Boeing Canada Winnipeg:

Methods of Improving Ply Collation Time

Final Design Report

Team #10:

Rafael Hurtado Rosas

Jackson Paraluch

Xiaran Qiu

Submitted to: Dr. Paul E. Labossiere, P.Eng

Project Advisor: Dr. Sean O'Brien, P.Eng

Date of Submission: December 6th, 2017

EXECUTIVE SUMMARY

Our team was tasked with designing a method to improve ply collation times at Boeing Canada Winnipeg. For this process, pre-impregnated composite sheets are nested and cut with a CNC gantry system on a cloth cutting table with a length of 15.6m. The plies are then manually collated, in a specific order, and placed on a cart. The scope of this project is to develop a method to improve the cycle time of the collation step of this process. To achieve this, the design process was divided into three phases: problem definition, concept generation and selection, and final concept development.

During the problem definition phase, customer needs and target specifications were collected. The most crucial specifications included minimizing cycle time, minimizing the payback period for the initial investment, and maximizing employee safety.

For the concept generation and selection phase of the project, several manual and automated concepts were evaluated and compared against each other through a set of weighted criteria that were decided upon by the team. The best manual concept and the best automated concept were then compared against each other through these criteria, as well as time analyses. As a result of this comparison, the final design is a fully automated solution consisting of three components: a robotic rail system, a 4-axis robotic arm, and an end effector that would use suction cups to grip the plies.

For the third and final phase of this project, the main objectives were to select the equipment for the final design and to design the end effector. The 4-axis robot and the rail system were selected from external providers. The end-effector, in contrast, was designed to be built in house. Once the design and selection process were complete, the team performed a cost analysis to determine the benefits the new system would bring.

The first step in the design of the end effector consisted of selecting appropriate suction cups, and a method to provide them with the suction power. In the final design, 130 suction cups are needed for the end effector, and the Schmalz SPB1 30 ED-65 G1/8-IG cups were selected. For the end effector to grip the plies individually without gripping any other plies or scrap material, the suction cups must be individually controlled. For this purpose, the team implemented the *Schmalz Compact Terminal SCTMi* vacuum generation system in the design, which consists of compact vacuum generators that can be mounted on the end effector itself, and used to individually activate suction cups when needed.

Having selected the suction cups and vacuum system, the team proceeded with the structural design of the end effector. The final design consists of a structural frame built from T-slotted aluminum beams, and aluminum C-channels used to support the suction cups.

There is a center junction made from machined aluminum, which is where the end effector is fixed to the 4-axis robot. The suction cups are arranged in a 10x13 grid, with a total of 130 units. 130 compact vacuum ejectors are arranged in 10 blocks containing 13 each, and are mounted directly to the end effector. The outer dimensions of the end effector are 1.35x1.80mx0.20m.

The ABB IRB460, with a payload of 110kg and reach of 2.4m, was selected as the 4-axis robotic arm for the design. For the rail system, the ABB IRBT4004 rail system was selected to transport the robot. Since the robotic arm is also an ABB product, it will simplify the integration process, coding, and technical support.

The end effector, robotic arm, and rail system work together as one unit to collate plies of various shapes and sizes from the cutting table. The rail system runs parallel to the cutting table, allowing the robotic arm to reach its entire length. The plies are picked up, one-by-one, and placed on the collection table. The collection table is located on its own base on the same rail as the robotic arm, allowing the collection table to move down the length of the cutting table with the robotic arm.

To evaluate the improvements the new design offers over the current process, simulations were conducted through scripts written by the team in MATLAB for the current process and the new process. Simulations were conducted for different kit sizes, and it was determined that the cycle time improvement increased with the kit size. For the largest kit size that was examined (100 plies distributed over the entire length of the worktable), the automated process reduced collation times by 78.5% (from 54.7 to 11.8 minutes).

