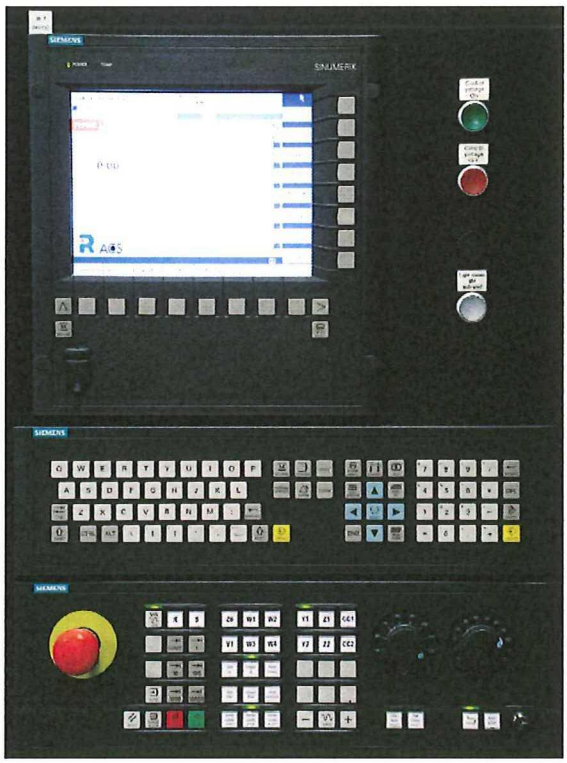

Figure 5.14: Picture of a Siemens Sinumerik 840D control system.

Next to controlling the ATL and movement of the integrated bridge and handling system, several other things are controlled by the same control unit during its cycle. First the ATL controller communicates the exact starting position and orientation of the large prepreg laminate layed down on the ATL lay-up table to the integrated bridge. Knowing the exact position and orientation of the prepreg laminate, the cutter knows its start position to cut the required shape. Next, the bi-stable solenoid actuators are individually controlled by the control unit, to open and close the required holes in the perforated plate. The backing

paper remover is also controlled by the controller. It is used to control the injection gun and vacuum roll. Finally the scale of the disposal container is connected to the control unit. If the weight of the backing paper matches the required weight added to the disposal container, the system can continue its cycle.

5.3.7 Sensors

Sensors are used in a system and automated process to control its operations and to react to different situations [39]. Different sensors can be integrated in the automated pick and place system. In total three main tasks of the sensors can be distinguished. First to recognize the object by distance measuring or by approach effect. Next, a sensor can check whether the gripping was succesful and finally sensors can be used to determine the position and orientation of the object. In this case, the prepregs always have the exact same dimensions and position, therefore the sensor equipment can be reduced to a minimum. To determine the distance of the object and the position, different sensors can be used; tactile sensors, optical sensors, acoustic sensors or capacitive sensors.
The first possible sensor is a sensor to identify the position in x and y-coordinates of the prepreg to be picked and handled by the system. To identify the position, no sensor is opted for the positioning, because the control unit communicates the exact coordinates of the prepregs to the controller and the integrated bridge and handling system know where to position and grip the prepreg. Requirement 3.1 in appendix E shows us that a repeated positioning of the reinforcements with a tolerance of $\pm$ 2,5mm as indicated in the technical drawings is required. The accuracy of the integrated bridge and handling system do not exceed $\pm$ 0,5mm, for this reason the tolerance of the equipment is less than the required tolerance during lay-up and the task can be performed without sensor.
To recognize the distance of the handling system to the prepreg, the handling system needs to be able to move in z-direction. Or the system picks the prepreg from the ATL lay-up table or it places it on the side lay-up table. The first approach is easier compared to the second, because in the first case no material has been gripped and for the second approach the view on the target is limited. Also in this case no sensors will be used, because the position can be approached without any sensor, depending on the tolerances. It is assured that with the tolerances the material will always be gripped, will not fall on the tool or the laid materials. Also, the gripping device will not apply too much pressure on the materials, which may cause distortions.
In the handling system a pressure sensor is installed. The pressure sensor measures the pressure in the handling system. In order to establish the required holding force, the volume flow generated by the vacuum generators is adjusted. This action is also controlled by the Siemens Simulink 840D control system. The controller will receive feedback if the needed vacuum pressure is reached and can pick the prepreg.
Finally sensors or an optical system can be used to check whether the backing paper is correctly and completely removed. A sensor could be used to weigh the backin paper in the collection unit. This way it can be checked whether all backin paper is removed. However it is considered that this method is too sensitive. If only a small piece of backing paper is left on the prepreg, the scale will not be able to measure it and will result eventually in scrapping of the shell. For this reason an optical system is needed to check whether all backing paper is removed. This optical system can identify when some white backing paper is left on the black prepreg reinfocement. If some backing paper is left on

the prepreg, the system will stop and a worker has to remove the backing paper left on the prepreg material.

5.4 Special attention points

This section describes special attention points with respect to the automated system. Special attention points are the ATL lay-up program, the orientation of the prepregs on the ATL lay-up table, qualification, safety and hazards and finally backing paper removal.

5.4.1 Automated tape layer lay-up program

To manually stack the prepregs according to the technical drawings, a worker first removes the backing paper with reference label. This is the lower side of the reinforcement. Next, the the prepreg is flipped over and laid down on the lay-up table or on another prepreg. Now the backing paper from the upper side can be removed.
The robotic system is not able to flip the reinforcements. To encounter this, the ATL lay-up program needs to be changed. The ATL has to lay the prepreg tapes in a different order compared to current production. In figure 5.15 the change in ATL program is shown.

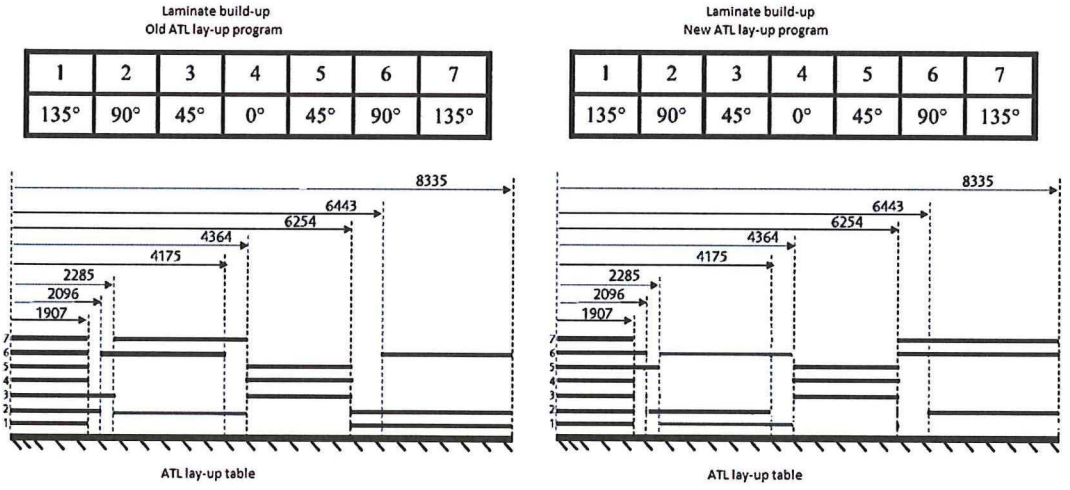

Figure 5.15: Change of ATL program in order for not flipping the prepreg material anymore during stacking. ATL program with flipping is shown on left side and for the new case on the right side.

5.4.2 Orientation prepregs

Some of the prepregs cut by the cutter are rotated 90 degrees compared to their lay-up direction. This is to guarantee the needed ply orientations in the reinforcements.

To reduce the cycle time of the ATL and limit material waste. Therefore the handling system needs to rotate 90 degrees during pick-up to be able to position the reinforcements correctly. The laminates that are rotated 90 degrees are A006, B017 and B018, according to table G.1 in appendix G.

5.4.3 Qualification

To confirm its characteristics, the robotic system needs to be qualified. To qualify the system it has to be determined whether the system meets the minimum standards. Within Airbus no procedure to such qualify a process is present. In order for a process to be qualified, the process has to work conform to the Airbus process instructions (AIPI) [32]. AIPI is a process instruction that establishes the requirements and defines the necessary procedures for manufacturing of monolithic structures, made of carbon, glass, ceramic or hybrid fibre reinforced thermoset prepreg material, giving complete detailed in-house process instructions. Next, the AIPI meets the requirements established in AIPS 03-02-019, manufacture of monolithic parts with thermoset prepreg materials [31]. To conclude this, in order for the robotic system to be qualified, it needs to be proven that all standards set by the AIPI can be met by the robotic system.
Furthermore the manufacturer of the robotic cell should have designed the robotic system according to the machinery directive 2006/42/EC. The machinery directive is a European directive for the machinery industry on the safety criteria that machinery must satisfy. The directive includes protecting of rotating parts if possible, instalment of warning markers, etc. All present risks should be minimized as much as possible, according to the guidelines set by the European Union.

5.4.4 Safety and hazards

Some safety instructions to operate the robotic handling system properly are included. During the robotic handling activity some personnel may be required in the working envelope of the robotic cell while working. Therefore a worker can be hit by the robot, trapped between the robot and another component or hit by flying objects released by the robot.

Types of accidents There are different types of accidents that can occur and they can be grouped in four categories: Impact or collision accidents, crushing and trapping accidents, mechanical part accidents and other accidents.
The impact or collision accidents are characterized by unpredicted movements or component malfunctions leading to contact accidents. Crushing and trapping accidents occur if a body part is trapped between the robot arm and other equipment. For this reason a minimum clearance between the components of $600mm$ is required. If breakdown of components occurs, such as the end-effector or power source, it is considered as a mechanical part accidents. The dropping of a prepreg from the handling system is an example of a mechanical part accident and may be avoided by installing a redundant system. Finally other accidents include failure from electronics and pressurized fluids.

Sources of hazards Hazards may be expected from different sources; human errors, control errors, unauthorized access, mechanical failures, environmental sources, power systems or improper installation.
First, human errors may be caused by inherent prior programming; interfacing activated peripheral equipment can lead to unpredicted movement of the robot. Next, control errors are errors in the control system caused by software errors or electromagnetic or radio frequency interference. Unauthorized access by entering the safe area may be hazardous to unauthorized persons. Also due to mechanical failure, part failures and unexpected operations might occur. Futhermore, environmental sources, such as electromagnetic and radio frequency interference exert an undesirable influence on the robotic operation. Next, power systems may introduce hazards by electrical shocks, fire risks due to electrical overloads and malfunctioning of the power source may lead to disrupted electrical signals to the control and or power supply. Finally improper installation of the equipment of the robot system can lead to hazards.

Safeguarding To protect the workers from these accidents and hazards one should consider different safeguarding opportunities.
To safeguard the system, risk assessments should be performed at different development stages of the system and subsystems to safeguard the personnel. The personnel should be safeguarded from hazards in the working envelope of the robotic system. This safeguarding can be achieved by mechanical limiting devices, non-mechanical limiting devices, presence-sensing safeguarding devices, fixed barriers and interlocked barrier guards. Workers can be made aware of a running program by including chain barriers with supporting flashing lights, signs and sounds to make workers aware of a moving robot.
The robot teacher should be safeguarded when programming the robot in a teach dependent way. The programmer can be in the restricted envelope and can activate improper functions, resulting in accidents. The robot operator should be protected by activating all safety devices of the robot and should at no time be present in the restricted envelope. Also, maintenance should occur regularly and within the periodic inspection program. Maintenance programs are essential for minimizing hazards of malfunctioning, breakage or unpredicted movements. Finally the operators should get good safety training and be able to operate the system in a safe way.

5.4.5 Backing paper removal

The handling system is equipped with an injection needle and a vacuum roll to remove the backing paper. In order to prevent the prepreg from contamination, the backing paper is removed as late as possible to prevent the prepreg from contamination, according to requirement 2.1.

5.5 Economic analysis

An economic analysis of the entire robotic system is included in this section. For Airbus to continue and implement a new technology a positive business case needs to be present. How does Airbus interpret a positive business case? One can speak of a positive business

case when an ROI whitin a maximum of two years is achieved, as stated in requirement 1.3 in appendix E. For this reason an economic analysis is included to confirm, whether a positive business case can be achieved.

5.5.1 Savings

First it is investigated which savings an automation of the process offers compared to the manual stacking process.
The first saving achieved is the lead time reduction by automating the process. For this reason it is first determined how long the current manual stacking of skin, doublers and front and aft spar reinforcements take. All these data are obtained through the cost centres at the Airbus Stade plant. Data obtained are the current production numbers, production costs and manufacturing times for the entire production of the IBF shells. Figure 5.16 shows a detailed process time breakdown of the ATL, laminating and curing processing step. The total processing time of these three steps is respectively $350 Industrial Minutes$, $1025 Industrial Minutes$ and $168 Industrial Minutes$. In the figure it can also be seen that current manual stacking of the reinforcement takes 30% of the $1025IM$ or $307{,}5IM$.

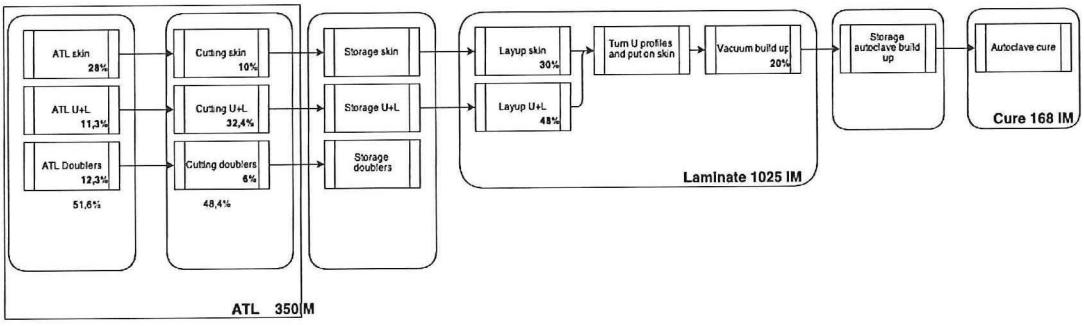

Figure 5.16: Work breakdown of ATL, laminating and curing step.

Next step is to investigate what lead time reduction can be achieved by using a robotic handling system. For this investigation some assumptions are made. First, it is assumed that the actual pick-up of the laminate will take 10 seconds [11], according to Buckingham in terms of speed lay-up and consolidation it took in the order of 15 seconds. For this reason the same value is used in this estimation. Next from literature it was found that the backing paper is best peeled-off at a speed of $0.1m/s$. The actual dropping of the backing paper in the disposal container is estimated at 20 seconds. These 20 seconds include dropping it into the container, weighing the backing paper and giving positive feedback to continue the cycle. As mentioned before, the integrated bridge is only able to travel at a maximum speed of $2m/s$. Finally for the calculations it is assumed that the big laminate layed by the ATL is centred in the middle of the ATL lay-up table and the handling system picks the middle set of the three sets.
The calculation of the automated cycle time to stack the skin, doublers and reinforcements can be seen in appendix I. A summary of the analysis can be found in table 5.4. It can be seen that the total process time of the automated solution is reduced from 307,5IM

Table 5.4: Cycle time manual versus automated process.

Process	processing time $[IM]$
Manual process	307,50
Automated process	91,10

to 99,43IM. This means that a total process time reduction of the laminating processing step of 67,8 % is achieved by automating the process.
Apart from the lead time reduction, some extra savings can be achieved by automating the process. The first saving is achieved by discarding the labelling step, labelling of the prepregs is present for the workers to identify the different reinforcements. By identifying the reinforcements, the worker has an indication of which reinforcement to take to stack the reinforcements correctly on the skin in the right order. By automating the laminating process step, there is no need to label the prepregs. The robotic system knows the exact positions of all prepregs on the ATL lay-up table, therefore there is no need to label them. Removing the labelling step results in a lead time reduction of $14IM$. The labelling step takes 25% of the cutting skin and doublers step, which takes 16% of the ATL processing step of $350IM$, as can be seen in figure 5.16. The lead time reduction of $14IM$ is for three sets of skin, doublers and reinforcements. Therefore, in the analysis an extra saving of $4{,}67IM$ per shell is achieved. This saving reduces the recurring cost of the integrated bridge. The integrated bridge operates at a cost of $226euro$ an hour.

5.5.2 Investment cost

Now it is important to estimate the total investment cost of the entire robotic system. Total savings and investment cost are needed in order to calculate the total ROI of the technology. Table 5.7 lists the costs of the entire robotic system. The total cost of the robotic system is divided into ATL cost, integrated bridge cost, handling system cost and the cost of other equipment. The estimations of the costs of the robotic system are obtained from several companies. These companies are summarized in appendix F.
First in the ATL cost, one can see that the only cost present is the reprogramming cost of the ATL. Reprogramming of the ATL program is needed, because the ATL needs to lay the tapes in a reverse order, as in figure 5.15. For this reason it is not necessary to flip the prepregs. In total four ATL lay-up programs need to be reprogrammed; UL, UR, LL and LR. Reprogramming one set takes four hours for an engineer with a cost of 86 euros an hour.
The second main cost component is the integrated bridge. Current integrated bridge manufacturer provided that redesign and production of new integrated bridge is possible, will take between half a year and one year. The design part is divided into three main components; control, electical design and mechanical design. Control, electrical and mechanical design will take around 60 to 70% of total project time. The production part includes actual production, as well as extra required material to produce the integrated bridge. It can also be seen that the controller cost is 0 euro, this is because the controller can be reused from the current integrated bridge. This is also the case for several other parts from current integrated bridge, reducing the total cost.

Table 5.5: Cycle time manual versus automated process.

ATL	
Part	cost [*euro*]
Reprogramming ATL	1,376
Integrated bridge	
Part	cost [*euro*]
Design control system	70,373
Design electrical system	70,373
Design mechanics system	70,373
Production of system	90,480
Controller Siemens 840D	0
Materials bridge	250000
Multi-actuator handling system	
Part	cost [*euro*]
Vacuum pump	25,872
Solenoid valves	33,024
Vacuum roll	16,000
Linear guidings	4,000
Vacuum box	4,000
Injection	5,000
Master tool	2,500
Other equipment	
Part	cost [*euro*]
Two lay-up tables	22,000
Two disposal containers	3,000
Total	668,371

The third main cost component is the multi-actuator handling system. The main components of the handling system are the 20 vacuum pumps, the vacuum roll, the vacuum box, the peel initiator, the master tool and other small equipment.
Furthermore on both sides of the ATL lay-up table a small lay-up table to stack the reinforcements on the skin and a disposal container with scale to drop the backing paper is required.
Finally, during this economic analysis some Airbus standards are used for this analysis. The cost of a worker on the shop floor costs 52 euros an hour for Airbus. For an engineer this is 86 euros and machinery cost is 225 euros an hour.

5.5.3 Production rate

Finally in order to know the actual savings, one need to know how many parts are produced on a monthly basis. First to estimate the amount of produced IBF on a monthly basis, it is important to know that the A320 current engine option (CEO) will be replaced by the A320 new engine option (NEO). The A320 NEO is part of the modernisation

Table 5.6: Amount of planned of delivered IBF per month

Year 2015												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Number of planned shells	108	108	136	120	76	116	68	80	104	108	96	80
Year 2016												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Number of planned shells	100	92	100	100	88	108	80	76	100	92	96	84
Year 2017												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Number of planned shells	112	96	112	92	92	104	80	72	104	104	104	76
Year 2018												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Number of planned shells	104	100	104	92	96	100	92	84	96	108	104	72

program and will be introduced in October 2015. For this reason the A320 CEO will be ramped down and the production of the A320 NEO will be ramped up. This will influence the number of produced shells for the IBF. However it will not influence the automated pick and place activity, since no changes to the stacking of the prepreg reinforcment is present. Table 5.6 summarizes the amount of planned production rate on monthly basis of the IBF shells for the year 2015, 2016, 2017 and 2018. Appendix J summarizes the detailed number of estimated A320 CEO and NEO airplanes from 2015 to 2018 in more detail.

5.5.4 Return of investment

Knowing the achieved savings, the investment cost and the production cost. The ROI of the entire robotic system can be determined. For the ROI calculations, some assumptions were made. To deal with these uncertainties, a sensitivity analysis is made. The uncertainties in the economic analysis are the peeling speed of $0{,}1m/s$, the pick-up time of $10s$, the disposal time of $20s$, the placement time of $15s$ and the travelling speed of the integrated bridge of $2m/s$. For the sensitivity analysis, a one-at-a-time methodology is used to see which effect the individual inputs have on the total ROI of the robotic system. The analysis will ensure whether it is usefull to invest more resources in this research and one can act to limit the uncertainties. Moreover, is it possible to meet the ROI within 2 years?

Peeling speed In this sensitivity analysis, the first parameter is the peeling speed. According to Buckingham [11], the minimum peeling speed required to ensure full backing paper removal is $0.1m/s$. For this reason the influence of the peeling speed on the total cycle time is examined and varied from $100mm/s$ to $2000mm/s$.

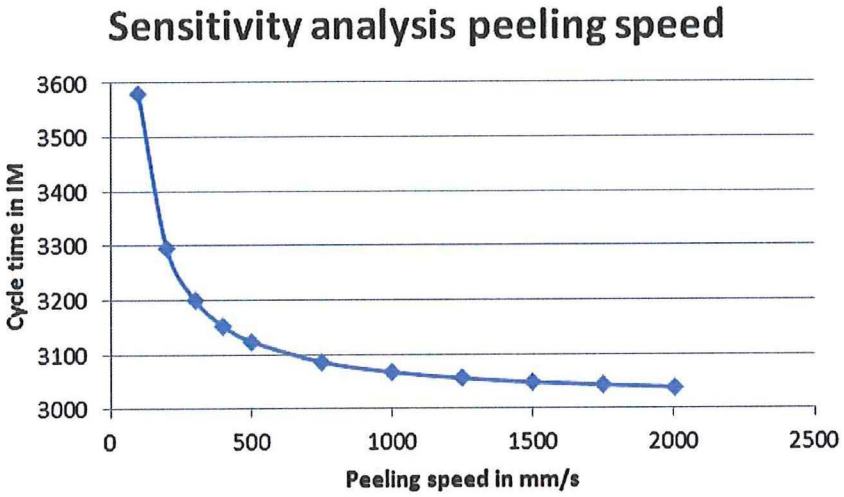

Figure 5.17: Sensitivity analysis of peeling speed and its influence on the total cycle time.

It can be seen that by increasing the peeling speed from 100 to $200mm/s$ already 4.74 minutes can be saved. By increasing the peeling speed even to $2000mm/s$, the total cycle time of the automated handling system can be reduced to 9.02 minutes. From figure 5.17 it can be seen that by increasing the peeling speed, the reduction in cycle time increases. However by increasing the peeling speed, the netto reduction in cycle time is reduced. In other words, in this graph it can be sean that from the curved line, it means the speed is increasing, since the slope represents the speed in a distance vs time graph.

Pick-up time The next parameter is the pick-up time, this is the time needed for the handling system to pick the prepreg. Buckingham [11] concluded in his study that the time required to grip the prepreg material took 10 seconds. The pick-up time is varied from 10 to 5 seconds.

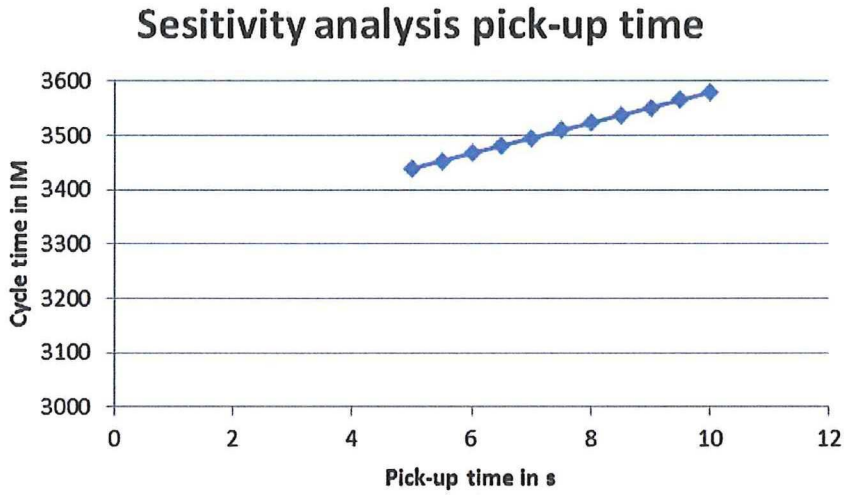

Figure 5.18: Sensitivity analysis of pick-up time and its influence on the total cycle time.

It can be seen that by varying the pick-up time, the cycle time reduction that can be achieved is rather small. By halving the cycle time from 10 to 5 seconds, a cycle time of 2,33 minutes can be achieved as can be seen in figure 5.18.

Disposal container time The next parameter being varied is the disposal container time. The disposal container time is the time it takes for dropping the backing paper from either the upper or lower side of the prepreg. No data for the disposal of the backing paper into the disposal container is available and a value of 20 seconds is estimated. Also in this case the disposal of the backing paper into the container time is halved to examine its effect.

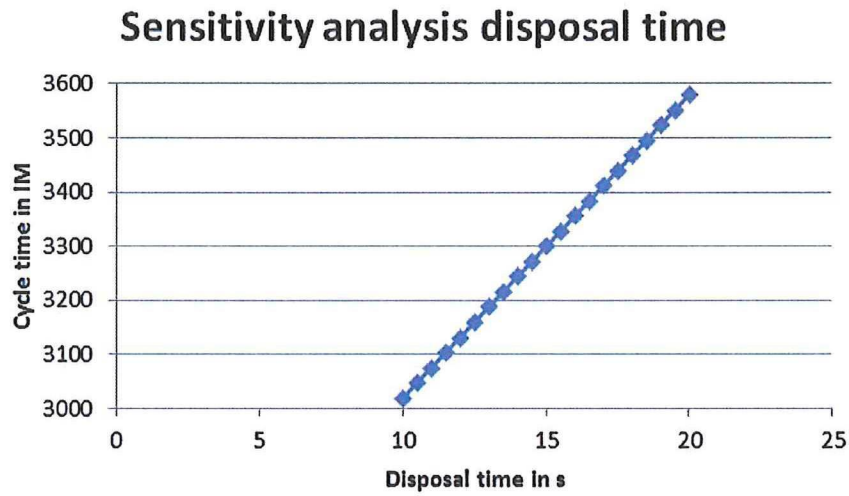

Figure 5.19: Sensitivity analysis of disposal time and its influence on the total cycle time.

It can be seen in figure 5.19 that the disposal into the container time is an important parameter. By reducing the disposal time from 20 till 10 seconds, a cycle time reduction of 9,33 minutes is achieved. This is mainly because the backing paper from the upper, as well as the lower side needs to be removed. The disposal time of 20 seconds is a rather conservative value and for this reason it is important that the disposal time is studied into more detail.

Placement time The following parameter is the placement time, it is the time required for the handling system to accurately place the prepreg on the side lay-up table. Also in this case Buckingham [11] concluded that is took 15 seconds to place a prepreg on a flat table or another layer of prepreg reinfocement. The placement time is halved from 15 seconds to 7,5 seconds to investigate the influence.

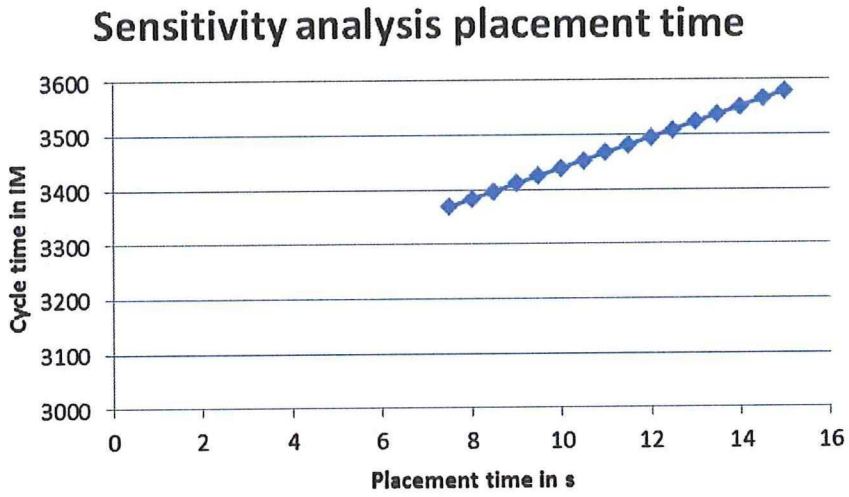

Figure 5.20: Sensitivity analysis of placement time and its influence on the total cycle time.

In figure 5.20 it can be seen that by halving the placement time a cycle time reduction of 3,5 minutes can be achieved. Therefore it can be seen that the placement time is just a small contributor in the total cycle time of the pick and place system.

Travelling speed integrated bridge The last parameter influenced is the travelling speed of the integrated bridge. The maximum travelling speed of current integrated bridge with cutter attached to it amounts $2m/s$. In this case the travelling speed is doubled from $2000mm/s$ to $4000mm/s$ to examine the influence.

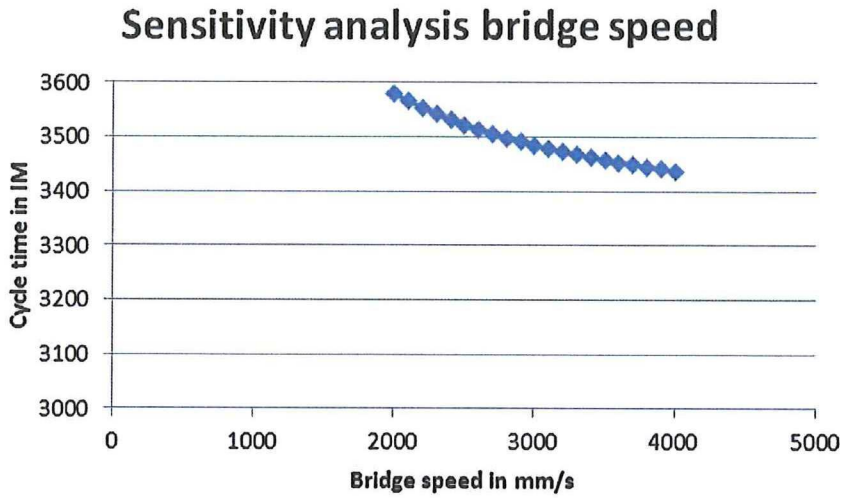

Figure 5.21: Sensitivity analysis of travelling speed of the integrated bridge and its influence on the total cycle time.

From figure 5.21 it can be seen that by doubling the travelling speed of the integrated bridge, the achieved cycle time reduction is minimal. By doubling the travelling speed from $2000mm/s$ to $4000mm/s$ a cycle time of only 2,37 minutes can be achieved.

ROI The actual ROI can now be estimated based on the achieved savings, investment cost and production rate. To estimate the ROI of the automated handling system different cases are considered. The cases considered is the normal case, where conservative values are used. Next cases are the ultimate cases of all parameters and finally an ultimate case is considered. The ultimate case includes the best scenarios for all parameters. The different cases and their ROI are summarized in table 5.7.

Table 5.7: The ROI of the automated hadling system, depending on the different cases.

Case	Saving per part	ROI
Normal case	-3.54 euro	no ROI
Vacuum roller	41.40	6.71 years
Pick-up time	8.09 euro	34.93 years
Disposal time	42.99 euro	6.46 years
Placement time	13.92 euro	20.30 years
Bridge speed	8.27 euro	34.16 years
Ultimate case	133.98	**1.86 years**

Finally in figure 5.22 the ROI for the ultimate case is shown. It can be seen that the ROI of the automated system amounts 45 months. Because the ATL lays the skin, doublers and front and aft spar reinforcement of the inboard, as well as the outboard flap. The costs of the handling system can be divided into two. This way the ROI can be reduced with a factor two.

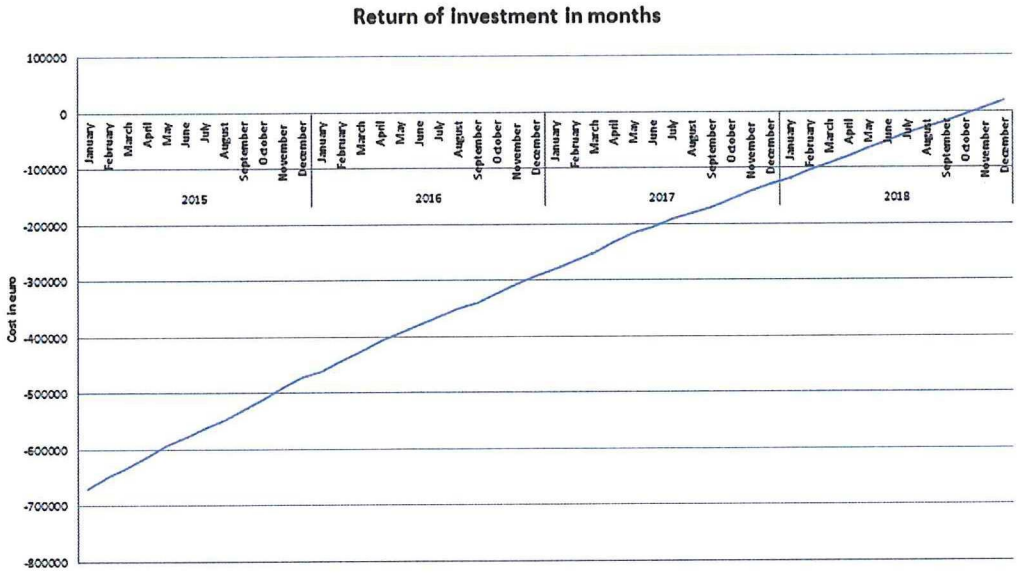

Figure 5.22: The ROI of the ultimate autoamation case of the inboard flap shells.

5.6 Conclusion

The goal of this chapter was to describe the final lay-out of the robotic cell in more detail. With this more detailled design an economic analysis needed to carried out to ensure the killer requirement of the robotic system to have a return of investment in a maximum of two years.
A detailed cell lay-out and process steps are generated to get better understanding of the robotic system. More particularly, how all components function and how they are physically arranged. The robotic process is controlled with a single controller and it is concluded that no sensors are needed to detect whether the handling system is correctly positioned and eventually in contact with the prepreg. The integrated bridge and handling system are controlled with the same single controller, which is also responsible for cutting the prepregs. Because of this reason, the controller has the exact coordinates and position of all prepregs and there is no need for sensors. However an optical system is required to check whether full backing paper removal is achieved. If no backing paper is left on the material, the system can continue its cycle.
During the detailled design some special findings were made. First, in today's process a worker has to remove the backing paper from one side of the prepreg and flip the prepreg. The robotic system will not be able to flip the prepreg, for this reason the ATL lay-up program needs to be changed. Next, some prepregs are rotated 90 degrees with respect to their positioning on the side lay-up table. For this reason the handling system should be able to rotate 90 degrees before pick-up of these specific reinforcements. Furthermore, to qualify the system, no exact rules exist. The automated pick and place robotic system should be able to perform the tasks as good or better than current manual laminating process and operate according to safety regulations. Finally special safety measures have to be taken to protect workers against possible hazards.
From the economic analysis it could be seen that no savings can be achieved compared

to the manual process for the conservative case. For this reason a sensitivity analysis is conducted to deal with the uncertainties. It can be concluded that an ROI whitin a maximum of two years can be achieved if the robotic handling system is able to peel the backing paper at a speed of $2000mm/s$, the pick-up time can be reduced to 5 seconds, the disposal time of the backing paper into the disposal container takes maximum 10 seconds and finally if the bridge speed can be raised to $4m/s$. Since the peeling speed of the backing paper and the disposal of the backing paper have the largest contribution in the cycle time, they need deeper investigation to ensure that these values can be achieved and therefore an ROI within a maximum of two years can be achieved.

Chapter 6

Validation of detailed design

In this chapter, the automated robotic pick and place cell is validated. It is verified whether the physical design is able to perform the required functions and satisfies the required performance. First the experimental facilities are introduced in section 6.1. Next, different experiments are performed and discussed; first a simulation of the entire robotic cell is executed in section 6.2. Next, in section 6.3 a physical experiment with an end-effector is performed to validate handling, peel initiation and peel continuation concept. Finally, a compliance matrix is used to check whether all requirements are met, in section 6.4.

6.1 Experimental facilities

Different facilities, tools and components are available and will be briefly discussed.
First ABB robotstudio 5.61 is used as simulation software to assess the performance of the robotic system. A trial version of this software is freely available with all functions enabled for a period of 30 days. The software is used for off-line programming of robots and can later on be used to connect to the actual robotic system. Simulation of the robotic cell is useful, since it reduces risks by visualizing the cell and it proofs solutions and lay-outs before it's actually built.
Next, a 6-axis articulated industrial robot is provided by the German Aerospace Center or DLR in Stade. It is a Kuka KR 240-2 Serie 2000 robot with a maximum payload of $240kg$, a maximum reach of $2700mm$ and a position repeatability $< \pm 0,06mm$. The robot is connected to a KUKA smartpad to control it.
An end-effector is connected to the Kuka articulated robot. The end-effector is an aluminium plate with several holes to attach the vacuum cups to it. The aluminium plate has a length of $664mm$ and a width of $560mm$. The 28 vacuum cups are positioned in matrix form. 7 vacuum cumps along the length with a spacing of $75mm$ and 4 vacuum cups along the width with a spacing of $95mm$. For the experiment, Festo ESG-40-CS-HA-QS vacuum cup with a diameter of $40mm$ are used. All vacuum cups can be manually actuated and are connected to a vacuum pump, which is controlled by the KUKA smartpad. Futhermore, it is possible to attach an aluminium vacuum roll to the end-effector in order

to peel-off the backing paper. The vacuum roll has a wall thickness of $10mm$ and three different vacuum roll diameters are available. The first one has a diameter of $150mm$. Apart from that, there is one with diameter of $200mm$ and the last one has a diameter of $300mm$. The vacuum roll is equipped with holes with a diameter of $2{,}5mm$ and individual spacing of $27{,}5mm$. The spacing off the vacuum holes and their hole diameter is the same as the vacuum holes of the ATL lay-up table, used to fix the prepregs to the table. The vacuum roll is completely air-tight and can be attached to a second vacuum pump. The vacuum roll itself is able to rotate thanks to the use of bearings.
To initiate backing paper removal, an injection gun is used. The injection gun is connected to the pressurized air system on the shop floor. The injection gun can be equipped with different needles and the injection height can be adapted.
Finally, Hexcel Hexply 6376 prepregs covered with Cytec E3760 white backing paper on both sides are used for the experiments. This material combination is also used for current production of the IBF shells. Different orientations of the laminates are used, but they are similar to the prepregs used in the IBF.
In figure 6.1 the experimental lay-out at the DLR can be seen. It shows the KUKA articulated robot including end-effector. The exact component list can be found in table K.1 in appendix K.

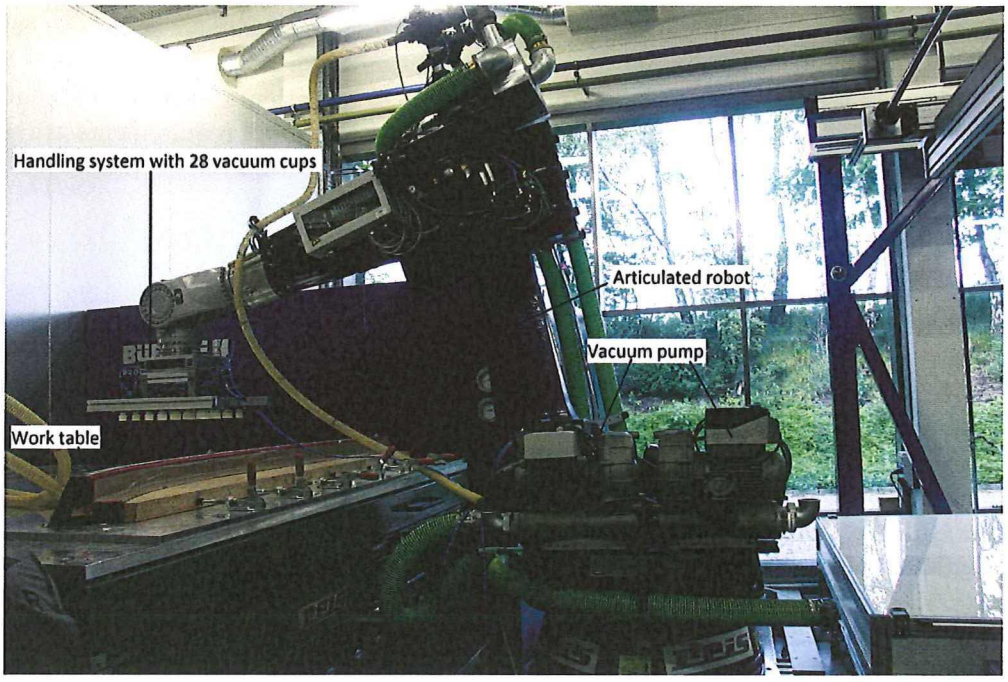

Figure 6.1: Experimental set-up of end-effector attached to the articulated robot.

6.2 Simulation

To estimate the performance of the robotic system, simulation software is used. The simulation software used is ABB robotstudio 5.61 and is provided to assess the performance of the robotic cell by visualisation [40].

ABB robotstudio is simulation software used for offline programming and allows computers to program different robots and interactions without interfering production. By using the software possible risks can be detected before installing the robots. By using simulation software, quicker start-up and increased productivity can be ensured. To simulate the robotic cell a fictive controlled is used, the software written in this software is an exact copy of the software used to run the robots in actual production. Therefore realistic simulations are achieved. A simulation is carried out to validate the robotic cell lay-out and the estimated cycle time used in the economic analysis. For the simulation some assumptions are made. The assumptions correspond to the assumptions made in section . Finally in appendix L the simulation steps are visualised.

Simulation steps In order to start with the simulation of the robotic cell, the robotic cell components need to be imported into the ABB robotstudio simulation software. The components that need to be imported are the ATL, ATL lay-up table, side lay-up table, disposal container, integrated bridge and the handling system. These components are not available in the simulation software and therefore they are drawn using Catia V5R20 software with correct dimensions. Next, the components can be imported in the software and positioned at the required coordinates according to a global reference frame. Where the middle of the ATL lay-up table is used as origin. In the simulation, all components are static, except for the integrated bridge and handling system. The integrated bridge is attached to an ABB IRBT 4004 linear guiding system, which is available as standard in the simulation software. The linear track unit is positioned at the side of the ATL lay-up table. Because the integrated bridge is attached to linear track unit, the integrated bridge is able to move along the entire length of the ATL lay-up table till the end of the side lay-up table. For the simulation, the linear guiding system is set invisible. Next in order to be able to rotate the handling system to position it above the disposal container and side lay-up table, a mechanism needs to be created. The mechanism ensures that the handling system is able to rotate 90 degrees along the z-axis and linear movement in y-direction. Next, different targets have to be created. The targets are needed for the integrated bridge to position itself correctly above the predetermined prepreg. The positions are created by defining these different coordinate points. After creating the targets, a path is programmed to ensure that the integrated bridge can move to the wanted targets. Furthermore the travelling speed and position accuracy of the integrated bridge are defined. A travelling speed of $2000mm/s$ and a positioning accuracy of $0{,}5mm$ have been programmed. After finishing all these steps, the path has to be configured with the controller. This way the controller can instruct the linear unit how to move. Finally the simulation can start and the output values obtained are the cycle time and possible collisions during the entire cycle.
Some steps of the simulation are shown in the figures. The first step shown is the pick-up of a prepreg from the ATL lay-up table by the handling system in figure 6.2. Figure 6.3 shows the positioning of the handling system above the disposal container, for either the removal of the backing paper of the lower side or the upper side. Finally in figure 6.4 the integrated bridge and handling system are positioned on top of the side lay-up table to place the prepreg after removal of the backing paper from the lower side. After removal the prepreg is placed and the backing paper from the upper side can be removed.