A cost analysis was also performed, in which it was assumed that production would stay at the current level, but operation hours per day would be reduced due to the increased production rate of the new process. The total initial cost of design is approximately 282,000 CAD. Depending on the average daily kit size, the calculated payback period for the initial investment ranges from 6 to 9 months.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

This report provides a method for improving ply collation time at Boeing Canada Winnipeg (BCW). In the following sections, our team provides a project definition, a concept generation and selection process, and a detailed design. The project definition section provides an overview of the problem statement, outlines the scope, and identifies target specifications that ensures all customer needs are met. In the concept development section, various concepts are presented, for which the evaluation and selection process is thoroughly explained. The detailed design section presents the final design, process simulations and coding, and a detailed cost analysis.

1.1 PROJECT DESCRIPTION

BCW designs and manufactures a wide variety of composite parts and assemblies for Boeing Commercial Airplanes. Some of the major products include engine strut forward fairings, engine strut aft fairings, main landing gear doors, and the engine's acoustic inner barrel for the new 737 MAX. The company has been operating in Winnipeg since 1971 and is currently one of the largest aerospace composite manufacturers in Canada.

BCW tasked our team with designing a method to reduce the cycle time of the cloth-cutting and collation process, which is a step in the manufacturing process for composite plies. The current manual process for the collation operation is repetitive and time consuming. The final design provided by our design team may be manual or automated. Our client specified that design must achieve the goal of a sub-10-year payback period for an initial and non-recurring investment of less than 2,000,000 CAD, with ideal values of 5 years and 500,000 CAD, respectively.

1.2 Scope and Assumptions

The steps involved in the cloth cutting and collation process are shown in Figure 1. The scope of this project is limited to the nesting and collating steps of this process, highlighted in red.

Figure 1. Cloth cutting process flow chart and project focusing steps.

The team was responsible for designing a custom solution or selecting a commercially available solution. The working mechanism of the design and the required materials are to be presented. If an automated design is selected, a logic tree describing the process flow is required. Any custom designed components require engineering drawings and stress analysis. Additionally, a cost analysis is necessary to determine the payback period of the initial cost.

Assumptions were made to address the lack of cost information available to the team. Through consultation with the client, the following list of assumptions was developed:

1. The labour cost is 100 CAD per hour.
2. The operating time is 24 hours a day, 7 days a week.
3. The material cost for pre-impregnated carbon-fiber fabric is approximately 10 CAD per square foot [1].

It is important to note that the values listed above do not represent the actual labour and material costs used by BCW. They are assumptions based on publicly available information and the client's recommendations.

1.3 Current Manual Process Details

The two main materials used in the fabrication of composite panels are carbon or glass fiber pre-impregnated fabric and honeycomb core. The general process for building composite panels at BCW is outlined below in TABLE I.

TABLE I GENERAL PROCESS FOR BUILDING COMPOSITE PANELS AT BOEING COMPANY WINNIPEG.

Step	Process	Description
1	CNC Cloth Cutting	Part-specific kits of pre-impregnated composite plies are created.
2	Core Fabrication	Honeycomb core is formed into part-specific shapes.
3	Layup	Composite plies and core are assembled on a layup mandrel (LM).
4	Autoclave Cure	Panels are cured in autoclaves.
5	NC (numerical control) Trim	Excess material is trimmed, and drilling operation is performed.
6	NDI (non-destructive inspection)	Parts are inspected for defects.
7	Assembly	Manual drilling operations and final product assembly.
8	Paint	Painting operation.

Each panel is composed of a unique kit of differently shaped plies of pre-impregnated composite fabric, which later are stacked up to form the panel. To create these kits, BCW uses a CNC cloth-cutter to cut the part-specific plies in large, dynamically nested sets. The CNC cloth-cutter consists of a large table, approximately 6ft by 50ft, to support the fabric, and a gantry that guides an ultrasonic knife to perform the cuts. The cut plies are then manually collated into a stack containing all necessary plies for one panel. The plies range in size from 3”x12” to 60”x80”. The process flow for CNC cloth-cutting and collation consists of the following five steps:

1. A roll of pre-impregnated composite fabric is manually rolled out onto the worktable. It is held in place by a vacuum applied through small perforations in the table.
2. The plies to be cut out for one panel are dynamically nested, prioritizing the maximum material usage to minimize waste. The order in which the plies must be collated is not considered by the nesting algorithm.
3. The gantry uses its CNC printer to print information on each of the ply shapes (which have not yet been cut). The information printed includes a ply identification number and a collation order number. The collation order numbers are sequential and represent the order in which the ply cut-outs are to be manually picked up. The pick-up order is determined by the order in which the plies will be placed during the lay-up process.
4. The ultrasonic knife cuts the sheet of composite fabric according to the nest generated in Step 2.
5. The technician manually collects each ply, one by one, in the order dictated by the printouts from the CNC machine. The plies are stacked on a cart which is later used during the lay-up procedure, step 3 from TABLE I

Step 5 from the list above is the focus of this project. Additional information on the CNC cloth cutter and risk of prepreg damage is available in Appendix A.

1.4 Customer Needs and Target Specifications

During the team's first meeting with the client, a preliminary set of project requirements and expectations were determined. The information was then refined and organized to create a final list of nine customer needs, shown in TABLE II. Each item is ranked from 1 to 3 on its relative importance, which was defined by the team, with 3 being the most important and 1 being the least.

TABLE II: CUSTOMER NEEDS AND THEIR INDIVIDUAL IMPORTANCE

Item #	Customer Needs	Importance
1	The design will reduce the current cutting and collation operation cycle time	3
2	The design will minimize material waste	3
3	The design will be safe for technicians	3
4	The design will be ergonomic for technicians	2
5	The design will be intuitive	1
6	The design will not damage pre pregs	3
7	The design will be economical	3
8	The design will be quiet	1
9	The design can be easily integrated with the current equipment	2

The needs that were ranked as less crucial can be worked around, if not met. The needs ranked more crucial have more serious consequences, if not met.

To ensure the final design meets the customer's needs, the team further analyzed the list of needs to develop a set of metrics. Each metric directly addressed one or more of the nine customer needs. Each metric was ranked for its importance, assigned a unit, a marginal value, and an ideal value. The marginal and ideal values were determined by consulting our client.

TABLE III shows the details of each metric and which customer need they are addressing.

TABLE III: TARGET SPECIFICATIONS AND WHICH CUSTOMER NEED THEY ARE ADDRESSING

#	Metric #	1	2	3	4	5	6	7	8	9	10	11	12	13	
#	**Need**	Collation cycle time for small kit (3 m length)	Collation cycle time for large kit (15.2 m length)	Material utilization	Risk of injury to technicians in immediate vicinity	Repetitiveness of tasks	Comfort of design for technicians	Intuitiveness	Risk of damage to prepregs	Initial cost	Payback period	Operating noise level at 3m distance	Ease of installation	Manufacturability	**Importance**
1	Design will reduce the current cutting and collation cycle time	•	•												3
2	Design will minimize material waste			•											3
3	Design will be safe for technicians				•	•									3
4	Design will be ergonomic for technicians				•	•	•								2
5	Design will be intuitive							•							1
6	Design will not damage pre pregs								•						3
7	Design will be economical	•	•	•					•	•	•			•	3
8	Design will be quiet											•			1
9	Design can be easily integrated with the current equipment												•		2
	Importance	3	3	3	3	3	2	1	3	2	3	1	2	2	
	Units	min	min	%	subj	subj	subj	subj	subj	1M CAD	Years	dB	subj	subj	
	Marginal Value	5-10	60	75-85	-	-	-	-	-	<2	<10	<100**	-	-	
	Ideal Value	Min	Min	Max	Min	Min	Max	Max	Min	0.5	5	Min	Max	Max	

** *This value is based on the acceptable 8-hour exposure value of 80 dB. It is assumed that the technician has access to ear protection that lowers the sound level by 20 dB* [2].

The team used these target specifications to ensure that all customer needs were met. The team aimed to either minimize or maximize subjective metrics.

2 Concept Generation and Selection

As both manual and automated solutions were acceptable, the team brainstormed a variety of concepts for both situations. During the brainstorming process, the team realized that it would be difficult to directly compare all concepts against each other.