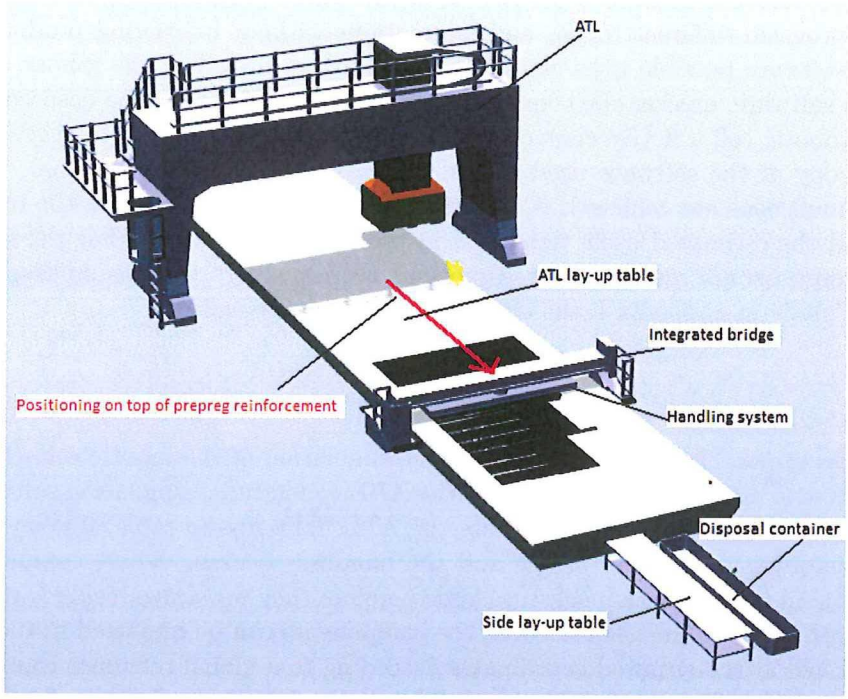

Figure 6.2: Simulation of robotic cell in ABB robot studio showing pick-up of prepreg from ATL lay-up table.

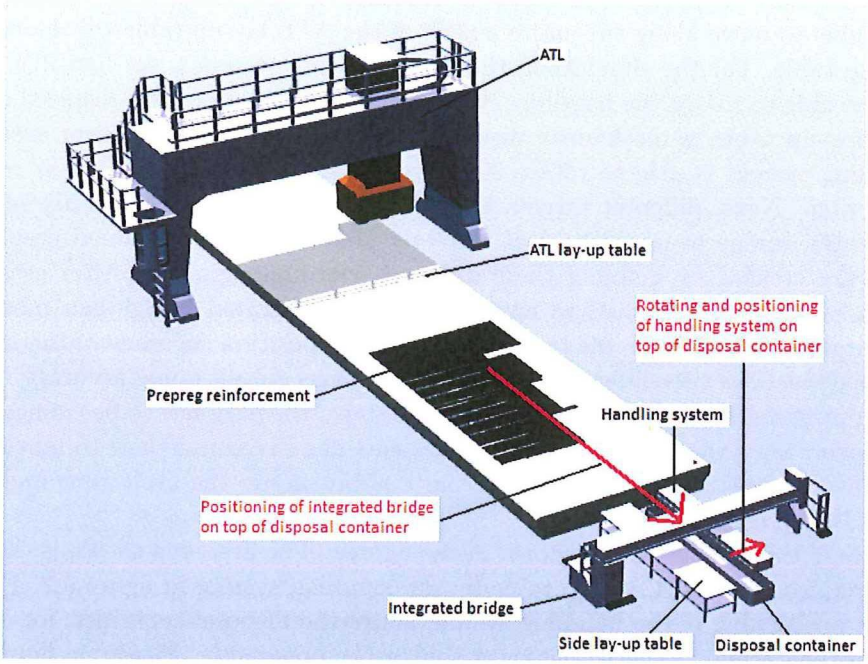

Figure 6.3: Simulation of robotic cell in ABB robot studio showing positioning of integrated bridge and handling system on top of disposal container.

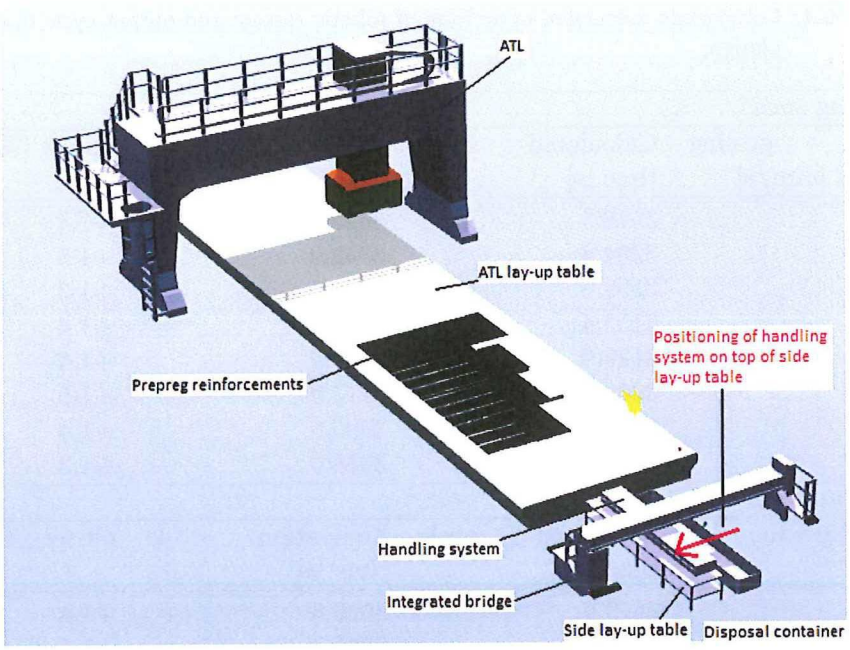

Figure 6.4: Simulation of robotic cell in ABB robot studio showing positioning of integrated bridge and handling system on top of side lay-up table.

Results From the simulation it can be concluded that no collisions occur between the handling system and the ATL lay-up table, side lay-up table and disposal container during the entire operation. Next, another important finding is that the disposal container and side lay-up table need to be placed in the length of the ATL lay-up table. This configuration is required to be able to place all prepregs in the correct position and orientation on the side lay-up table, according to the technical drawings. The required orientation and position of the disposal container and side lay-up table can be seen in figure 6.1.
Finally for the economic analysis, the cycle time of the robotic system was calculated. The simulation is used to compare the calculated cycle time with the actual cycle time of the entire cycle of the robotic system, resulting from the simulation. Table 6.1 summarizes the calculated cycle time for different cases and the actual cycle time resulting from the simulation. The calculated and actual cycle times include the entire cycle of the robotic system, handling all prepregs. The standard cycle time includes the assumptions of a peeling speed of $100mm/s$, a pick-up time of $10s$, a disposal time of $20s$, a placement time of $15s$ and a travelling speed of the integrated bridge of $2000mm/s$. Table 6.1 shows a change in one of these assumptions and the influence on the calculated and actual cycle time. From the results, it can clearly be observed that the actual cycle times takes around 1,3 to 1,5% longer compared to the calculated cycle time. The longer cycle time is the result from the accelerations and decelerations that are included in the simulation and not in the calculation. Finally, the longer cycle time also results from the correct positioning of the prepregs on the side lay-up table.

Table 6.1: Comparison calculated cycle time of robotic system and output cycle time simulation.

Peeling speed			
Case peeling speed $[mm/s]$	Calculated cycle time $[s]$	Actual cycle time $[s]$	off-set [%]
100	3579.5	3629.6	+1.4
200	3294.8	3342.9	+1.5
300	3199.8	3240.5	+1.3
400	3152.4	3196.5	+1.4
500	3123.9	3167.9	+1.4
1000	3066.9	3113.0	+1.5
1500	3048.0	3090.6	+1.4
2000	3038.5	3078.0	+1.3
Pick-up time			
Pick-up time $[s]$	Estimated cycle time $[s]$	Simulation cycle time $[s]$	off-set [%]
10	3579.5	3629.6	+1.4
9	3551.5	3601.3	+1.4
8	3523.5	3572.9	+1.4
7	3495.5	3541.0	+1.3
6	3467.5	3516.1	+1.4
5	3439.5	3484.2	+1.3
Disposal time			
Disposal time $[s]$	Estimated cycle time $[s]$	Simulation cycle time $[s]$	off-set [%]
20	3579.5	3629.6	+1.4
18	3467.5	3516.1	+1.4
16	3355.5	3402.5	+1.4
14	3243.5	3288.9	+1.4
12	3131.5	3175.4	+1.4
10	3019.5	3061,8	+1.4
Placement time			
Placement time $[s]$	Estimated cycle time $[s]$	Simulation cycle time $[s]$	off-set [%]
15	3579.5	3629.6	+1.4
13.5	3537.5	3587.1	+1.4
12	3495.5	3544.5	+1.4
10.5	3453.5	3501.9	+1.4
9	3411.5	3459.3	+1.4
7.5	3369.5	3416.7	+1.4
Travelling speed integrated bridge			
Integrated bridge speed $[mm/s]$	Estimated cycle time $[s]$	Simulation cycle time $[s]$	off-set [%]
2000	3579.5	3629.6	+1.4
2400	3532.2	3581.7	+1.4
2800	3498.4	3547.4	+1.4
3200	3473.0	3521.7	+1.4
3600	3453.2	3501.6	+1.4
4000	3437.6	3485.7	+1.4

6.3 Physical experiments

This section discusses handling, peel initiation and peel continuation experiments performed to validate the conceptual design of the removal of the backing paper and the requirements. First the test sample preparation is discussed and after that the different experiments are reviewed.

6.3.1 Test sample preparation

For all experiments, some test samples need to be prepared. For the test samples, Hexcel hexply 6376 tape is used in combination with Cytec E3760 white backing paper. The test samples are prepared in the following way; first one layer of the Cytec backing paper is laid on a flat lay-up table. Next, three layers of the Hexcel prepreg tape with a width of $300mm$ are laminated in the right orientation. In this case the orientation is $[0, 0, +45]°$, it is the most common orientation used for the IBF. The prepreg test samples can therefore be used to initiate and continue peeling with either a 0-degree layer at the outer surface or a 45-degree layer as outer surface. Zero degree means that the orientation of the fibres is parallel to the length of the test sample. Next, the prepreg is covered with another layer of backing paper. Subsequently all test samples can be cut in the preferred dimensions, in this case all samples have a width of $150mm$ and a length of $300mm$. Finally, the prepreg test samples are debulked for 10 minutes with a vacuum pressure of $100mbar$.

6.3.2 Handling

To validate the pick and placement activity, the robot was taught a small program. The goal of the program was to separate a prepreg from the table, lift it and after a while put it back on the table.
For the handling, three different prepreg test samples were used. The first set of prepreg test samples have a length of $75mm$ and a width of $75mm$. The second set has a length of $75mm$ and width of $150mm$ and the third set has a length of $150mm$ and a width of $150mm$. All prepregs are cut from a bigger prepreg laminate and are therefore surrounded by other prepreg material. First the required vacuum cups are manually actuated, depending on the required position. Next, the vacuum pump is automatically turned on and the end-effector is lowered. A vacuum pressure of 0,2 bars is created. Next, the frame is raised and the prepreg is held for 10 seconds. Now the end-effector is lowered and the prepreg is placed on the table and the vacuum is turned off. It is investigated whether it is possible to grip prepreg test samples from it surrounding material.

Results From the experiments, it can be concluded that all prepreg test samples could be separated from its surrounding material. All reinforcements could be lifted and later on be placed on the table again. However, there is one attention point. If a prepreg is not properly cut from the surrounding material, then the surrounding material is also lifted. This can have serious consequences for the skin and doublers and eventually can lead to scrap of one or more sets of skins, doublers and front and aft spar reinforcements. For this reason proper cutting of the reinforcements has to be ensured at all time.

6.3.3 Peel initiation

To validate the peel initiation concept, an injection gun is assembled. The injection gun consists of a frame and a pressure gun. Figure 6.5 shows the injection gun and prepreg. Thanks to the frame it is possible to vary the height of the injection needle, as well as the initiation position and the initiation angle. Finally it is possible to attach different injection needles to the injection gun. The injection needles vary in tip angle. For the peel initiation, some parameters are fixed. The parameters fixed are the injection pressure, the injection needle diameter and finally the prepreg materials.
For the peel initiation experiments, the injection gun is connected to the compressed air system on the shop floor. The pressurized air is fixed at $7bar$. The prepreg is placed on a flat table and two iron plates are clamped at the edge of the samples. Because of the iron plates a foot is created to ensure that the air is guided towards the middle of the samples.

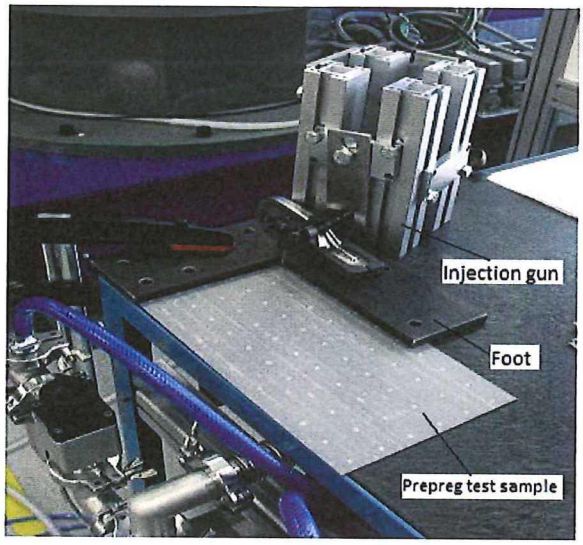

Figure 6.5: Peel initiation test set-up of injection gun and prepreg test sample.

Results From the peel initiation experiment, different conclusions can be made. First, the injection angle was varied from 0 degrees to 45 degrees with steps of 15 degrees, defined perpendicular to the prepreg surface. It could be observed that it was impossible to initiate the backing paper from a 15, 30 and 45 degrees initiation angle. This can be justified because the compressed air escaped on top of the prepreg and didn't initiate the backing paper. It was not possible to penetrate the prepreg material completely. The same result can be seen when the tip of the injection needle was modified, changing the tip angle of the injection needle with steps of 15 degrees leaded to no initiation. Zero degrees means that the entire tip of the injection needle is in contact with the prepreg. For a change in tip angle, it is not possible anymore for the entire tip of the injection needle to be in contact with the material. Therefore it was only possible to initiate peeling if a sharpened flat injection needle was used in combination with a zero degree initiation angle. Figure 6.6 shows the injection needle penetrating the backing paper before initiation and

figure 6.7 shows the initiated area after initiation.

Figure 6.6: Positioning of injection needle before peel initiation.

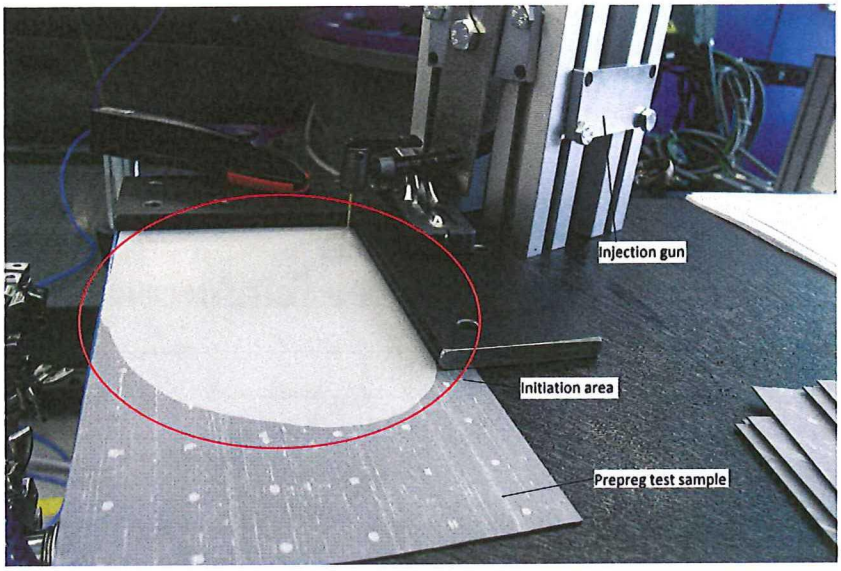

Figure 6.7: Initiation area on prepreg after injection of pressurized air.

Two different experiments are run; the first one is peel initiation for the test samples where the initation side is the 0-degree orientation. The second test run is the 45-degree orientation side. Figure 6.8 shows the initiation area in maximum length and width of the air bubble of the 0-degree orientation outer surface test samples and figure 6.9 shows the maximum length and with of the air bubble for the 45-degree initiation outer surface test samples. From the figures it can be seen that the initiation area is more scattered in the 0-degree orientation outer surface side compared to the 45-degree orientation side test samples. However in both figures it can be observed that the width of the initiation area

varies between 120 and 140mm. This can be justified, because the initiation point varied in distance from the edge of the test sample which has a width of 150mm. However in figure 6.8 it can be seen that there are three samples that have an initiation width lower than 120mm. The three test samples reached an initiation width of respectively 58mm, 97.5mm and 102mm. The three outliers are indicated in red. These outliers are the test samples where the initiation area was not able to grow over the entire width. No exact conclusion can be made, however it is expected that it is more difficult for the peel initiation area to grow perpendicular to the fibre orientation.

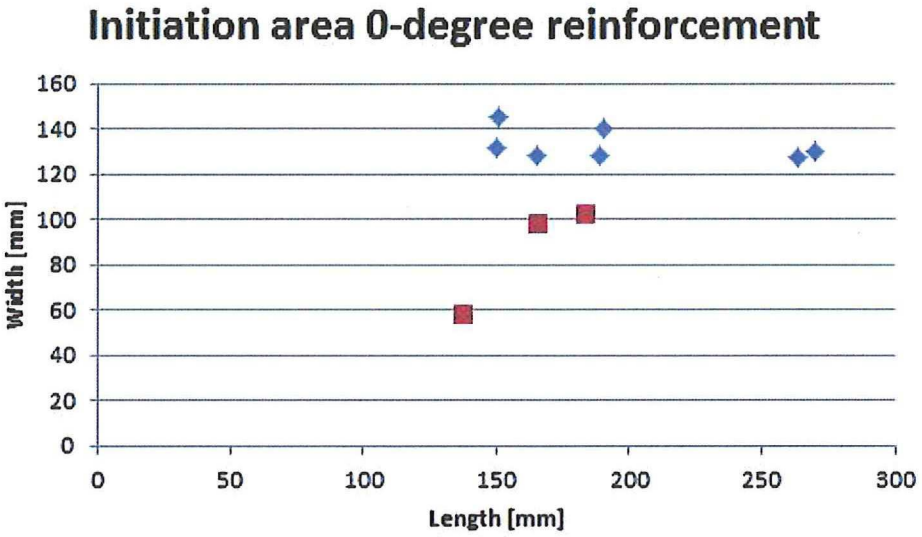

Figure 6.8: Peel initiation test set-up of injection gun and prepreg test sample.

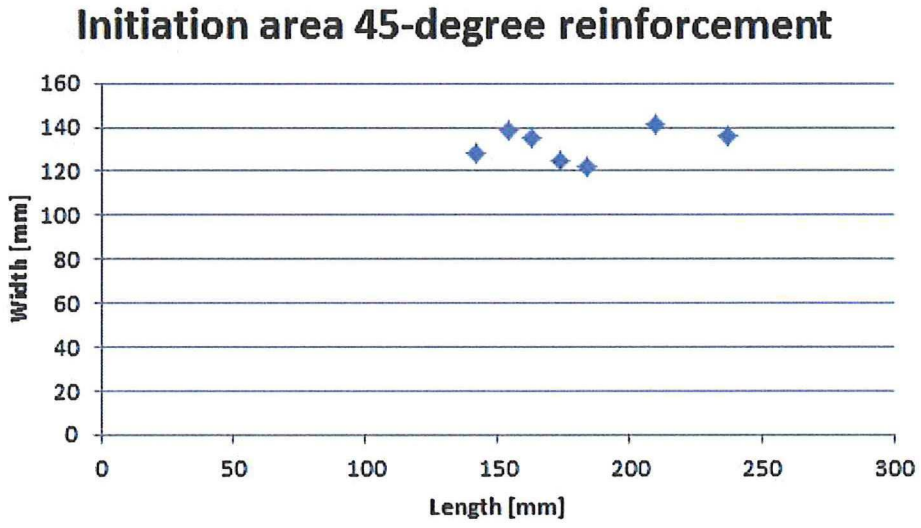

Figure 6.9: Peel initiation test set-up of injection gun and prepreg test sample.

Next, the initiation area can be linked to the corresponding initiation time. Some peel

initiation experiments were filmed and later on checked frame by frame to assess the growth of the initiation area over time. The growth of the initiation area over time can be an important factor, because if it is possible to have a small initiation area to continue peeling, smaller initiation time is required and can be quantified in this way. In total two test samples are analysed. The growth of the air bubble for both samples is shown in figure 6.10.

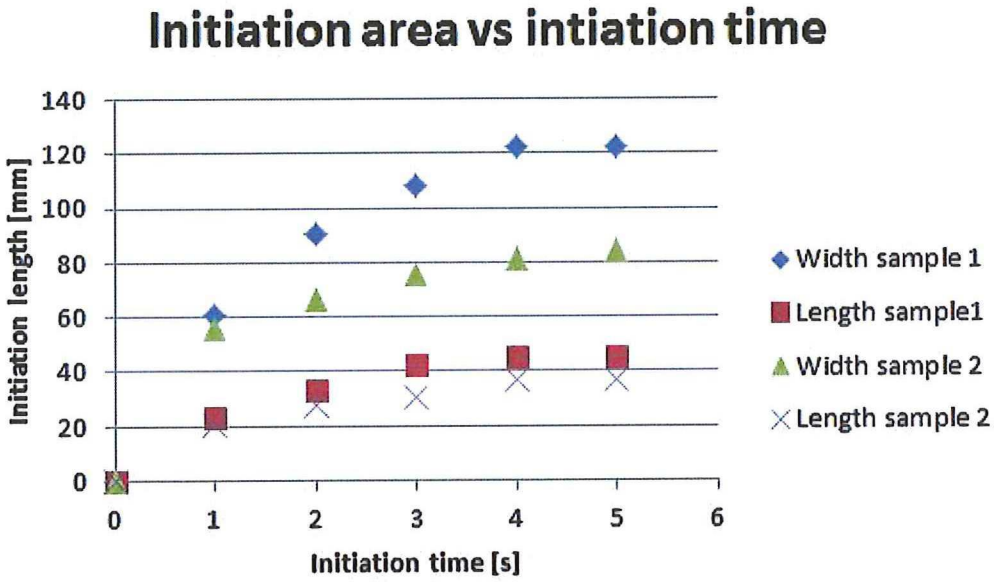

Figure 6.10: Peel initiation test set-up of injection gun and prepreg test sample.

It can be observed that the growth of the initiation area grows fast in the first second and the growth of the initiation area reduces if its size increases.

6.3.4 Peel continuation

For the validation of the peel continuation, an aluminium vacuum roll is connected to the end-effector. The configuration of the end-effector connected to the articulated robot and the vacuum roll attached to the end-effector is shown in figure 6.1. The vacuum roll is connected to two bearings, therefore it is possible for it to rotate around its axis. The vacuum roll in its way is connected to a Scrolvac SC 15D vacuum pump with a suction capacity of $13m^3/h$. In total three different vacuum rolls are used, varying in diameter. The first roll has a diameter of $150mm$, the second has a diameter of $200mm$ and finally, the third vacuum roll has a diameter of $300mm$.
To be able to continue peeling, a new program needs to be written. First, a set-off position is programmed. Next, the end-effector including the vacuum roll is lowered till it touches the table. Next a linear movement is programmed towards the length of the prepreg. After that, a linear motion of $500mm$, the end-effector is raised and travels back to the starting position and the program is completed. The set-off position can be seen in figure 6.11, next the lowered end-effector is shown in figure 6.12. After a linear movement of

$500mm$, the position of the vacuum roll is shown in figure 6.13 and finally in figure 4 the frame is raised again and is ready to get back into set-off position.

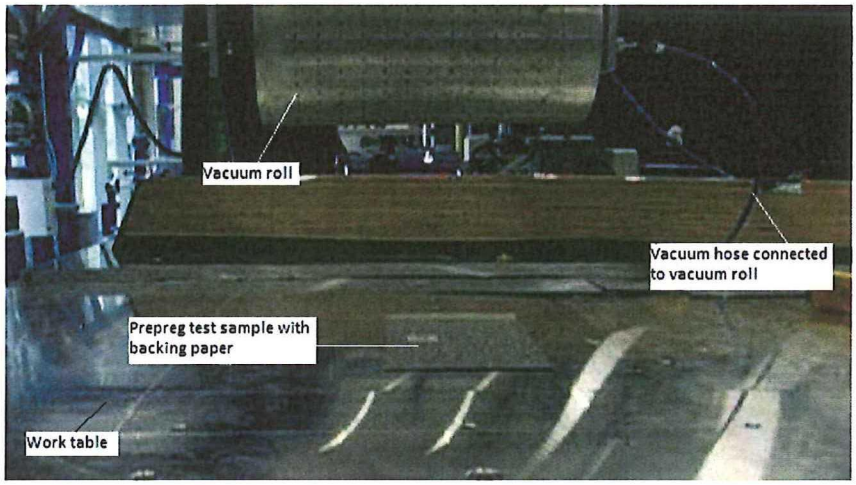

Figure 6.11: Positioning of injection needle before peel initiation.

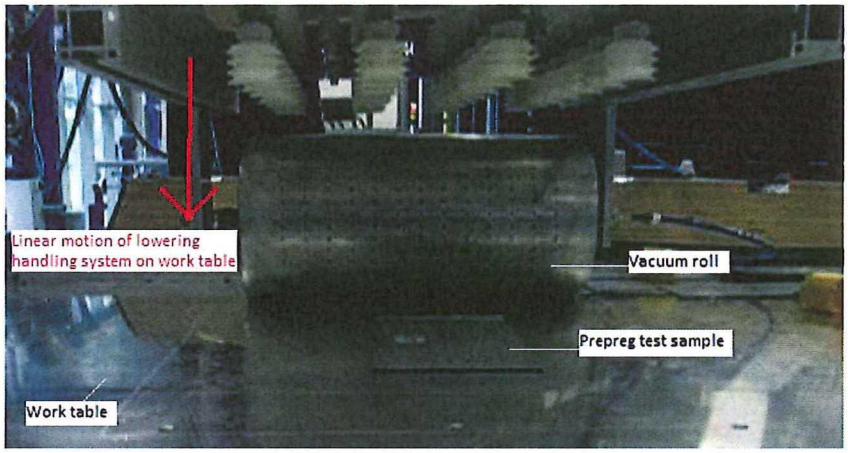

Figure 6.12: Positioning of injection needle before peel initiation.

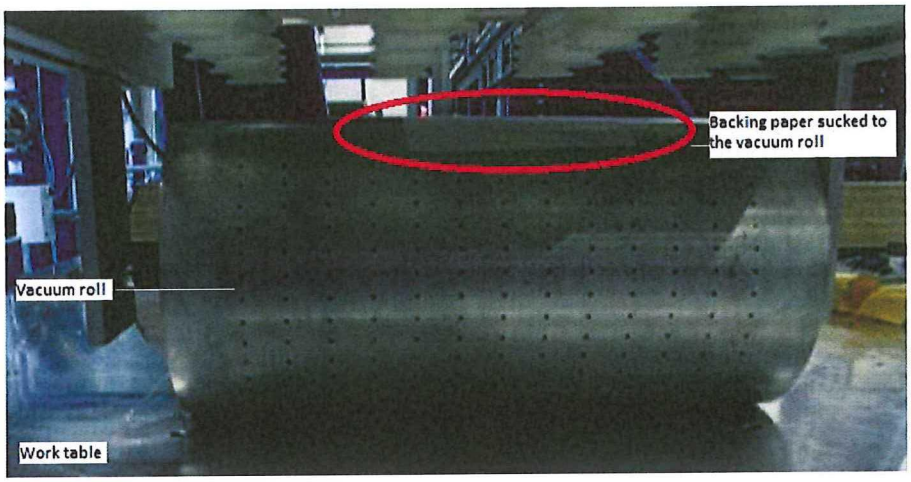

Figure 6.13: Positioning of injection needle before peel initiation.

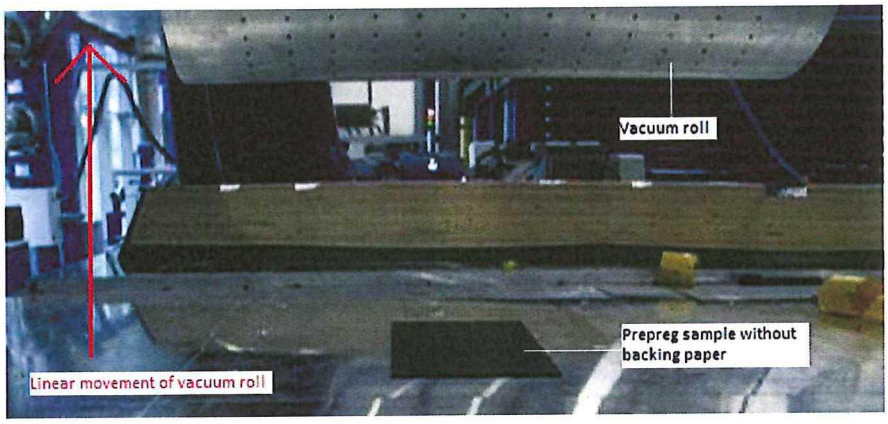

Figure 6.14: Positioning of injection needle before peel initiation.

To validate, the peel continuation a total of 100 prepreg test samples with a length of $300mm$ and a width of $100mm$ were used. The prepreg test samples have a $[0, 0, +45]$ orientation. These samples are used to investigate whether full backing paper removal can be achieved, with varying the peeling speed. Both a 0-degree outer side orientation is tested, as well as a 45-degree outer side orientation. For each peeling test, both prepreg test samples were fixed to the table with double side tape, to ensure proper adhesion. Next, the aluminium vacuum roll is connected to the vacuum pump and vacuum is applied. To validate the maximum peeling speed, the linear peeling speed is systematically raised with small steps and changed in the control of the articulated robot. For every raise in peeling speed, two new test samples are placed on the table. All test samples have an initiation area of $10mm$ along the length of the sample and are initiated of the entire width. Furthermore, all test samples are used within 2 days after defrosting of the ATL prepreg tape. The test samples are at all time kept and stored under clean area conditions at all times and a standard vacuum pressure of $200mbar$ was used to peel the backing paper. During the experiment, the backing paper was removed from the upper side and no attempt was made to remove it from the lower side.

Results For the peel continuation experiment, several conclusions can be made. First, it could be observed that by subsequently increasing the linear peeling speed of the robot, it was possible to succesfully remove the backing paper from all prepreg test samples. In all cases no backing paper was left on the samples. Full removal was achieved both in the 0-degree outer surface samples, as well as the 45-degree outer surface test samples. The linear speed was raised up to $5000mm/s$, which is the limit of the industrial robot. For this reason no maximum peel continuation speed can be quantified, however the peeling speed lays far above the expected linear peeling speed achieved with the robotic pick and place system. Furthermore, it could be observed that full contact between the vacuum roll and the prepreg is needed in order to wrap the backing paper around the vacuum roll. However if the roll didn't have full contact with the roll, it was still able to peel the backing paper. However the wrapping paper was not wrapped around the roll. The next finding is that, if the suction force on the table is less than the suction force of the vacuum roll, the entire prepreg is wrapped around the aluminium roll. This is unwanted and therefore it needs to be avoided at all times. If the vacuum pressure in the vacuum roll is reduced, it can lead to non succesful removal of the backing paper. For this reason all test are performed under maximum vacuum pressure. Finally, some small trials were made, where only a small corner of the prepreg was initiated and a peeling speed of $2000mm/s$ was programmed. The initiation was initiated at the right corner in a triangle shape with a length of 20 to $40mm$. For these test cases it can be concluded that it is also possible to peel the paper if only a small corner of the reinforcement is initiated. However the peel initiation area needs to coincide with a hole of the vacuum roll to succeed.

6.4 Compliance

In this section the compliance of the robotic system is examined to check whether all requirements are met and are responded to. All requirements are shortly repeated one by one to check their compliance.

Requirement 1.1 *The manual stacking of the prepreg skin, doublers and front and aft spar reinforcements, shall be automated by means of a robotic pick and place system in order to achieve a lead time reduction for the production of the inboard flap shells of the A320.*: The robotic cell lay-out with integrated bridge and multi-actuator handling system is able to grip the skin, all doublers and reinforcements for the UL, UR, LL and LR IBF shells. Furthermore the robotic system is able to remove the backing paper from the upper and the lower side of the prepreg. In the best case scenario, the lead time of the robotic system can be reduced from $307{,}5IM$ for the manual process to $50.79IM$.

Requirement 1.2 *The robotic cell shall be a conceptual design of an entire system, including end-effector for the handling of prepreg material of different dimensions.*: A full conceptual design; including robotic cell, end-effector, handling system and backing paper removal is carried out in this research. After trade-off, the integrated bridge with multi-actuator handling system including vacuum box is concluded to meet best the requirements. To remove the backing paper, peel initiation can be achieved by injecting

compressed air and peel continuation by wrapping the backing paper around a vacuum roll.

Requirement 1.3 *The system shall have a maximum return of investment of 2 years.*: From the economic analysis in section 5.5, it can be concluded that the robotic system can have an ROI in two years. In order to meet this requirement, the system should be able to peel the backing paper at a speed of $2000mm/s$, the pick-up time needs to be reduced to 5 seconds and finally, the disposal time of the backing paper into the disposal container takes maximum 10 seconds. Apart from these parameters, the integrated bridge should be implemented and used to handle all prepreg of the IBF and the OBF. From the sensitivity analysis in section 5.5.4, it could be seen that the peeling speed of the backing paper and the disposal of the backing paper offer the largest potential to lead time reduction. For this reason they need extra investigation to ensure that these values and therefore an ROI within two years can be achieved. However, from the economic analysis it can be seen that an initial investment cost of 668,371 euro is required. For the ultimate case, a saving per shell of 133,98 euro is achieved. Leading to a ROI of 1,86 years, if the system is used for the inboard and outboard flap reinforcements. The ROI could be reduced even more if the production numbers of the A320 are increased.

Requirement 1.4 *The maturity of the different end-effectors shall be analysed.*: During the conceptual design phase and especially during the trade-off of the concepts, the maturity of the different technologies is considered. Technologies that are not mature enough are excluded, because they don't meet the requirements. A good example of this, is the electro adhesive end-effector. It is a light and highly flexible solution to pick and place prepregs, however the technology is not mature enough today.

Requirement 1.5 *The system shall be universal, so it can be easily implemented for other pick and place activities at Airbus.*: The final robotic system can be slightly adapted and implemented for other pick and place activities at Airbus. Adaptions required are resizing of the handling system in order to be able to handle other dimensions of prepreg reinforcements.

Requirement 1.6 *The robotic system shall be able to pick flat prepreg material from the ATL lay-up table and place them on a flat lay-up table.*: The integrated bridge is able to handle flat prepregs and pick them from the flat ATL lay-up table. After handling, the prepregs can be placed on a flat side lay-up table. There is no solution available to place them on a double curved mould so that needs further research.

Requirement 1.7 *The robotic system shall be able to be integrated in current production lay-out without interference.*: All concepts are traded on an implementability criterion. This means that if a concept showed high potential, but it is not implementable in current production lay-out, the concept is scrapped. For this reason the final solution can be implemented in current production lay-out without interference.

Requirement 2.1 *The handling system, including the end-effectors, shall avoid deformation or any contamination to the laminate during handling.*: The robotic cell is able to pick the prepregs from the flat ATL lay-up table and place them on the flat side lay-up table. Due to the flat handling, no deformations are expected at any time. Next, no concepts using water vapour or adhesive is opted for to prevent the prepregs from contamination.

Requirement 2.2 *To immobilize the prepreg during cutting operation, it is covered with backing paper on both sides of the material. Therefore the system shall be able to automatically remove the backing paper from both sides of the material.*: To automatically remove the backing paper, the backing paper operation is divided into a peel initiation and peel continuation operation. To initiate the peeling off of the backing paper, compressed air is injected just under the backing paper. After initiation, a vacuum roll is used to complete the peeling motion. A peeling strategy in order to be able to remove the backing paper from both the upper and lower side of a prepreg is included in section 5.3. The peel initiation and peel continuation concepts are validated to ensure the working principle.

Requirement 2.3 *The prepreg material, skin, doublers and front and aft spar reinforcements, shall be stacked on top of each other. Fulfilling the orientations called out in the technical drawings and minimizing the amount of air occluded below the ply.*: The robotic cell is able to pick all prepregs from the ATL lay-up table and place them on the side lay-up table. In order to fullfil correct positioning and stacking on the side lay-up table, the handling system is able to rotate 90 degrees. Another founding is that, in order to be able to place all reinforcements at the right position, the side lay-up table needs to be placed tangential to the length of the ATL lay-up table.

Requirement 2.4 *During stacking, the prepreg plies shall be placed, in such a way that the backing paper is on its external face. Subsequently removing it just before application of the next prepreg ply.*: Before placement of a prepreg on the side lay-up table, the handling system is positioned on top of the disposal container and the backing paper is removed from the lower side and deposited in the disposal container. Next the handling systems positions on top of the side lay-up table and the prepreg is placed on the side lay-up table. Next, the backing paper can be removed from the upper side and after the handling system positions on top of the disposal container and the backing paper can be placed into the disposal container. The integrated bridge and handling system travel to the following prepreg and the cycle starts over again. However it can be seen that the backing paper from the upper side is not removed just before application of the next prepreg. The prepreg will lay unprotected on the side lay-up table for around 1 minute. However this is not considered as unacceptable, since it is comparable. Furthermore the lay-up process is performed under clean area conditions, minimizing possible contamination.

Requirement 2.5 *The robotic system shall have sufficient holding force, being able to grip the prepreg material and handle it till placement, without dropping it.*: At this moment, the requirement needs validation. However for the calculation of the theoretical

holding force, a guide is used that is provided by Schmalz. By including a safety factor it is expected that the theoretical holding force exceeds the actual required holding force.

Requirement 2.6 *The structural integrity of the prepreg material shall be maintained at all times.*: At this moment it can't be ensured that the structural integrity of the prepreg material is maintained at all times. During handling of the prepreg, no structural integrity changes are expected. However the injection needle used for peel initiation may influence the prepreg fibres. For this reason this requirements needs further research. However it is expected that the injection needle will not cause severe unwanted structural changes. Injection occurs at the edge of the reinforcement, which is later trimmed.

Requirement 2.7 *The robotic system shall be able to separate the prepreg material from the ATL lay-up table after cutting without interfering with the surrounding prepreg material.*: From the experiments, it could be seen that different prepregs could be cleared from surrounding material without any problems. However, one condition is that the prepregs must be completely cut. If the reinforcement is not properly cut, it will lift all surrounding material and will drop if the required lifting force exceeds the maximum holding force of the handling system.

Requirement 2.8 *The robotic system shall be able to handle a large variation in dimensions, with the largest prepreg part with a length of 4390,2mm and a width of 622,5mm.*: The multi-actuator handling system makes it possible to handle a large variation in dimensions by individually opening and closing specific vacuum holes. From the configuration, it can be seen that all prepregs can be handled.

Requirement 2.9 *The robotic system shall not collide at any point with other systems in the environment.*: From the simulation of the robotic cell it can be ensured that the robotic cell and other components does not collide at any moment during the entire cycle.

Requirement 2.10 *The robotic system shall have a quality control to guarantee whether the backing paper is completely removed.*: An optical system will be included in the system to idendify when some white backing paper is left on the black prepreg reinfocement. If some backing paper is left on the prepreg, the system will stop and a worker has to remove the backing paper left on the prepreg material.

Requirement 3.1 *After cutting, the prepreg material shall not show any contamination, shears, cuts or geometry deviations other than indicated in the drawing set or discepancies exceeding the requirements of its applicable Airbus Material Specification.*: The requirement ment for cutting activities is set by Airbus. The cutting principle will not be changed in any form. For this reason it can be guaranteed that the requirement is met.

Requirement 3.2 *The backing paper shall be removed with great care. So not detaching strands, altering their alignment or producing damages.*: From the experiments, it could be seen that all backing paper was removed from the prepreg test samples by varying the peeling speed up to $5m/s$ without showing any visual damages to the prepreg material. To be able to assure this requirement, extra tests have to be performed to ensure the quality of the material after peeling.

Requirement 3.3 *The orientation tolerance for UD-prepreg tape positioning on top of one other shall not exceed a tolerance of* $\pm$ *3° as regards to the fibre direction.*: Thanks to automation, high positioning and orientation tolerances can be achieved. The orientation tolerance of the handling system will never exceed $\pm$ 0.5°.

Requirement 3.4 *The positioning tolerance for the end of one prepreg ply shall not exceed the tolerance of* $\pm$ *2,5 mm according to the technical drawing.*: Due to automation, high positioning and orientation tolerances can be achieved. The positioning tolerance of the handling system will never exceed $\pm$ $0.5mm$.

Requirement 3.5 *The robotic system shall be able to repeat all the requirements for every new pick and place cycle.*: Automation of a process results in high repeatability, cycle after cycle. The robotic system therefore will operate within the preset requirements.

Requirement 3.6 *The robotic system shall be able to carry the handling system within it constraints.*: The handling system is connected to the integrated bridge and the frame is able to rotate, being lowered and lifted. Furthermore from the simulation it could be seen that there are no collisions during the entire cycle.

Requirement 3.7 *The robot system shall meet the range between the ATL lay-up table and the flat lay-up table. The range of the robotic system shall be at least 30 meters.*: Thanks to the linear guidings, the integrated bridge is able to travel along the entire length of the ATL lay-up table. By extending the linear guidings, the integrated bridge is able to move on top of the disposal container and side lay-up table.

Requirement 3.8 *The robotic system shall be able to build 1248 shells of A320 inboard flaps on a yearly basis.*: Currently 1248 inboard flap shells are built on a yearly basis, in a three 8-hours shift schedule for 5 days a week. By automating the process, a cycle time reduction from 307,5 industrial minutes to 76,07 industrial minutes can be achieved. This is a cycle time reduction of 75%, making it able to produce all shells on yearly basis.

Requirement 4.1 *The picking, handling and placing of the prepreg material by the robotic system shall be performed in clean isolated areas with controlled temperature and humidity, which must be recorded and meet the requirements.*: The entire robotic system will be integrated in the current clean area. Therefore the system will operate within the required temperature and humidity.

Requirement 4.2 *The tools used for picking, handling and placing the prepreg material shall be cleaned and maintained appropriately at all time.*: The requirement is not considered in this research, however it is expected that the robotic system will have a maintenance program and will be maintained and cleaned at predetermined moments.

Requirement 4.3 *To improve the tackiness of the prepregs, a controlled heating system may be used to warm the material directly or indirectly during a short time $\leq$ 2 min at a maximum of 65°Celsius.*: No controlled heating is used to improve the tackiness of the prepreg. For this reason, the requirement can be scrapped.

Requirement 4.4 *The prepreg material shall be used within the shelf life of 6 months at -18°Celsius and tack life of 10 days at 23°Celsius.*: First, the prepreg tapes are transported from the freezer to the ATL area. After that the prepreg tapes are defrosted for 24 hours. After defrosting, the ATL lays the material on the ATL lay-up table and after lay-up activity the integrated bridge will start its activity and handle all prepregs. Because of the immediate action of the integrated bridge, because otherwise it will lead to large unavailability of the ATL lay-up area, the prepreg material will never exceed the tack life. Currently it happens that prepreg reinforcements exceed this tack life because they are stored too long before being used for laminating. This results in scrapping of the reinforcements and increases the cost for Airbus.

Requirement 4.5 *If the lay-up is suspended or more then 3 hours, the laminate shall be covered with a temporary vacuum bag maintaining a minimum pressure of 13,2 kPa.*: If the lay-up is suspended, the side lay-up table is equipped with a vacuum surface and a rubber vacuum bag is integrated in the side lay-up table. This way the prepreg laminate can be temporary covered with the rubber vacuum bag.

Requirement 5.1 *The end-effector shall be able to pick and place prepreg UD laminates with Hexcel Hexply 6376 prepregs with Cytec E3760 white backing papers on both sides of the laminate.*: The pick and place activity is designed to handle Hexcel Hexply 6376 prepreg material covered with Cytec E3760 white backing paper. All experiments are performed using this material combination. If other material types want to be handled, extra experiments are required to insure proper performance.