To deal with this issue, the concept evaluation was broken into a series of smaller component-specific evaluations. First, the concepts were broken into two categories, one for manual concepts, and the other for automated concepts. The manual concepts and automated concepts were evaluated individually, then the winners from each category were evaluated against each other to determine the final concept.

The automated concepts were further broken down into three independent components. Each component had a list of concepts generated and evaluated. The winning concepts from each of the three components came together to form the final automated design. Figure 2 shows a logic tree for the concept evaluation.

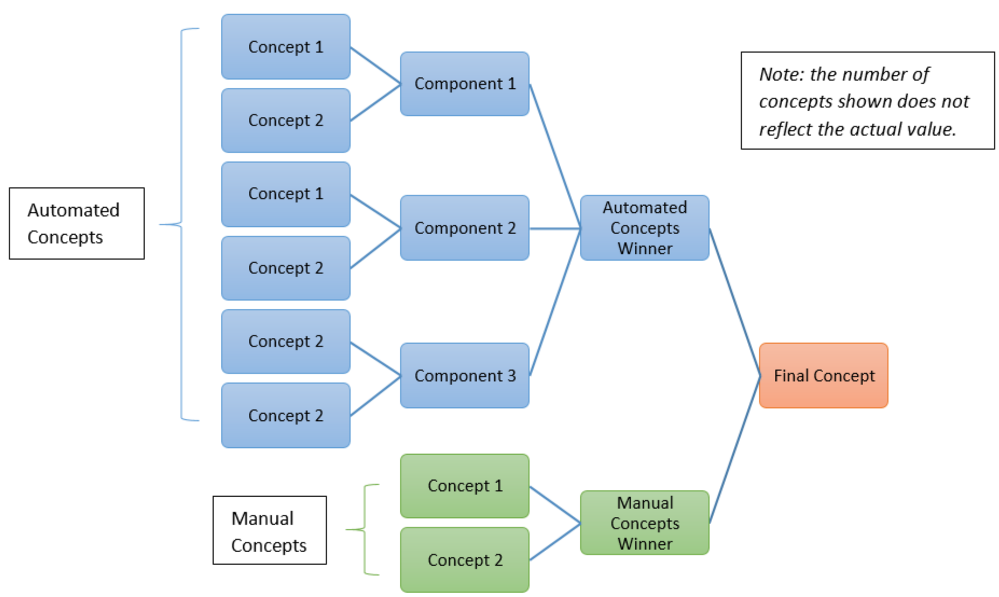


Figure 2. Logic tree showing the final concept selection process.

The criteria used for assessing concepts were derived from our customers needs and target specifications. A weighting matrix was used to compare each criterion against the others and determine the relative weight of each criterion. A more detailed overview of the criteria weighting can be found in Appendix B. The following is the complete list of weighted criteria that was used to evaluate each concept:

- Cycle time for small kit (3m length) [0.090]
- Cycle time for large kit (15.2m length) [0.103]
- Material utilization [0.077]
- Risk of injury to technicians [0.154]
- Repetitiveness of tasks [0.026]
- Comfort of design for technicians [0.038]
- Intuitiveness [0.013]
- Risk of damage to prepregs [0.128]
- Initial cost [0.064]
- Payback period [0.115]
- Operating noise level at 3m distance [0.000]
- Ease of installation [0.051]
- Manufacturability [0.141]

The weight listed to the right of each criterion represent the relative importance relative to the rest of the criteria. These weights were considered when evaluating concepts.

The risk of injury to technicians, risk of damage to prepregs, and manufacturability have the highest weight, and are therefore considered the most important criteria. The payback period and cycle times, for large and small kits, are also heavily weighted.

From the brainstorming process, the two most feasible manual concepts were selected for further evaluation. The concepts that were selected were:

- Focus light/monitor: uses a laser pointing system or monitor to visually indicate the next ply to be collected.
- Group nesting: reduces the average time spent searching for plies by nesting plies in smaller groups containing plies adjacent in the picking order.