Requirement 6.1 *No design changes to the shells of the IBF are allowed in order for better pick and placement.*: For the pick and place activity, current prepreg reinforcements can be handled and the backing paper can be removed automatically. The only change required is reprogramming the ATL lay-up program to eliminate the flipping of the prepreg material step. Although, some ply drops are present, it is not considered unacceptable. As for current lay-up, the ply drop zones will be cut and won't be part of the actual skin build up.

Requirement 6.2 *The proof of concept of the robotic system shall be finished at 30^{th} June 2014.*: A complete conceptual and detailed design is performed before the 30^{th} of June. Apart from the design phase, validation of the conceptual design is performed. The final presentation of the robotic system will be at Wednesday 16^{th} of July 2014 in Delft.

6.5 Conclusion

The goal of this chapter was to validate the robotic pick and place automated system. More particularly whether it is physically possible to move all parts in required direction and positions. Next, the peel initiation and peel continuation concept needed validation to proof the working principle of these two concepts. Finally, the maximum peeling speed is validated.
The simulation of the robotic cell was performed to validate the physical lay-out of the robotic system. It is seen that the integrated bridge and handling system were able to perform all required movements and positions without any collisions. Furthermore, it could be concluded that in order to place all prepregs at the required position and orientation, the side lay-up table should be placed in the same length as the ATL lay-up table.
Next, the working principles of the peel initiation and peel continuation concept were validated. It can be concluded that both the injection of compressed air and the vacuum roller to peel the backing paper are suitable methods to automatically remove the backing paper from the prepregs. It was observed for the injection of compressed air concept, that it was impossible to initiatie the backing paper from a 15, 30 and 45 degrees initiation angle. This was also the case if the tip angle was validated from 15 till 45 degrees. In these cases, the compressed air escaped on top of the prepregs and no initiation occured. However if a flat, but sharp injection needle was initiated perpendicular to the prepreg, all prepregs could be initiated without any problems. The growth of the initiation area is more difficult perpendicular to the fiber orientation, than in direction of the fiber orientation.
For the peel continuation with the aluminium vacuum roller it could be observed that the backing paper could be successfully removed for all prepreg test samples up to a peeling speed of $5m/s$. This was also the case if only a small tip at the corner of the test sample was initiated. No peel continuation differences are observed for the 0 degrees and 45 degrees outer surface orientation of the test samples.

Chapter 7

Conclusions and future research

This chapter describes the conclusions from this thesis in section 7.1 and the recommendations for future research in section 7.2.

7.1 Conclusions

The challenge of this research was to design a pick and place robotic system that is able to handle prepregs of different dimensions. Until today there was no pre-existing standard method to handle prepreg materials at Airbus not in literature. It was defined that a robotic system is an individual solution and a proper solution should be found to fulfill all requirements. As mentioned before, the system should be able to handle a large variation of dimensions, from the smallest prepreg with a width of $41mm$ and a length of $403mm$ to the skin with a width of $618mm$ and a length of $4380mm$. Finally it was defined that the robotic system should be able to automatically remove the backing paper from both sides of the prepreg. The automated backing paper removal is considered the biggest challenge. Till today no solutions are available and implemented in the industry. During this thesis research a conceptual robotic pick and place system is developed. The conceptual robotic system needed to fulfill all requirements. To be able to handle all prepregss and have proficient working space at the ATL lay-up table, reach all components at the ATL lay-up table, an integrated bridge is opted for to move along the entire length of the table. The integrated bridge offers a large working enveloppe and operates at a travelling speed of $2m/s$. The linear track offers the same advantages, but supplementary high repeatability of $< 0,08mm$. However the system can not be implemented in current production lay-out. Nevertheless when new production cell is considered, one should take into account to implement room for the linear track to be installed. This way the system can operate at a lower cost.
To grip the prepregs, it was concluded that the vacuum system meets the requirements most. The vacuum gripper offers high grab reliability, is independent of ambient conditions and has low investment cost. The electrostatic gripper showed high potential, but is not mature enough to be implemented today.
To be able to handle all different dimensions, the multi-actuator handling system meets

all requirements best. The multi-actuator handling system is a large vacuum box, with small holes at the bottom plate of the box. All these vacuum holes can be individually opened and closed by using bi-stable solenoid valves. This way predetermined vacuum holes can be opened and the system is able to grip prepregs of different dimensions. By using the multi-actuator system a highly flexible system is created with large working envelope. Because of the flexibility and large working envelope, it is possible to implement the handling system for other automated handling activities at Airbus. From the experiments it could be seen that different prepregs could be cleared from the surrounding material and be placed again on a flat surface. However it is concluded that all prepregs should be properly cut. If not, the surrounding material will be lifted and this can lead to scrapping of the part.

An important finding in this research is that until today, no solutions are present to automatically remove the backing paper from both sides of a prepreg. To remove the backing paper, one should first initiate peeling of the backing paper. After initiation, peel continuation of the backing paper is the next step. To initiate peeling, compressed air will be injected between the prepreg material and the backing paper. By injecting the compressed air, an air bubble will be created, easing peel continuation. The peel continuation of the backing paper is done with a vacuum roll. Also in this case, these concepts meet the requirements best. The vacuum roll is equiped with a vacuum zone and rotates around a center tube.

To confirm the peel initiation and peel continuation concepts, both concepts are validated. It can be concluded that both the injection of compressed air, as the vacuum roll are suitable methods within the requirements to peel the backing paper from the prepreg. However some small attention points are found during validation. First, to initiate peeling, a flat needle should be used and the initiation angle should be perpendicular to the prepreg. Using a non-flat needle or a non-perpendicular penetration angle leads to non-initiation of the backing paper. Furthermore a difference on peel initiation could be observed, depending on the orientation of the outer layer of the prepreg layer. In this case the orientation is either 0-degrees or 45-degrees. From the peel initiation experiments, it could be seen that for the 45-degree surface orientation side, all initiation areas were able to grow over the entire width of the prepreg test samples. However for the 0-degree surface orientation side, not all initiation areas were able to grow over the entire width of the test sample. Therefore it can be concluded that the growth of the initiation area experiences more resistance, perpendicular to the fibre direction. In both initiation cases, namely the 0-degree or 45-degree surface orientation side, the air bubble grows fast within the first second. After the first second, the growth of the initiation area reduces if the area of the initiation area is increased. After the first second, all test samples grew $20mm$ over the length of the test sample and $60mm$ over the width.

For Airbus, in order to implement a new technology, it is important to have a positive business case. A positive business case is achieved when the system has an ROI within a maximum of two years. From this research it can be concluded that an ROI within a maximum of two years can be achieved, if the system fulfills some requirements. It is concluded that a positive business case for this technology implementation is hard to be met. However it is not impossible, first the vacuum roll should be able to peel the backing paper at a speed of $2m/s$ and second, the pick-up time of the prepreg should not exceed five seconds. Next, the time to drop the backing paper into the disposal container should be reduced to 10 seconds for one side of the reinforcement or in total to 20 seconds for

both sides. The time for the robotic system to place the prepreg on the side lay-up table should take no more than 7.5 seconds and finally, the integrated bridge and handling system need to be used for handling of the IBF and OBF reinforcements. This way the robotic system has an ROI within a maximum of two years.
From a sensitivity analysis in the economic study of the system, it is observed that the time to drop the backing paper into the disposal container and the peeling speed of the backing paper offer the largest lead time reduction of these requirements. For this reason an experiment to validate the maximum peeling speed is performed. It is observed that for all test samples full backing paper removal could be achieved up to $5m/s$. Furthermore, it could be seen that full contact between the vacuum roll and prepreg is needed at all time. This way full wrapping of the backing paper around the vacuum roll can be ensured. Next, the initiation area is also an important factor on the peel continuation activity. It is concluded that a small initiation area at the corner of a prepreg is sufficient to continue peeling with the vacuum roll. Therefore the peel initiation time does not require longer than 1 second. Initiation for 1 second resulted in an initiation area of $20mm$ of length and $60mm$ of width. This is sufficient for the vacuum roll to continue peeling.
To summarize, during this research a conceptual design of a robotic handling system thay is able to handle prepregs of different dimensions is succesfully developed. The robotic system meets all preset requirements. Furthermore it is proven that the a positive business case can be achieved. This allows Airbus to automate the laminating process of the IBF of the A320. The automation will lead to lower process costs, a reduction in lead time of 83,5%, reduced need for inspection and finally an inproved product quality and repeatability.

7.2 Recommendations

Future recommendations are made in this section, the recommendations are divided in three different stages. First recommendation concerns immediate action, next recommendations are actions required on short term and finally long terms actions are made. The recommendations are treated separately in section 7.2.1, 7.2.2 and 7.2.3.
For Airbus it was the first in-depth research in the pick and place activity for prepreg material. Lots of knowledge of the handling of prepregs are out of the scope of this thesis, but are valuable for Airbus. Hence they are recommended in this section.

7.2.1 Immediate action

Three actions can be completed immediately, namely the automated handling system implementation opportunities at Airbus. The investigation of technology implementation possibilities includes the implementation of the handling and peeling technologies in different process opportunies. Second the implementation possibilities are investigated on their economic viability. Last action completed is the validation of the suction force.
The main focus points of this research are to develop a handling system which is able to handle a large variation in dimensions of prepregs and second the development of a method to automatically remove the backing paper from both sides of the prepreg. The handling of different dimensions and backing paper removal topic are combined and integrated into a complete robotic system which can be implemented in todays production

of the IBF of the A320.
The technology of handling different dimensions and backing paper removal can be implemented in other manufacturing processes and needs investigation in the short term. Figure L.6 shows four different implementation cases that can be examined. The implementation cases can be divided into two main topics, the first one being the implementation of the technology with an industrial robot and the second being the implementation of the technology into a complete robotic cell.

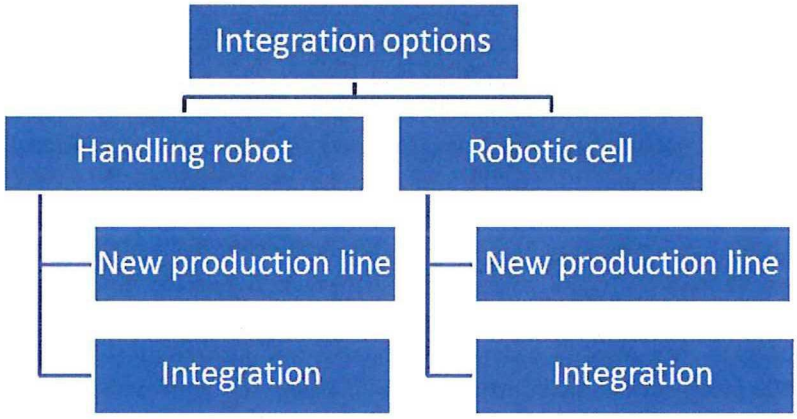

Figure 7.1: Different cases that need investigation, to integrate the handling system and backing paper technology.

The first research point is the implementation of the handling and backing paper technology on an industrial robot. For this subject two possible topics exist. The first is the implementation of an industrial robot into a new production line of a specific part. The industrial robot is part of a continuous serial production line and replaces manual lay-up of prepregs. The second topic of this case is the integration of a fixed articulated robot into today's manufacturing process of the IBF. By this the manual stacking of the reinforcements is not performed manually, but the prepregs are picked from a storage unit and stacked on the side lay-up table.
The second research point is the integration of the technology into a complete production line. The first case here is the new development of a new ATL for a particular part. By developing an entire new production hall of a part, one can take the automated handling system into account. It is most likely that other choises will be made during trade-off. It is most likely that the linear track unit will be opted for to reach the entire length of the ATL lay-up table. During this research the option is discarded because it could not be implemented because of the ATL. The linear track unit will reduce overall investment cost. Last research case is the integration of a complete robotic in current production lay-out, including its limitations. This research case is the focus of this thesed and therefore it does not need further investigation.
Besides focussing on the different implementation options of the technologies and the eventuel problems. One should asses the business cases of these implementation options.

If this study results into more positive business cases, the handling and the backing paper removal technology is more likely to be further developed and implemented at Airbus.
Finally, one should validate the calculated suction force. The calculations used for this research are provided by Schmalz. This is a leading company for the use of vacuum systems. It is believed that the theoretical suction force exceeds the physical required suction force. However for qualification of the system, one should perform a small experiment. This way the statement can be proven. All equipment needed to validate the theoretical holding force is available from this research at Airbus.

7.2.2 Short-term

Two research projects are suggested that could be executed in the short term, i.e. 2014-2015. First further development of the peel initiation and peel continuation concepts. Second, the usage of this technology should be proven to be suitable to use with other material combinations.
First short-term action point is the more detailed development of the peel initiation and peel continuation concepts. During this research first proof of concept of the peel initiation and peel continuation concepts are performed. However more knowledge and understanding of the concepts is required before it can be implemented.
First the vacuum roll needs further development, different parameters should be considered. Different parameters to be deterimined are the maximum and minimum web width, in this case is the maximum web width $618mm$ and the minimum web width $41mm$. The wrap angle should be taken into account, as well as the peeling material and the backing paper thickness. For proper design of the vacuum roll, one should take the peeling speed into account. In this case, the experiments showed that succesfull peeling could be achieved till $5m/s$. Other parameters that should be known for the design of the vacuum roll are the required tension and tension differential ranges and the orientation of the center of the vacuum zone, will it be facing upward or downward and will the vacuum width be variable or not? Finally the operating environment should be considered. All these parameters will result in a fully designed vacuum roll with ideal roll diameter, web thickness, vacuum zone width and angle, vacuum pump requirement and finally proper roll surface.
Another short-term research area is reconsidering the peel initation concept. During the experiments, it could be observed that large non-flat vacuum cups initiated backing paper removal. Initiation by means of non-flat vacuum cups is not considered in the conceptual design phase. However it a simple and cheap solution to initiate backing paper removal. Furthermore the initiation area achieved is large enough to continue peeling of the backing paper. Airbus studies show that non-flat vacuum cups tend to lead to small deformations and sucking of the prepreg material into the vacuum cup. However intensive study showed that after autoclave cycle, non of these deformations remains in the material. From this research, it can not be ensured that for the injection of compressed air, that the structural integrity of the prepreg material is influenced. It is expected that initiation will occur at the edge of the prepreg material, which is later on trimmed away. For this reason eventual influencing of the material can be considered as acceptable, since it will not be part of the final part.
Finally the peeling strategy should be validated, this is of great importance because the

sensitivity analysis showed that the dropping of the backing paper into the disposal container has a large contribution in the lead time reduction of the robotic system. Proper peeling strategy can therefore reduce the lead time reduction even more. In this research a peeling strategy is proposed, however not extensive research have been made. Next, in this research, the peel continuation experimented with was only able to remove the backing paper from the upper side of the prepreg. One should perform experiments, proving that it is able to remove the lower side of the prepreg, while being hold by the handling system.
Second short-term research needing to be performed is a feasibility study of the handling and backing paper removal for other material combinations of prepregs, resin systems and backin paper types. In this research, the focus is layed on a Hexcel hexply 6376 prepreg material in combination with a Cytec E3760 white backing paper. This material combination is used for the production of the IBF shells of the A320. From the requirements, it is known that the robotic handling system should be a flexible product, which can be implemented relatively easy for the production of other parts at Airbus. Other parts at Airbus are often produced using other material combinations. Therefore it has to be ensured that the concept of handling, peel initiation and peel continuation is proven to work with other material combinations.

7.2.3 Long-term

The suggested long-term action is to monitor and investigate the development of the electrostatic gripper. As stated earlier, the electrostatic gripper offers high grabbing reliability and is able to grip prepregs within 0.1 seconds. Next, the electrostatic gripper has low weight compared to other gripping concepts. This is mainly becaus the electrostatic sheet used to grip the material has a thickness of only $1mm$. However, today the technology is not mature to be implemented. Despite all the advantages it offers. Today, several companies are continuously developing the electrostatic gripper in order to reduce the risks of the high electrical potentials and charging voltages that are required to grip the prepregs.
The lower weight of the electrostatic gripper can have some implications to the final design of the automated handling system. Because of the lower weight, it is possible that the handling system can be integrated with current integrated bridge. Because of the low weight, no redesign of the linear track units of the integrated bridge might be needed. Reducing the initial investment cost of the system. Besides, by using an electrostatic gripper, it is easy to grip prepreg of different dimensions. By applying electrical potentials and charging voltages to predetermined channels, is is possible to grip a large variation of dimensions.
Therefore it is important for Airbus to monitor the technology readiness level of the electrostatic gripper. If a negative business case results for the multi-actuator handling system, it can still mean that in the long run a positive business case can result if the electrostatic gripper is in a mature design phase.

7.2.4 Conclusions future research

The author recommends Airbus to continue with the suggested immediate action and short-term research actions.
The immediate and short-term actions will confirm the automated handling system and the action points can be finished in relatively short time and with little resources. The immediate action includes the research of different implementation options of the technologies. This cost-benefit analysis is outside the scope of the conceptual design phase of the robotic system. However it can lead to several positive implementation options of the automated handling technology. The short-term research provides further development of the peel initiation and peel continuation concepts. During the research, both concepts have been developed and proven to work. To reduce possible risks and understand unknown parameters, one should continue this research. Next, the handling system is developed to be used with material combinations used to produce the IBF shells of the A320. One should investigate the suitability of other material combinations. This way, the handling technology can be used for other parts at Airbus.
The long-term action point can eventually result in a positive business case. To ensure this Airbus should monitor the maturity stage of the electrostatic gripper technology and take utmost advantage of the technology if it meets the requirements.

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Appendix A

Work packages and Gantt chart

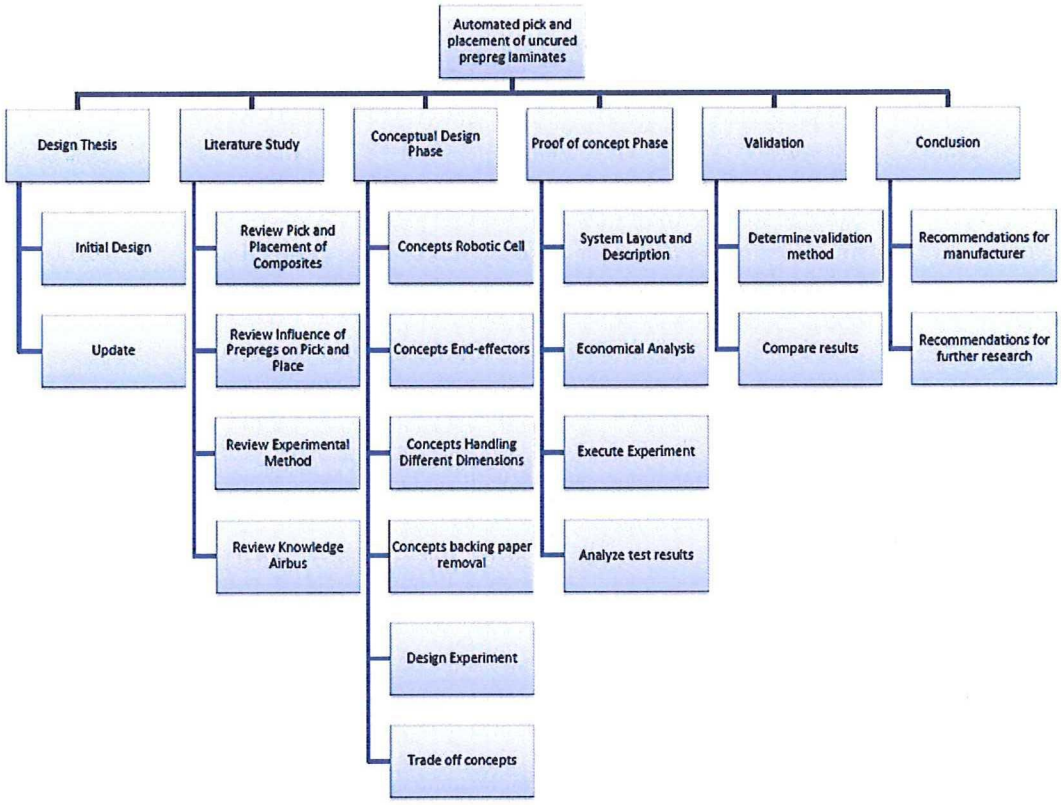

Figure A.1: Detailed work breakdown structure of the project.

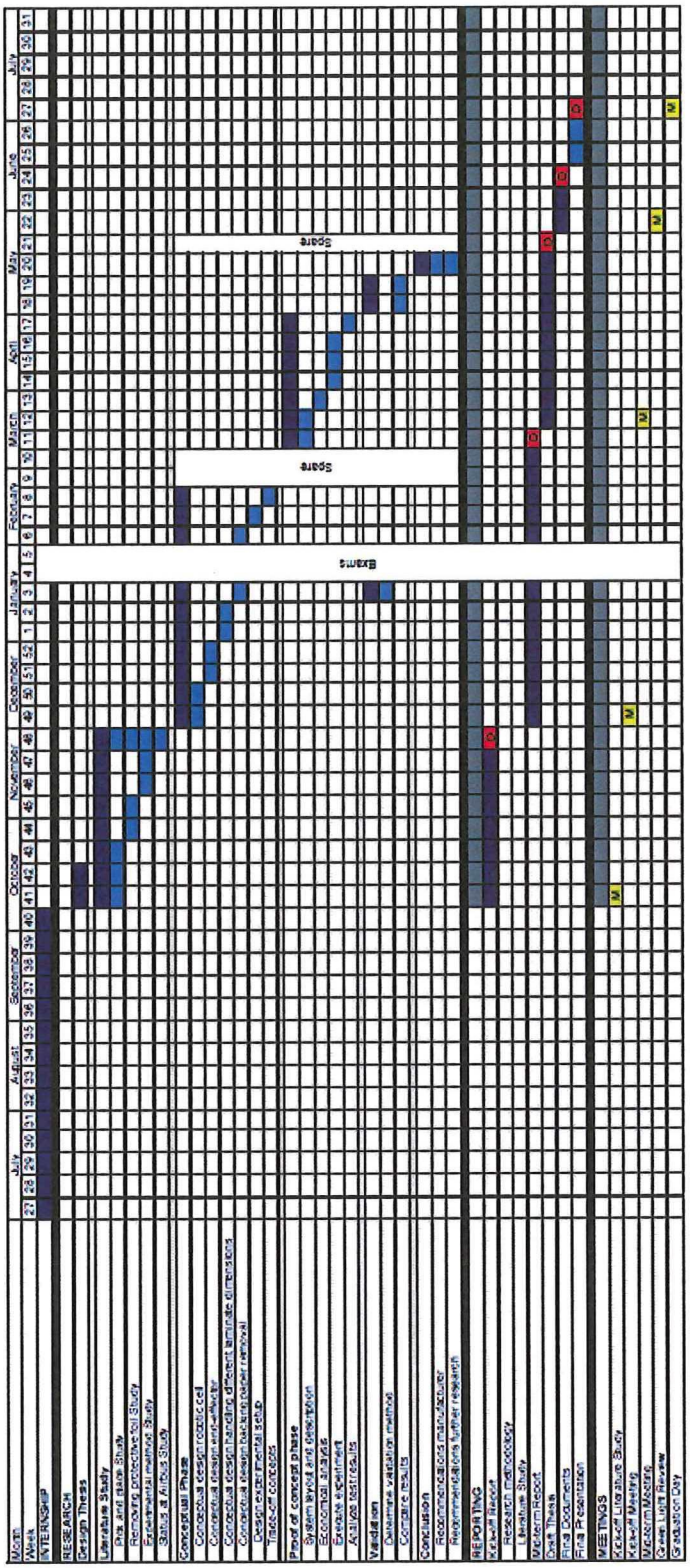

Figure A.2: Gantt chart of the project.