The manual concepts were evaluated using the weighted criteria, and the focus light/ monitor concept was chosen as the best design. It significantly reduced the cycle time of the collation process by reducing the time spent looking for the next ply to pick up.

The automated concepts were separated into three independently functioning components: the end effector, the arm, and the mobility system.

For the end effector gripping mechanism, the following commercially available products were selected as concepts to be evaluated:

- Adhesive grippers
- Needle grippers
- Suction cups (specifically designed to grip composite materials)

For the arm, the following concepts were selected to be evaluated:

- ABB IRB 2600: 6-axis robotic arm
- ABB IRB 260: 4-axis robotic arm
- Custom made, 3-axis robotic arm
- Gantry system

The team consider ABB robotic arms due to their current implementation at BCW. Choosing ABB robotic systems would greatly reduce required training and testing, as BCW employees are already familiar with the robotic software and functions.

For the mobility system, the following concepts were selected to be evaluated:

- Existing cloth cutting gantry

- Separate gantry system
- Rollon 7th Axis: independent rail system
- Series of static arm mounting points

For each of the three automation components, the concepts were evaluated individually with the weighted criteria. After the best automated design was selected, it was then compared to the best manual concept using the same weighted criteria. It was determined the automated concept was superior, largely due to its excellent employee safety and cycle time improvements. Further details on the selection process are available in Appendix B.

The preliminary automated design concept consisted of a Rollon 7th Axis rail system, IRB 260 4-axis robotic arm, and an end effector that used a composite-specific suction cup gripping mechanism.

However, after further analysis and optimization, all three of these components were replaced with different products. The IRB260's rated payload of 30kg was determined to be too low, and was replaced by a similar robotic arm, the IRB460, with a payload of 110kg. After obtaining quotations for different rail systems, the initially selected Rollon 7th Axis was replaced with the ABB IRBT 4004 rail system due to its lower cost and easier integration with the ABB robotic arm. Finally, the composite-specific suction cups were replaced with a less expensive suction cup designed for gripping smooth materials. After contacting the suction cup manufacturer, Schmalz, we determined that the composite-specific cup was designed to handle raw composite material. Raw composite material is porous and requires a large amount of airflow to grip the fabric, which requires a custom designed cup to avoid damage. However, the composites that will be gripped by our design are covered in a plastic backing sheet, which will allow a more general-purpose cup to be used. The details of each component of the automated design are discussed in the following sections.

3 END EFFECTOR DESIGN

In the concept development section of this report, suction cups were determined to be the best method for gripping the prepregs. However, the design of the end effector including the layout of cups and function were not determined through concept development.

The end effector must be capable of picking up a wide variety of ply shapes and sizes. The ply sizes range from 0.07x0.30 m to 1.5x2 m. The team considered the following end effector styles to be used as a final design:

1) **Static End Effector**: Uses a grid pattern of suction cups. The grid must be large enough to pick up the largest plies and have a high enough resolution to pick up the smallest plies. To avoid picking up the excess material left behind during the cutting operation, or adjacent plies, the vacuum to each suction cup must be controlled independently to allow only the cups located directly over the ply to activate.
2) **Dynamic End Effector**: Uses a small number of suction cups attached to hinged beams/sliders. This end effector would have the ability to relocate the suction cups to preprogrammed locations unique to each ply.

The static end effector was determined to be the superior design. The dynamic end effector would be more difficult to program due to its multiple moving components. It would also likely be less precise than the static end effector due to its multiple degrees of freedom that each add error.

In the following subsections, the pneumatic components and the end effector design are presented.

3.1 VACUUM COMPONENTS

This section discusses the team's methodology and final selection for the type of suction cups and vacuum generators.

3.1.1 SUCTION CUPS

Our team contacted a representative of Schmalz, a company that specializes in pneumatic components for industrial automation. After discussing various options, we decided that a suction cup designed for handling packaging, rather than the expensive alternatives designed for handling raw composites, may be suitable for gripping the plastic backing sheet on the composite material. The suction cup chosen was the **Schmalz *SPB1 30 ED-65 G1/8-IG***, which has a 30cm diameter and a G1/8 threaded connection. This cup also has bellows that allow it to expand and contract, which would account for slight vertical misalignment when picking up the composite material [3]. The selected cup is shown in Figure 3.

[redacted]

Figure 3. Schmalz SPB1 30 ED-65 G1/8-IG [3].

The representative from Schmalz did not believe that the cups would cause any damage to the composite material. However, our team recommends that testing is performed for a variety of suction cups to ensure part damage is avoided.

For the static end effector design, the suction cups need to be mounted in a grid pattern on the end effector. The factors our team considered when selecting the dimensions of the grid pattern are shown below:

- The length and width of the grid must be large enough to cover the largest ply size of 1.5x2m.
- The centre-to-centre spacing of the grid must be small enough to allow an acceptable amount of ply overhang around the edges of the ply. Our team used our best judgment to set an acceptable amount of ply overhang of less than 10 cm. With a 10 cm overhang, our team believes that the ply would not bend enough to cause material damage or fold over itself.
- The number of suction cups must be minimized to reduce cost and complexity.

To meet the criteria above, our team selected a 10x13 grid with 15cm centre-to-centre spacing, requiring a total of 130 suction cups. Therefore, the grid has dimensions of 1.35x1.80m which allow for a maximum of 10 cm ply overhang when picking up the largest ply. For smaller plies that are completely contained within the grid pattern, the maximum possible overhang is 7.5cm (half of the 15cm grid separation).

As the acceptable overhang values listed above are estimates, our team recommends performing physical tests with different cup spacing to determine the optimal configuration. If the overhang is too large, it may cause the ply to fold over itself when being dropped off onto the collection table.

3.1.2 Vacuum Generators

The *Schmalz Compact Terminal SCTMi* vacuum generation system, shown in Figure 4, was selected after consultation with a representative from Schmalz.

[redacted]

Figure 4. Schmalz Compact Terminal SCTMi [4].

This unit contains a series of compact vacuum ejector that can be individually controlled with a single 5-pin IO-Link cable. The important features of this system are listed below [4]:

- Maximum 16 ejectors per block (requires only one control cable per block).
- One block requires a single compressed air source.
- Each ejector outputs to a G1/8 F connection.
- Suction capacity up to 67L/min. The magnitude can be controlled.
- Once the desired vacuum level is reached, the compressed air is shut off and the vacuum is held with no additional required power. The vacuum level is monitored, and the suction is switched back on if the vacuum level drops.
- The ejectors can quickly switch from vacuum to compressed air for efficient part drop-off.
- Each ejector has an individual mass of 0.195kg.

The end effector will require 130 vacuum ejectors to individually control the 130 suction cups. The ejectors will be arranged in 10 blocks of 13 ejectors, each block having a mass of approximately 2.1kg (10x0.195kg + estimated mass of additional mounting hardware).

3.2 STRUCTURAL DESIGN OF END EFFECTOR

Our team began by designing the general layout of the end effector and how it will support the grid pattern of suction cups and the compact vacuum terminals. The design consists of several aluminum C-channel beams to support each row of suction cups. These C-channel beams, along with the compact vacuum ejectors, will be supported by high-strength aluminum T-slotted framing beams. The preliminary layout of the end effector is shown in Figure 5, where the thick blue lines and thin orange lines represent the structural support member and suction cup holding members, respectively.

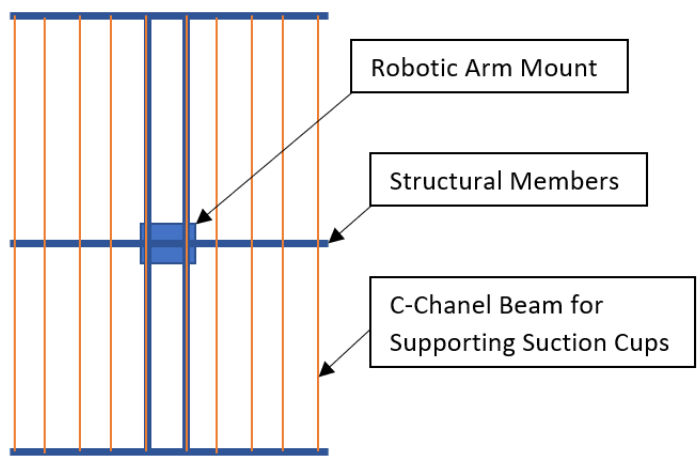


Figure 5. Preliminary end effector design, bottom view.