Appendix B

Automated tape layer cuts

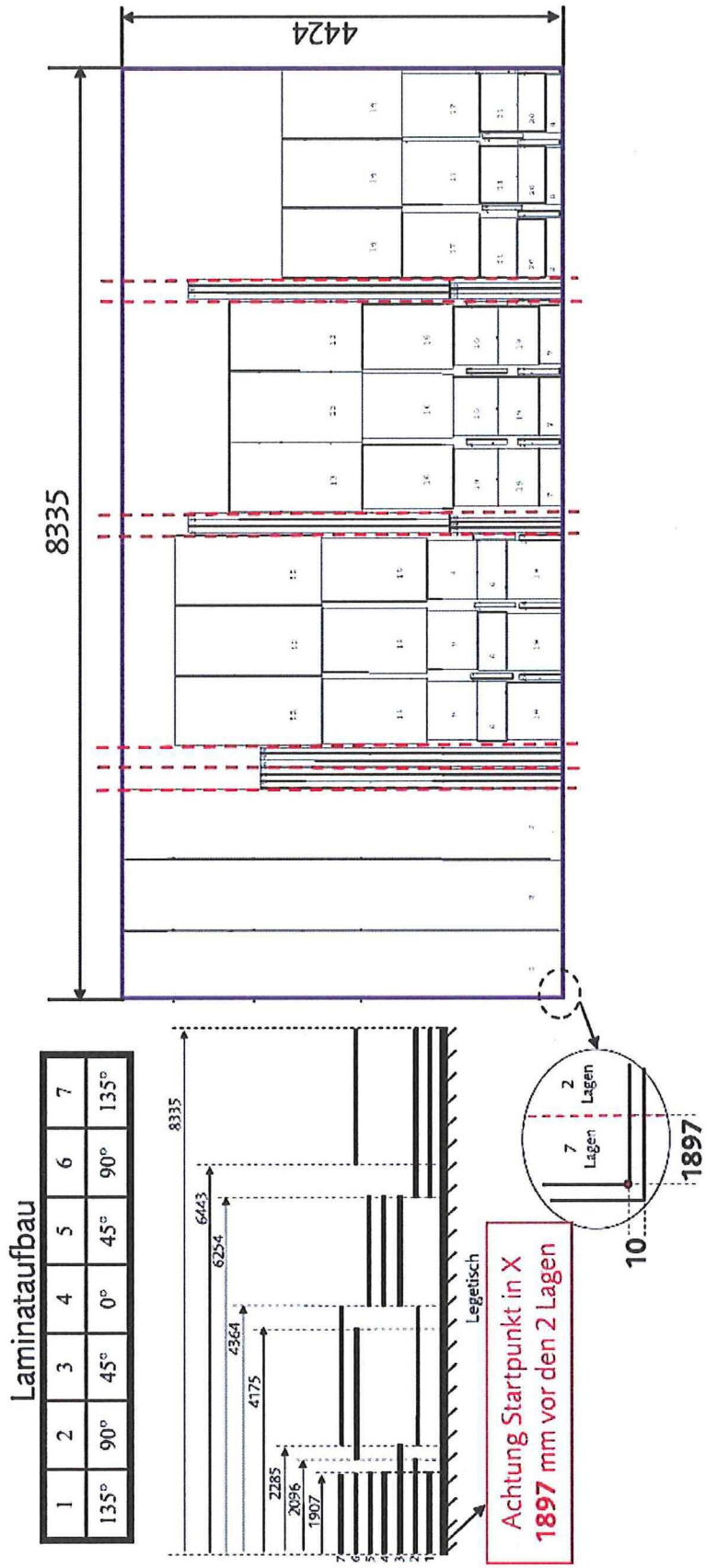

Figure B.1: Visualisation of three sets of IBF skins, doublers and front and aft spars cut by the CNC cutter at the ATL lay-up table for the upper shells.

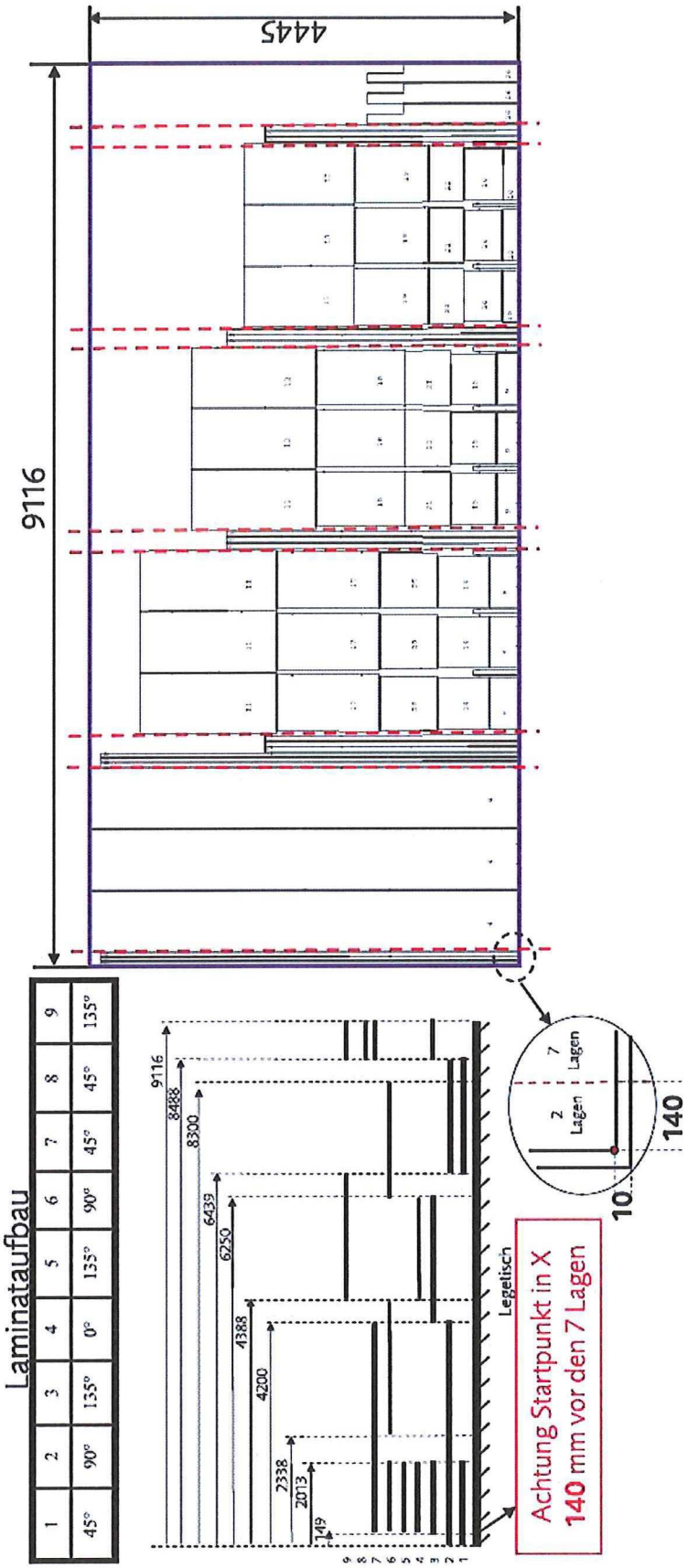

Figure B.2: Visualisation of three sets of IBF skins, doublers and front and aft spars cut by the CNC cutter at the ATL lay-up table for the lower shells.

Appendix C

Steps skin build-up upper shell

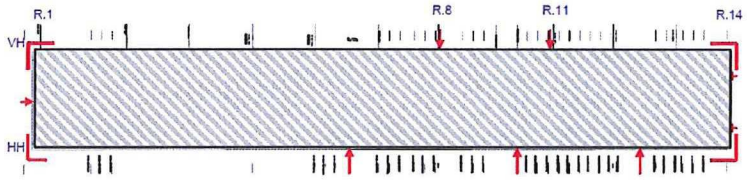

Figure C.1: First step in skin build-up of upper shell.

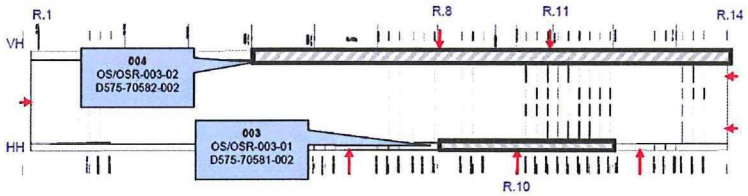

Figure C.2: Second step in skin build-up of upper shell.

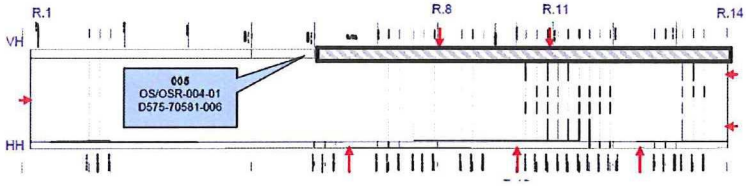

Figure C.3: Third step in skin build-up of upper shell.

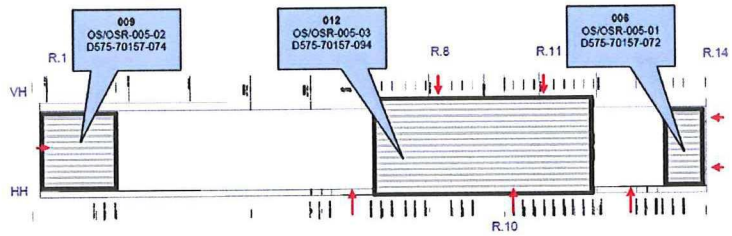

Figure C.4: Fourth step in skin build-up of upper shell.

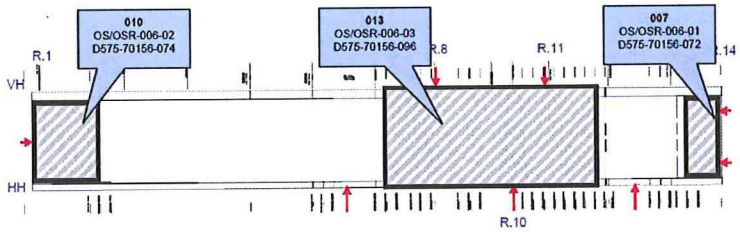

Figure C.5: Fifth step in skin build-up of upper shell.

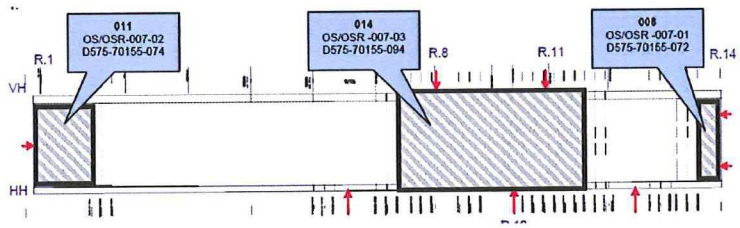

Figure C.6: Sixth step in skin build-up of upper shell.

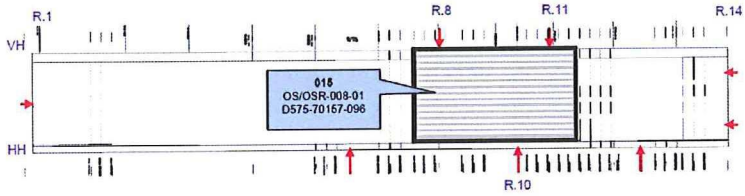

Figure C.7: Seventh step in skin build-up of upper shell.

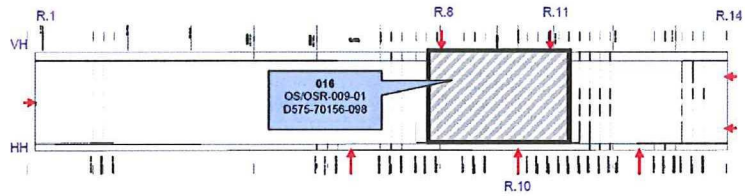

Figure C.8: Eight step in skin build-up of upper shell.

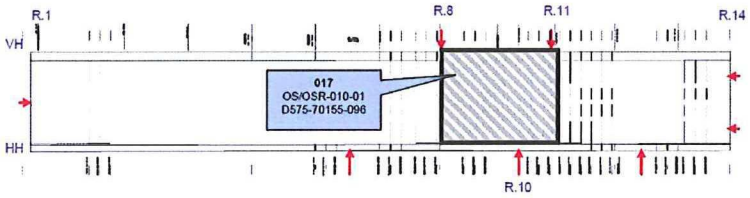

Figure C.9: Ninth step in skin build-up of upper shell.

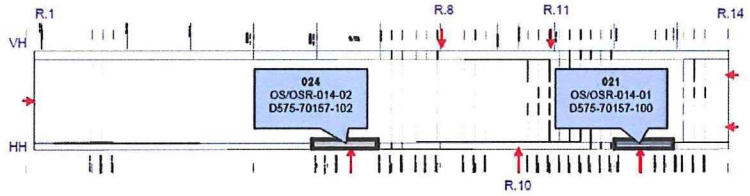

Figure C.10: Tenth step in skin build-up of upper shell.

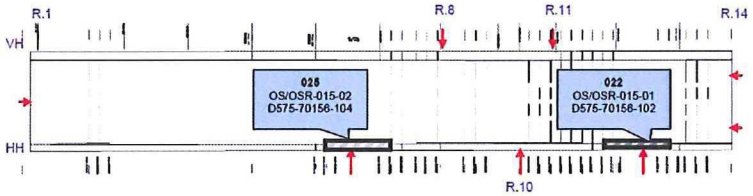

Figure C.11: Eleventh step in skin build-up of upper shell.

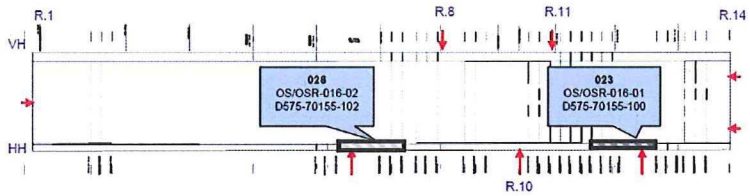

Figure C.12: Twelfth step in skin build-up of upper shell.

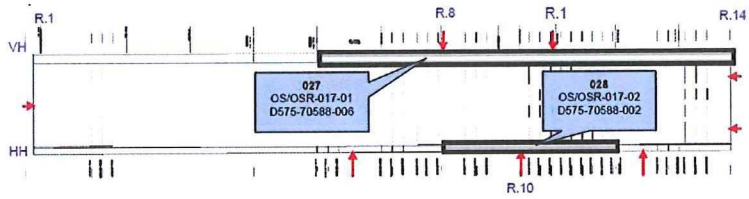

Figure C.13: Thirteenth step in skin build-up of upper shell.

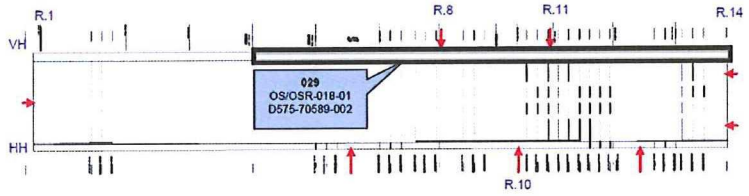

Figure C.14: Fourteenth step in skin build-up of upper shell.

Between step 14 and 15, the skin build up, should be hold vacuum for 10 minutes. After those 10 minutes, the vacuum can be removed. It needs to be checked whether the skin is still wrinkle free and perfectly alligned.

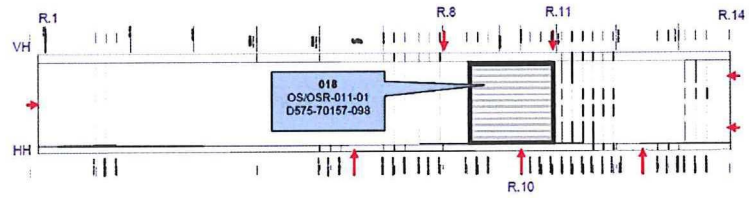

Figure C.15: Fifteenth step in skin build-up of upper shell.

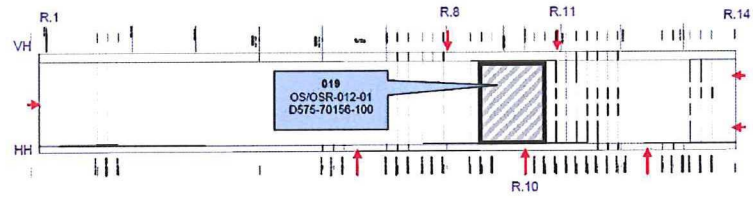

Figure C.16: Sixteenth step in skin build-up of upper shell.

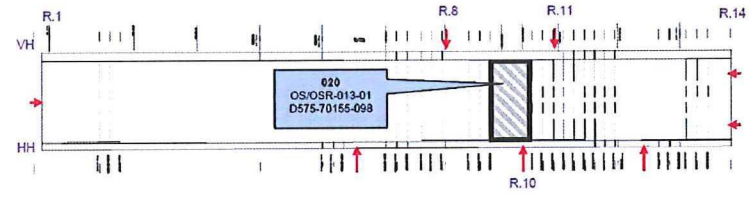

Figure C.17: Seventeenth step in skin build-up of upper shell.

Appendix D

Steps skin build-up lower shell

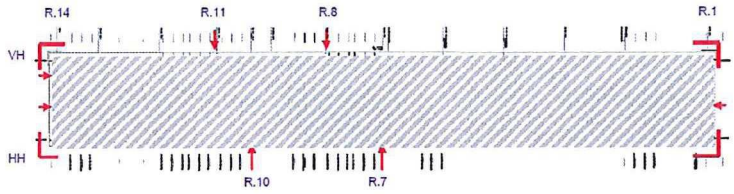

Figure D.1: First step in skin build-up of lower shell.

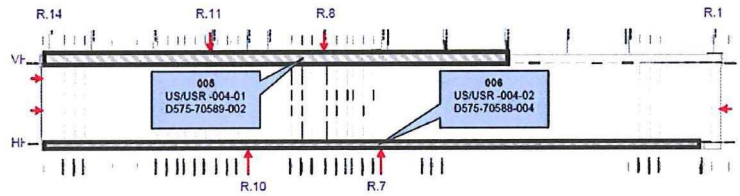

Figure D.2: Second step in skin build-up of lower shell.

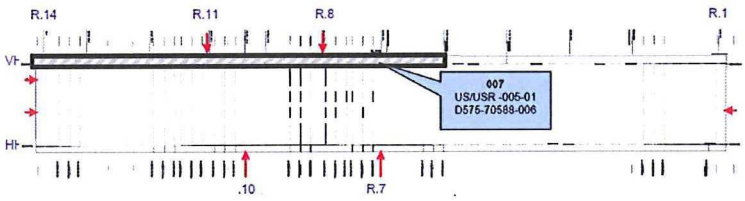

Figure D.3: Third step in skin build-up of lower shell.

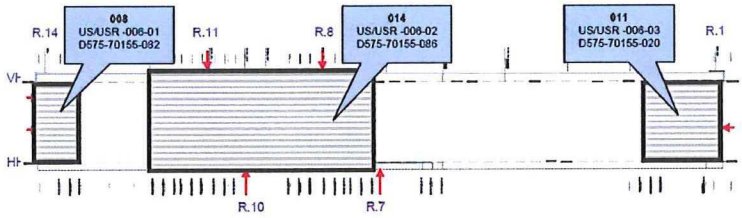

Figure D.4: Fourth step in skin build-up of lower shell.

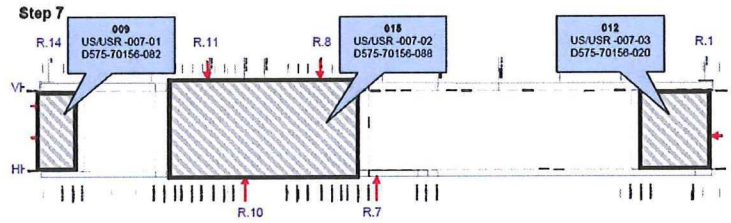

Figure D.5: Fifth step in skin build-up of lower shell.

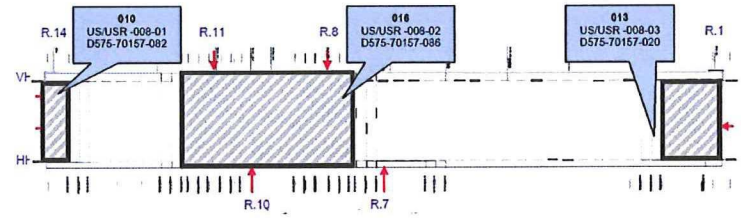

Figure D.6: Sixth step in skin build-up of lower shell.