Analytical calculations were performed to determine the required dimensions of each beam on the end effector. During this analysis, we aimed to minimize the weight and deflection of the structure, while ensuring the structure would not fail due to yielding. Details on the analytical approach are available in Appendix C.

For the structural support members, shown in blue in Figure 5, extruded aluminum T-slot tubing was selected. T-slotted tubing, shown in Figure 6, is a modular design that has a wide variety of attachments and hardware that can be fastened to it with or without drilling. We decided that this would be ideal for our design as it is widely used at BCW, is inexpensive, lightweight, and would allow for easy addition of new components to the end effector if necessary.

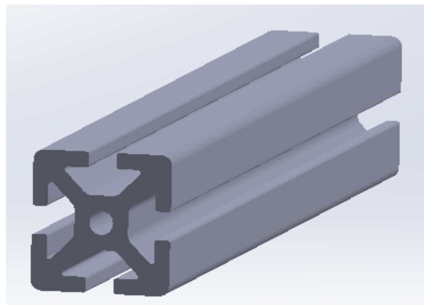


Figure 6. T-slot tubing (40x40mm).

Based on our analytical calculations, available in Appendix C, a commercially available C-Channel beam was selected. The beam has a height of 2”, width of 1”, and wall thickness of 1/8”. With further numerical analysis using SOLIDWORKS Simulation, cut-outs were added to the C-Channels to reduce weight. The final C-Channel design is shown in Figure 7.

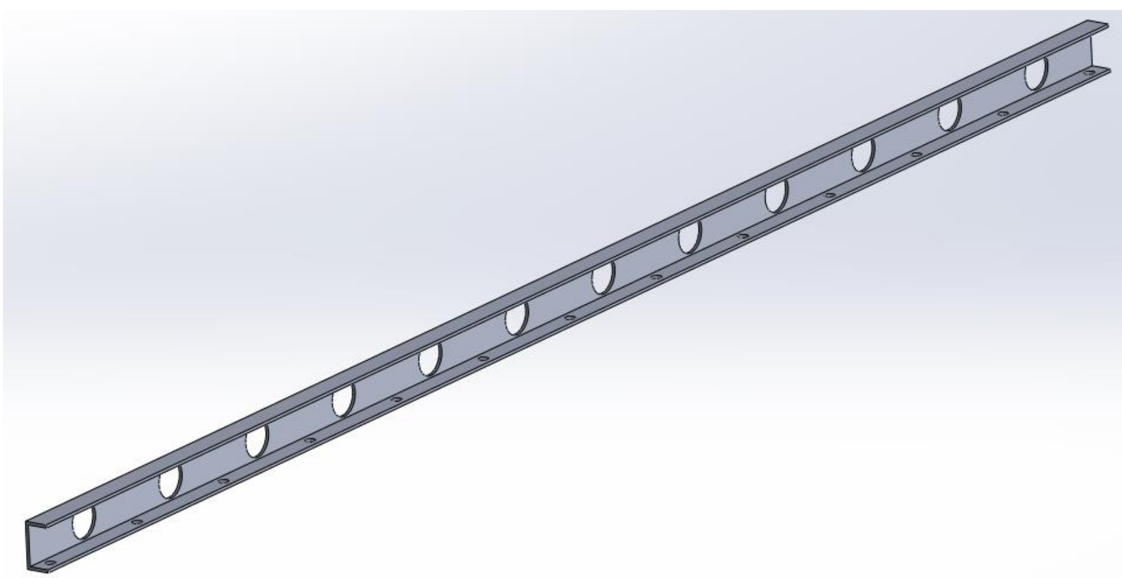


Figure 7. C-Channel for supporting suction cups.