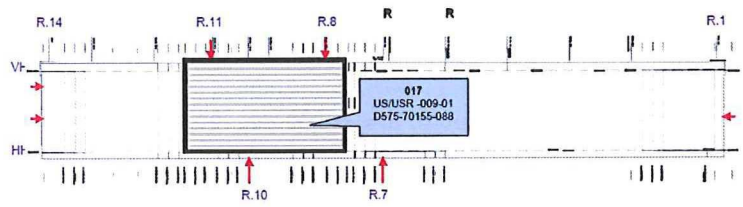

Figure D.7: Seventh step in skin build-up of lower shell.

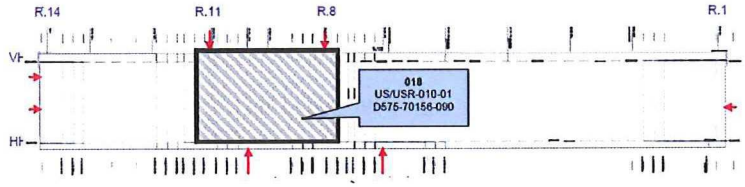

Figure D.8: Eight step in skin build-up of lower shell.

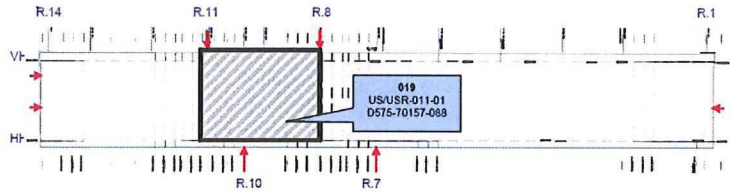

Figure D.9: Ninth step in skin build-up of lower shell.

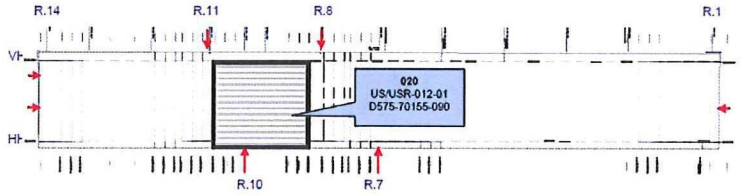

Figure D.10: Tenth step in skin build-up of lower shell.

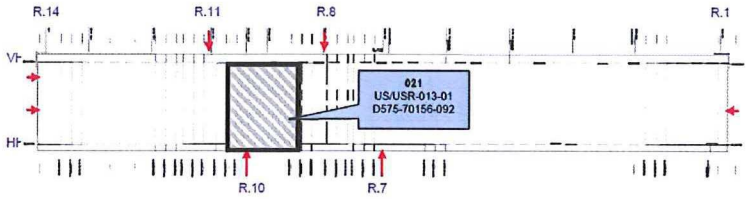

Figure D.11: Eleventh step in skin build-up of lower shell.

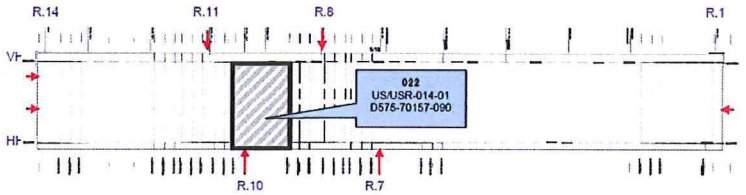

Figure D.12: Twelfth step in skin build-up of lower shell.

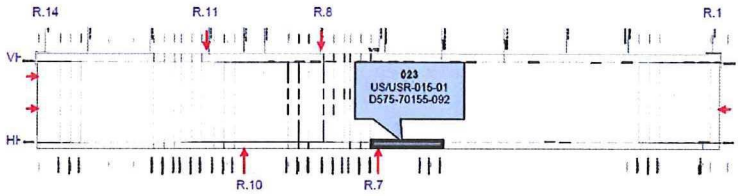

Figure D.13: Thirteenth step in skin build-up of lower shell.

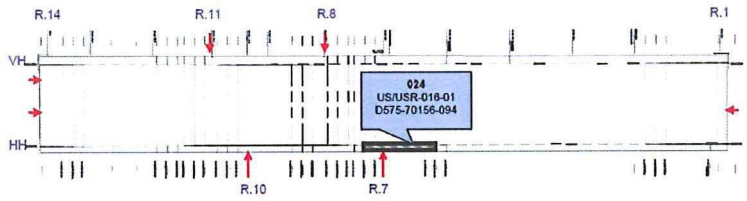

Figure D.14: Fourteenth step in skin build-up of lower shell.

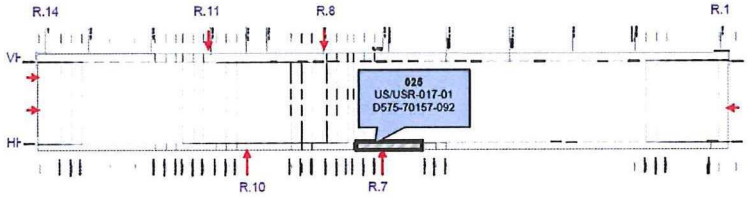

Figure D.15: Fifteenth step in skin build-up of lower shell.

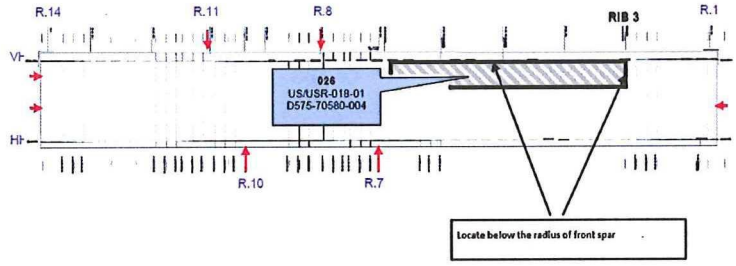

Figure D.16: Sixteenth step in skin build-up of lower shell.

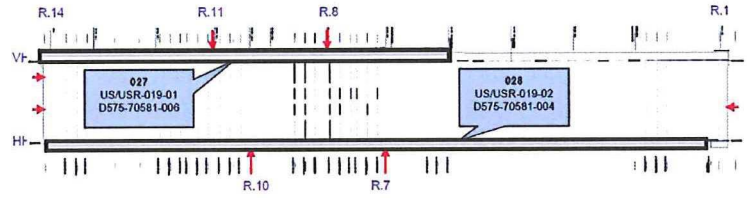

Figure D.17: Seventeenth step in skin build-up of lower shell.

Between step 17 and 18, the skin build up, should be hold vacuum for 10 minutes. After those 10 minutes, the vacuum can be removed. It needs to be checked whether the skin is still wrinkle free and perfectly alligned.

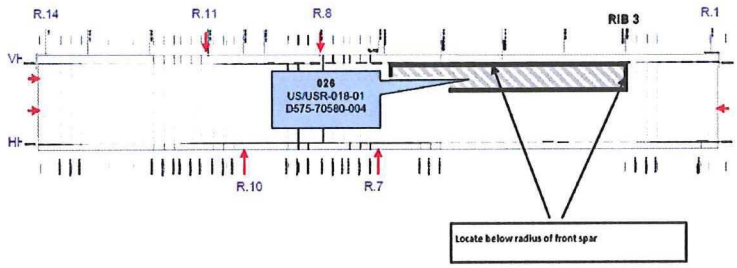

Figure D.18: Eighteenth step in skin build-up of lower shell.

Appendix E

Requirements list

Table E.1: Requirements for the robotic pick and place system.

Requirements list	
Customer requirements	
ID #	Requirement description
1.1	The manual stacking of the prepreg skin, doublers and front and aft spar reinforcements, shall be automated by means of a robotic pick and place system in order to achieve a lead time reduction for the production of the inboard flap shells of the A320.
1.2	The robotic cell shall be a conceptual design of an entire system, including end-effector for the handling of prepreg material of different dimensions.
1.3	The system shall have a maximum return of investment of 2 years.
1.4	The maturity of the diffent end-effectors shall be analysed.
1.5	The system shall be universal, so it can be easily implemented for other pick and place activities at Airbus.
1.6	The robotic system shall be able to pick flat prepreg material from the ATL lay-up table and place them onto a flat lay-up table.
1.7	The robotic system shall be able to be integrated in current production lay-out without interference.

Functional requirements	
ID #	Requirement description
2.1	The handling system, including the end-effectors, shall avoid deformation or any contamination to the laminate during handling.
2.2	To immobilize the prepreg during cutting operation, it is covered with backing paper on both sides of the material. Therefore the system shall be able to automatically remove the backing paper from both sides of the material.
2.3	The prepreg material, skin, doublers and front and aft spar reinforcements, shall be stacked on top of each other. Fulfilling the orientations called out in the technical drawings and minimizing the amount of air occluded below the ply.
2.4	During stacking, the prepreg plies shall be placed, in such a way that the backing paper is on its external face. Subsequently removing it just before application of the next prepreg ply.
2.5	The robotic system shall have sufficient holding force, being able to grip the prepreg material and handle it till placement, without dropping it.
2.6	The structural integrity of the prepreg material shall be maintained at all time.
2.7	The robotic system shall be able to separate the prepreg material from the ATL lay-up table after cutting without interfering with the surrounding prepreg material.
2.8	The robotic system shall be able to handle a large variation in dimensions, with the largest prepreg part with a length of 4390,2mm and a width of 622,5mm.
2.9	The robotic system shall not collide at any point with other systems in the environment.
2.10	The robotic system shall have a quality control to guarantee whether the backing paper is completely removed.

Performance requirements	
ID #	Requirement description
3.1	After cutting, the prepreg material shall not show any contamination, shears, cuts or geometry deviations other than indicated in the drawing set or discrepancies exceeding the requirements of its applicable Airbus Material Specification.
3.2	The backing paper shall be removed with great care. So not detaching strands, altering their alignment or producing damages.
3.3	The orientation tolerance for UD-prepreg tape positioning on top of one other shall not exceed a tolerance of $\pm$ 3° as regards to the fibre direction.
3.4	The positioning tolerance for the end of one prepreg ply shall not exceed the tolerance of $\pm$ 2,5 *mm* according to the technical drawing.
3.5	The robotic system shall be able to repeat all the requirements for every new pick and place cycle.
3.6	The robotic system shall be able to carry the handling system within it constraints.
3.7	The robot system shall meet the range between the ATL lay-up table and the flat lay-up table. The range of the robotic system shall be at least 30 meters.
3.8	The robotic system shall be able to build 1248 shells of A320 inboard flaps on a yearly basis.

Operational requirements	
ID #	Requirement description
4.1	The picking, handling and placing of the prepreg material by the robotic system shall be performed in clean isolated areas with controlled temperature and humidity, which must be recorded and meet the requirements.
4.2	The tools used for picking, handling and placing the prepreg material shall be cleaned and maintained appropriately at all time.
4.3	To improve the tackiness of the prepregs, a controlled heating system may be used to warm the material directly or indirectly the material during a short time $\leq 2\ min$ at a maximum of $65°Celsius$.
4.4	The prepreg material shall be used within the shelf life of 6 months at -18$°Celsius$ and tack life of 10 days at 23$°Celsius$.
4.5	If the lay-up is suspended for more than 3 hours, the laminate shall be covered with a temporary vacuum bag maintaining a minimum pressure of 13,2 kPa.
Interface requirements	
ID #	Requirement description
5.1	The end-effector shall be able to pick and place prepreg UD laminates with Hexcel Hexply 6376 prepregs with Cytec E3760 White backing papers on both sides of the laminate.
Constraints	
ID #	Requirement description
6.1	No design changes to the shells of the IBF are allowed in order for better pick and placement.
6.2	The proof of concept of the robotic system shall be finished at 30th June 2014.

Appendix F

Professional advice contact details

Table F.1: Contact details companies contacted for trading concepts and detailed design.

Company and Contact person	Function	Contact details
KUKA Systems GmbH	Project engineer	arnaud.kandem@kuka.de
Arnaud Kamden		+498217974658
ABB Automation GmbH	Sales engineer	markus-oliver.tacke@de.abb.com
Markus Tacke		+49603185219
Broetje automation GmbH	Key Account Manager	eberhard.goette@broetje-automation.de
Eberhard Goette		+494402966170
Broetje Automation GmbH	Product manager composites	Raphael.Reinhold@broetje-automation.de
Raphael Reinhold		+494454978270
Schmalz GmbH	System Developer	Markus.Bruemmer@schmalz.de
Markus Brmmer		+4915116748662
MTorres	Project and account manager	Jorge.Herrera@mtorres.com
Jorge Herrera		+491724297752
MTorres	Maintenance engineer	mikel.oguiza@mtorres.com
Mikel Oguiza		
MUK	Construction Engineer	m.peters@muk-elmshorn.de
Mark Peters		+494121465863
MUK	Consturction Engineer	m.kroeger@muk-elmshorn.de
Markus Kroeger		+494121465853
Airbus operations GmbH	Head of machines and automated systems	henning.schneider@airbus.com
Henning Schneider		+494141608689

Appendix G

Laminate dimensions

Table G.1: Different dimensions, weight, amount of layers tape and their orientation for the skin, doublers and front and aft spar reinforcements of the upper shell.

ID #	Length $[mm]$	Width $[mm]$	Weight $[g]$	# layers $[-]$	lay-up $[\circ]$
Upper skin					
A002	4380	618	4263,27	7	$[+45, 0, -45, 90]_S$
ID #	Length $[mm]$	Width $[mm]$	Weight $[g]$	# layers $[-]$	lay-up $[\circ]$
Front spar reinforcements upper shell					
A003	1100	41	20,30	2	$[+45, 0]$
A004	2990	55	74,00	2	$[-45, 0]$
A005	1590	55	39,35	2	$[+45, 0]$
ID #	Length $[mm]$	Width $[mm]$	Weight $[g]$	# layers $[-]$	lay-up $[\circ]$
Skin doublers upper shell					
A006	517	273	95,27	3	$[0, 0, +45]$
A007	518	208	72,73	3	$[-45, 90, -45]$
A008	518	140	48,95	3	$[+45, 0, 0]$
A009	518	493	172,38	3	$[0, 0, +45]$
B010	519	427	149,59	3	$[-45, 90, -45]$
B011	519	361	126,74	3	$[+45, 0, 0]$
B012	1462	615	606,91	3	$[0, 0, +45]$
B013	1329	615	551,70	3	$[-45, 90, -45]$
B014	1196	615	496,49	3	$[+45, 0, 0]$
B015	1042	570	400,91	3	$[0, 0, +45]$
B016	570	91	35,01	3	$[-45, 90, -45]$
B017	776	570	298,57	3	$[-45, 0, 0]$
B018	536	513	158,60	3	$[0, 0, +45]$
B019	512	403	139,28	3	$[-45, 90, -45]$
C020	512	27	9,33	3	$[+45, 0, 0]$
C021	415	41	11,49	3	$[0, 0, +45]$
C022	415	41	11,49	3	$[-45, 90, -45]$
C023	415	41	11,49	3	$[+45, 0, 0]$
C024	413	41	11,49	3	$[0, 0, +45]$
C025	413	41	11,49	3	$[-45, 90, -45]$
C026	403	41	11,49	3	$[+45, 0, 0]$
ID #	Length $[mm]$	Width $[mm]$	Weight $[g]$	# layers $[-]$	lay-up $[\circ]$
Rear spar doublers upper shell					
C027	2600	55	64,35	2	$[0, +45]$
C028	1100	41	20,30	2	$[0, +45]$
C029	2990	66	88,80	2	$[0, -45]$

Table G.2: Different dimensions, weight, amount of layers tape and their orientation for the skin, doublers and front and aft spar reinforcements of the lower shell.

ID #	Length $[mm]$	Width $[mm]$	Weight $[g]$	# layers $[-]$	lay-up $[\circ]$
Lower skin					
A004	4380	611	4212,10	7	$[+45, 0, -45, 90]_S$
ID #	Length $[mm]$	Width $[mm]$	Weight $[g]$	# layers $[-]$	lay-up $[\circ]$
Front spar reinforcements lower shell					
A005	2995	52	70,08	2	$[0, -45]$
A006	4280	52	100,15	2	$[0, +45]$
A007	2595	40	46,71	2	$[0, +45]$
ID #	Length $[mm]$	Width $[mm]$	Weight $[g]$	# layers $[-]$	lay-up $[\circ]$
Skin doublers lower shell					
A008	520	274	96,17	3	$[+45, 0, 0]$
A009	520	206	72,31	3	$[-45, 90, -45]$
B010	520	140	49,14	3	$[0, 0, +45]$
B011	517	513	179,02	3	$[+45, 0, 0]$
B012	517	447	155,99	3	$[-45, 90, -45]$
B013	516	380	132,35	3	$[0, 0, +45]$
B014	1400	607	573,62	3	$[+45, 0, 0]$
B015	1267	607	519,12	3	$[-45, 90, -45]$
B016	1135	607	465,04	3	$[0, 0, +45]$
B017	1052	563	399,79	3	$[+45, 0, 0]$
B018	949	565	361,92	3	$[-45, 90, -45]$
B019	785	565	299,38	3	$[0, 0, +45]$
C020	616	553	229,94	3	$[-45, 90, -45]$
C021	553	483	180,29	3	$[+45, 0, 0]$
C022	553	350	130,65	3	$[0, 0, +45]$
C023	454	40	12,26	3	$[-45, 90, -45]$
C024	453	40	12,23	3	$[+45, 0, 0]$
C025	454	40	12,26	3	$[0, 0, +45]$
C026	156	20	18,50	4	$[-45, 45, 45, -45]$
ID #	Length $[mm]$	Width $[mm]$	Weight $[g]$	# layers $[-]$	lay-up $[\circ]$
Rear spar reinforcements lower shell					
C027	260	52	60,96	2	$[+45, 0]$
C028	4282	40	77,08	2	$[+45, 0]$
C029	3000	52	70,20	2	$[-45, 0]$

Appendix H

Robotic cell lay-out

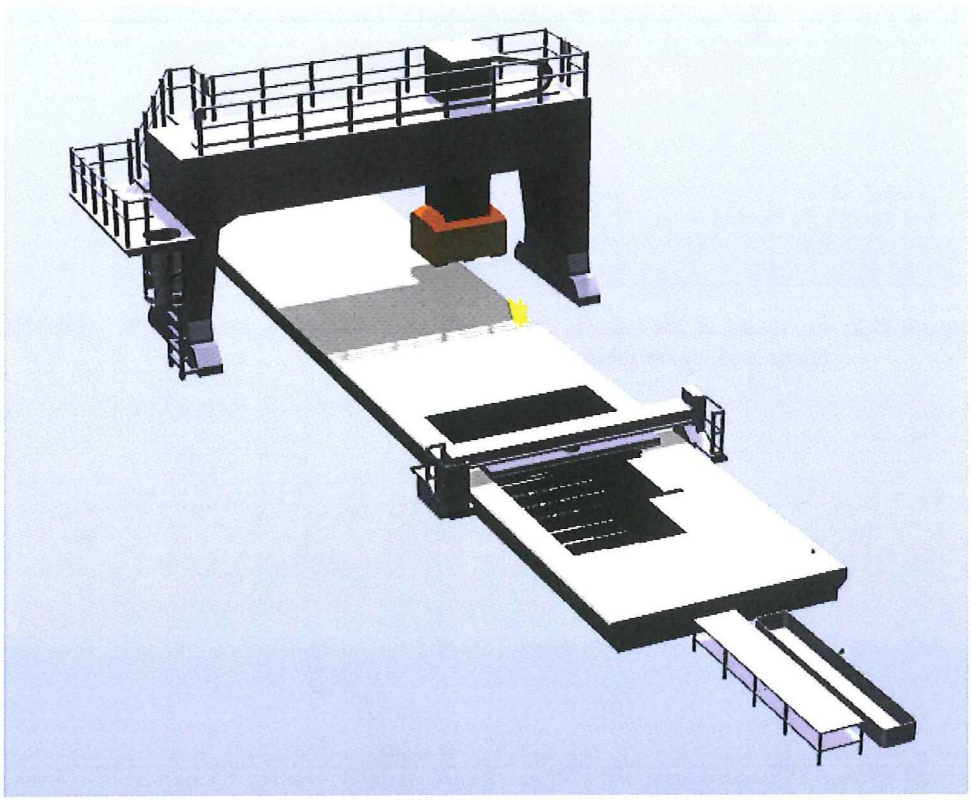

Figure H.1: Overview of the robotic cell lay-out with ATL, ATL lay-up table, integrated bridge and lay-up table.

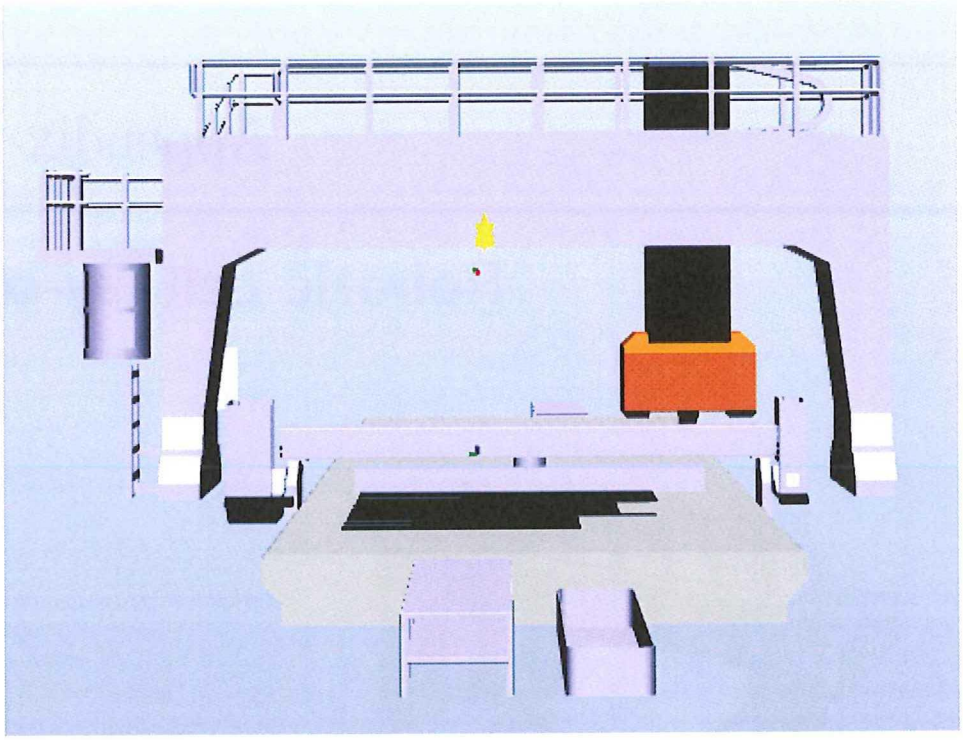

Figure H.2: Frontview of the robotic cell lay-out with ATL, ATL lay-up table, integrated bridge and lay-up table.

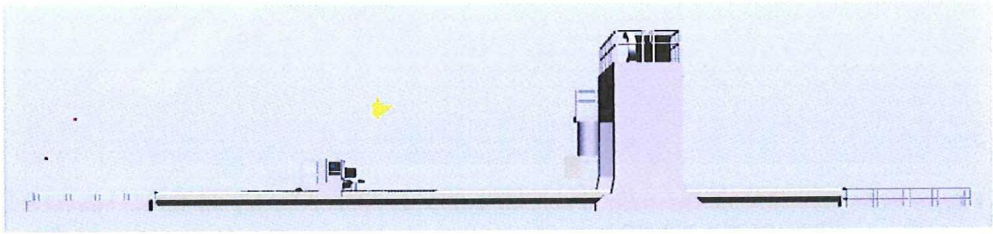

Figure H.3: Sideview of the robotic cell lay-out with ATL, ATL lay-up table, integrated bridge and lay-up table.

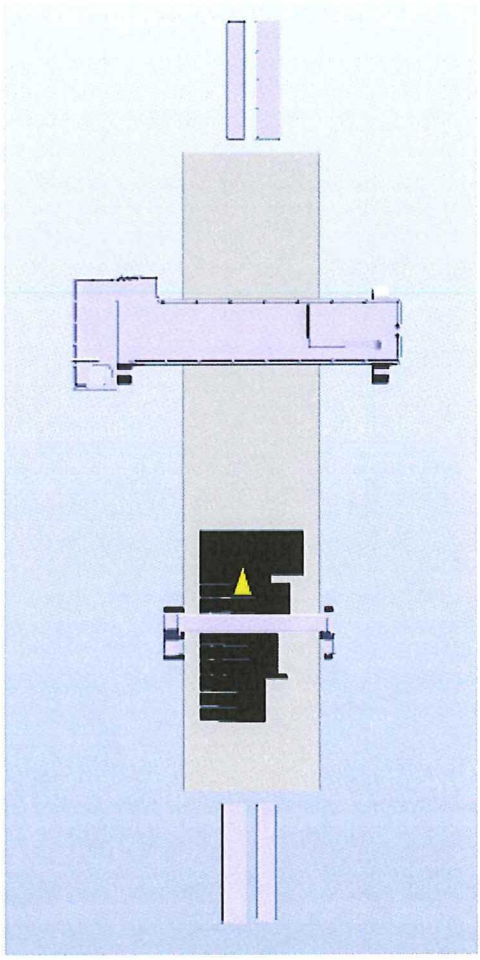

Figure H.4: Topview of the robotic cell lay-out with ATL, ATL lay-up table, integrated bridge and lay-up table.

Appendix I

Analysis of cycle time for one set of IBF

Table I.1: Cycle time analysis of prepreg reinforcement A002.

A002		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	6.54	13085.5
Removal backing paper lower side	43.8	4380
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	43.8	4380
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	3.93	7860

Table I.2: Cycle time analysis of prepreg reinforcement A003.

A003		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	6.54	13085.5
Removal backing paper lower side	43.8	4380
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	43.8	4380
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	3.93	7860

Table I.3: Cycle time analysis of prepreg reinforcement A004.

A004		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	3.93	7860
Removal backing paper lower side	11	1100
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	11	1100
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	5.94	11880

Table I.4: Cycle time analysis of prepreg reinforcement A005.

A005		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	3.93	7860
Removal backing paper lower side	15.9	1590
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	15.9	1590
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	5.44	10875

Table I.5: Cycle time analysis of prepreg reinforcement A006.

A006		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	5.44	10875
Removal backing paper lower side	5.17	517
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	5.17	517
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	5.44	10875

Table I.6: Cycle time analysis of prepreg reinforcement A009.

A009		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	5.44	10875
Removal backing paper lower side	5.18	518
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	5.18	518
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	5.44	10875

Table I.7: Cycle time analysis of prepreg reinforcement B012.

B012		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	5.44	10875
Removal backing paper lower side	14.62	1462
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	14.62	1462
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	4.43	8865

Table I.8: Cycle time analysis of prepreg reinforcement B010.

B010		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	4.43	8865
Removal backing paper lower side	4.27	427
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	4.27	427
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	4.43	8865

Table I.9: Cycle time analysis of prepreg reinforcement B013.

B013		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	4.43	8865
Removal backing paper lower side	13.29	1329
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	13.29	1329
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	4.43	8865

Table I.10: Cycle time analysis of prepreg reinforcement A007.

A007		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	4.43	8865
Removal backing paper lower side	2.08	208
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	2.08	208
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	3.43	6855

Table I.11: Cycle time analysis of prepreg reinforcement B011.

B011		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	3.43	6855
Removal backing paper lower side	3.61	361
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	3.61	361
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	3.43	6855

Table I.12: Cycle time analysis of prepreg reinforcement B014.

B014		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	3.43	6855
Removal backing paper lower side	11.96	1196
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	11.96	1196
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	3.43	6855

Table I.13: Cycle time analysis of prepreg reinforcement A008.

A008		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	3.43	6855
Removal backing paper lower side	1.4	140
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	1.4	140
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	3.68	7360

Table I.14: Cycle time analysis of prepreg reinforcement B015.

B015		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	3.68	7360
Removal backing paper lower side	10.42	1042
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	43.8	4380
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	5.44	10875

Table I.15: Cycle time analysis of prepreg reinforcement B016.

B016		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	5.44	10875
Removal backing paper lower side	0.91	91
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	0.91	91
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	3.43	6855

Table I.16: Cycle time analysis of prepreg reinforcement B017.

B017		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	3.43	6855
Removal backing paper lower side	7.76	776
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	7.76	776
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	5.28	10567.5

Table I.17: Cycle time analysis of prepreg reinforcement C024.

C024		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	5.28	10567.5
Removal backing paper lower side	4.13	413
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	4.13	413
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	5.28	10567.5

Table I.18: Cycle time analysis of prepreg reinforcement C027.

C027		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	5.28	10567.5
Removal backing paper lower side	4.15	415
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	4.15	415
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	4.28	8557.5

Table I.19: Cycle time analysis of prepreg reinforcement C025.

C025		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	4.28	8557.5
Removal backing paper lower side	4.13	413
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	4.13	413
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	4.28	8557.5

Table I.20: Cycle time analysis of prepreg reinforcement C022.

C022		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	4.28	8557.5
Removal backing paper lower side	4.15	415
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	4.15	415
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	3.27	6457.5

Table I.21: Cycle time analysis of prepreg reinforcement C026.

C026		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	3.27	6547.5
Removal backing paper lower side	4.03	403
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	4.03	403
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	3.27	6457.5

Table I.22: Cycle time analysis of prepreg reinforcement C023.

C023		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	3.27	6547.5
Removal backing paper lower side	4.15	415
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	4.15	415
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	4.94	9870

Table I.23: Cycle time analysis of prepreg reinforcement C027.

C027		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	4.94	9870
Removal backing paper lower side	26	2600
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	26	2600
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	4.94	9870

Table I.24: Cycle time analysis of prepreg reinforcement C028.

C028		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	4.94	9870
Removal backing paper lower side	11	1100
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	11	1100
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	6.04	12061.5

Table I.25: Cycle time analysis of prepreg reinforcement C029.

C029		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	6.03	12061.5
Removal backing paper lower side	29.9	2990
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	29.9	2990
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	5.44	10875

Table I.26: Cycle time analysis of prepreg reinforcement B018.

B018		
Process step	Distance/peeling [mm]	Time [s]
Pick-up prepreg reinforcement	10	-
Handling to disposal container	5.44	10875
Removal backing paper lower side	5.13	513
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	5.13	513
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	4.43	8865

Table I.27: Cycle time analysis of prepreg reinforcement B019.

B019		
Process step	Distance/peeling [mm]	Time [s]
Pick-up prepreg reinforcement	10	-
Handling to disposal container	4.43	8865
Removal backing paper lower side	4.03	403
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	5.13	513
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	3.43	6855

Table I.28: Cycle time analysis of prepreg reinforcement C020.

C020		
Process step	Distance/peeling $[mm]$	Time $[s]$
Pick-up prepreg reinforcement	10	-
Handling to disposal container	3.43	6855
Removal backing paper lower side	2.7	270
Disposal backing paper	20	-
Handling to side lay-up table	0.68	1350
Placement prepreg reinforcement	15	-
Removal backing paper upper side	2.7	270
Handling to disposal container	0.68	1350
Disposal backing paper	20	-
Handling to next part	3.43	6855

Appendix J

Planned production numbers of A320

Table J.1: Planned production numbers of A320 CEO and NEO.

Year 2015												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
A320 CEO	27	27	34	29	19	27	16	19	21	23	20	18
A320 NEO	0	0	0	1	0	2	1	1	5	4	4	2
Total a/c	27	27	34	30	19	29	17	20	26	27	24	20
Total shells	108	108	136	120	76	116	68	80	104	108	96	80
Year 2016												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
A320 CEO	22	18	19	17	14	16	10	9	10	11	8	8
A320 NEO	3	5	6	8	8	11	10	10	15	12	16	13
Total a/c	25	23	25	25	22	27	20	19	25	23	24	21
Total shells	100	92	100	100	88	108	80	76	100	92	96	84
Year 2017												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
A320 CEO	8	8	9	5	5	6	5	4	3	5	4	1
A320 NEO	20	16	19	18	18	20	15	14	23	21	22	18
Total a/c	28	24	28	23	23	26	20	18	26	26	26	19
Total shells	112	96	112	92	92	104	80	72	104	104	104	76
Year 2018												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
A320 CEO	2	2	2	2	0	0	0	0	0	0	0	0
A320 NEO	24	23	24	21	24	25	23	21	24	27	26	18
Total a/c	26	25	26	23	24	25	23	21	24	27	26	18
Total shells	104	100	104	92	96	100	92	84	96	108	104	72

Appendix K

Component list

Table K.1: Conponent list of physical experiment.

Component	Detailed information
Aluminium plate	560 x 664 mm
Attachment frame	Schmalz MO-PROF 40x40 3TN AL-1
Bearings	Inner diameter 25mm & outer diameter 47mm
Injection gun frame	Schmalz MO-PROF 40x40 3TN AL-1
Injection gun mountings	Schmalz VRS-PL-80x40 MO-PROF
Mounting elements	Several bolts and screws
Prepreg reinforcements	Hexcel hexply 6376 covered with Cytec E3760 white backing paper
Vacuum cups	Festo ESG-040-CS-HA-QS
Vacuum actuators	Festo HE-2-QSY-6
Vacuum hoses	Festo PUN-6x1-BL
Vacuum hoses	Festo PUN-8x1,25-BL
Vacuum roll	Length 430mm & diameter 150mm
Vacuum roll	Length 430mm & diameter 200mm
Vacuum roll	Length 430mm & diameter 300mm

Appendix L

Simulation steps

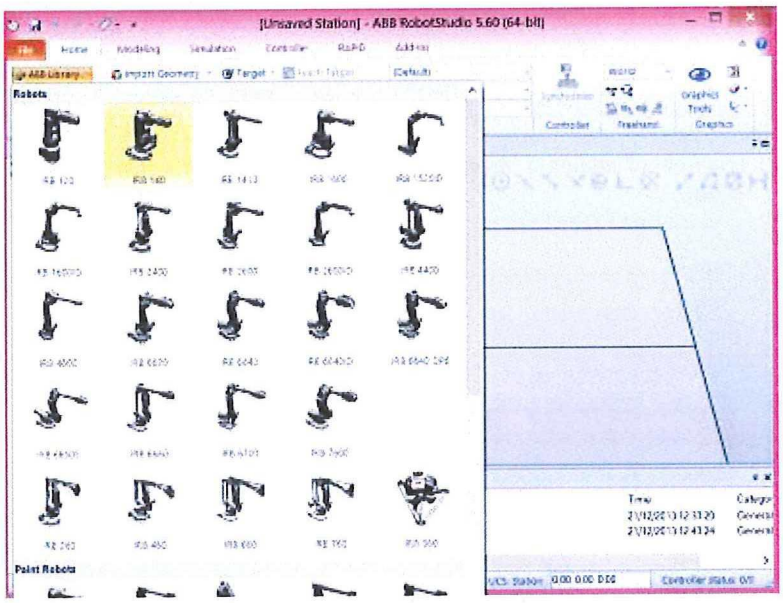

Figure L.1: Example of import of industrial robot, linear track unit or other CAD models.

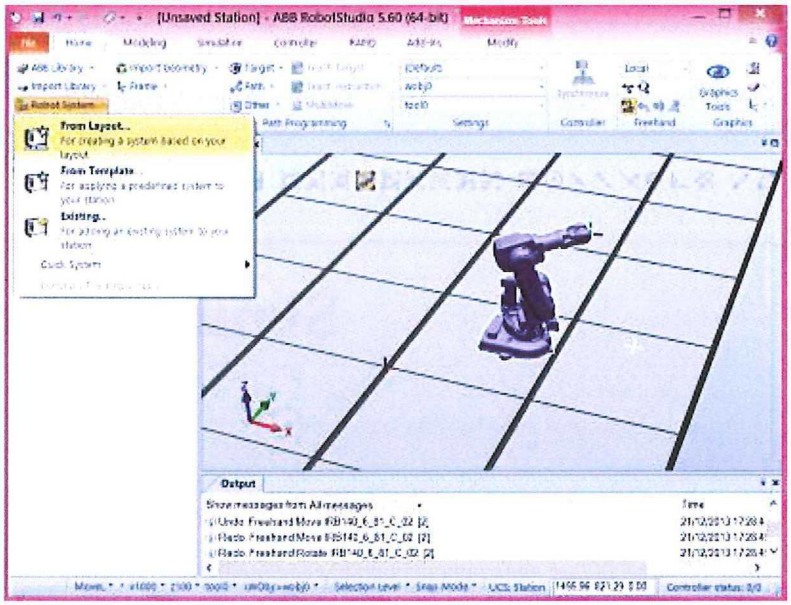

Figure L.2: Example of adding a virtual controller to the robotic cell to control the movements.

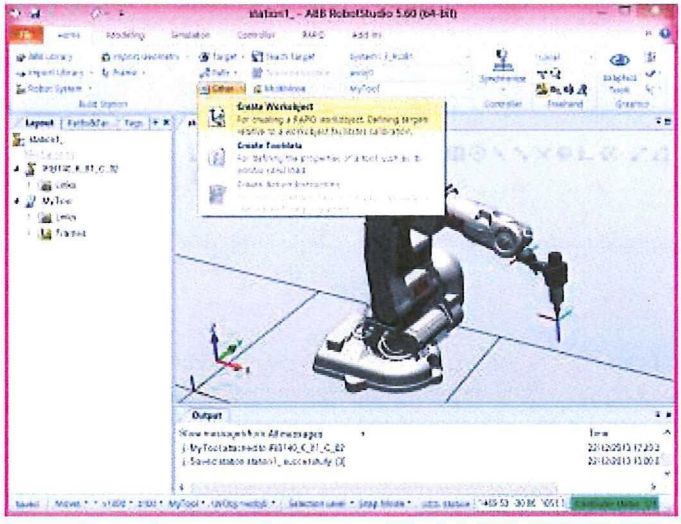

Figure L.3: Example of creating a workobject or reference system.

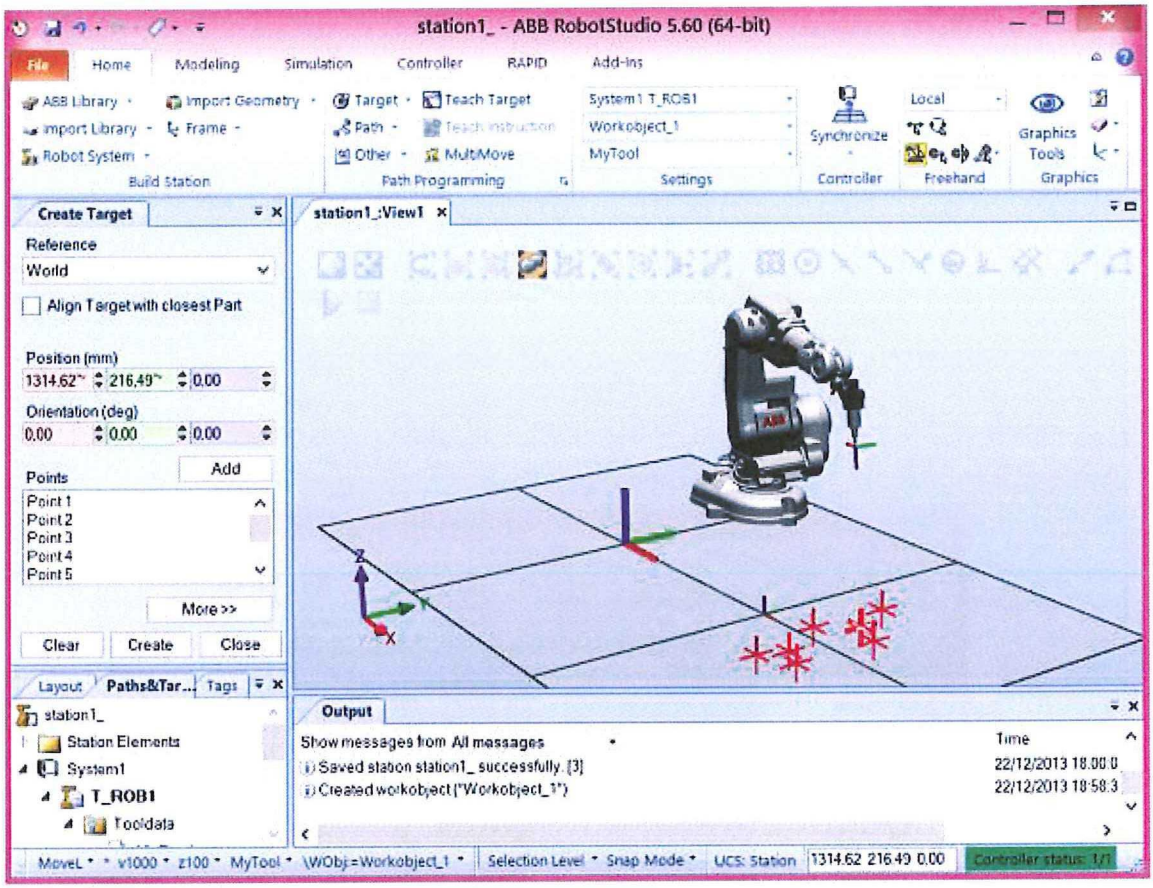

Figure L.4: Example of creation of targets which will be the basis for the robot path.

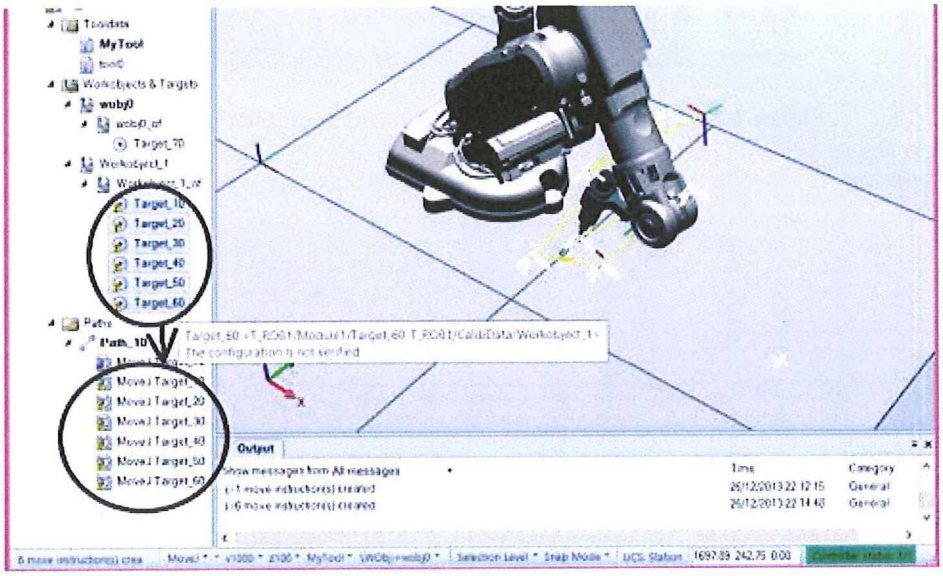

Figure L.5: Example of creating working path of robot.

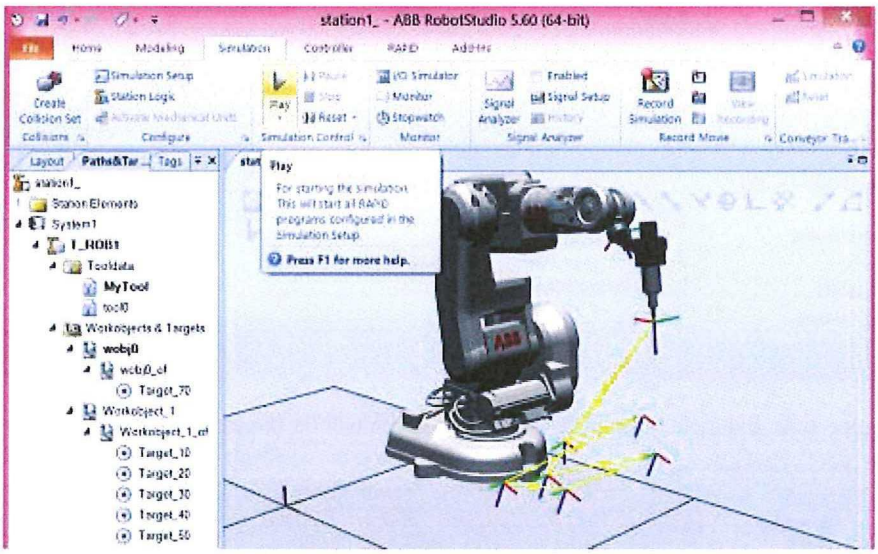

Figure L.6: Example of starting the simulation of robotic system.