The final design was modeled in SOLIDWORKS and is shown in Figure 8. A finite element analysis, available in Appendix C, was performed on the structure to ensure it would not deflect too much or experience yielding. The results of the numerical analysis showed that the structure deflects by 0.9 mm, and is subjected to 15.29 MPa of bending stress.

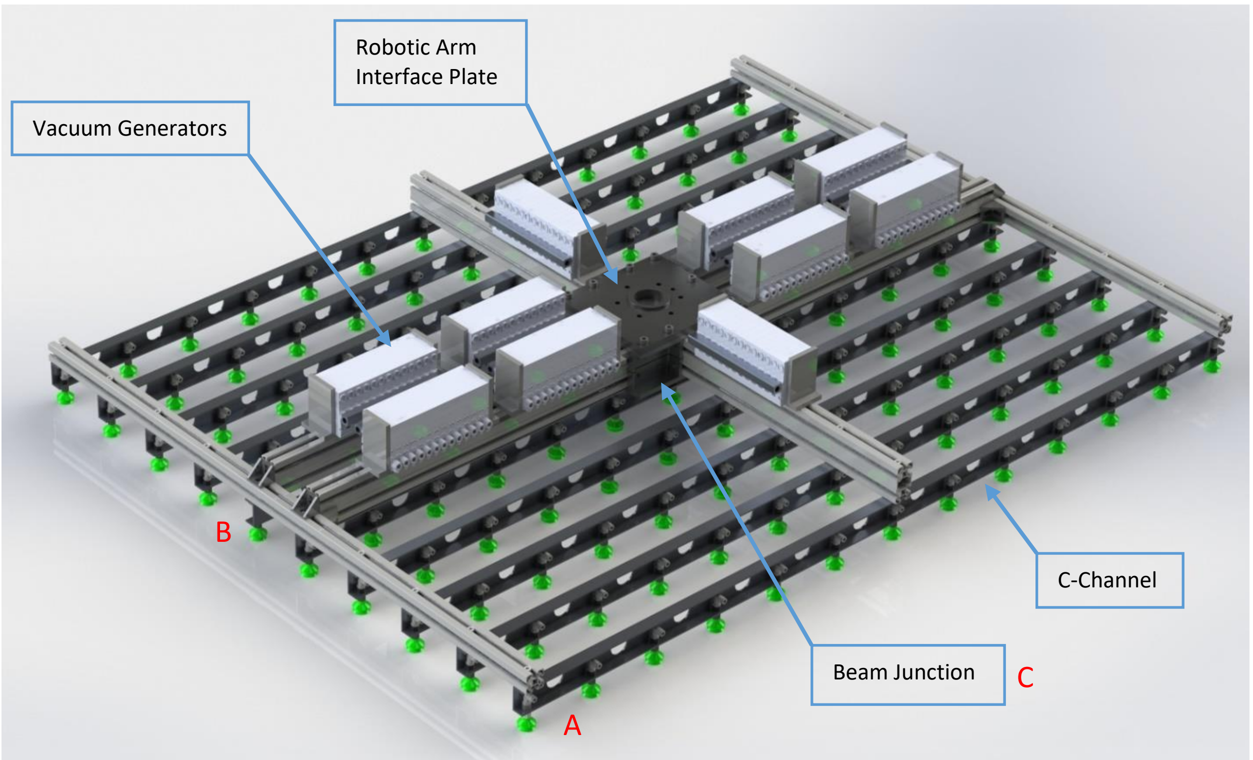


Figure 8. Final end effector design render.

The suction cups are mounted to the end effector by fastening to a G1/8 M to F adapter, which is inserted through a clearance hole in the bottom of the C-Channel, as shown in Figure 9. A 90^{o} G1/8 push connector for 6mm plastic tubing is fastened to the other end of the G1/8 M to F adapter. Additionally, Figure 9 shows that the C-channels are through-bolted to the 40x40mm T-Slotted framing.

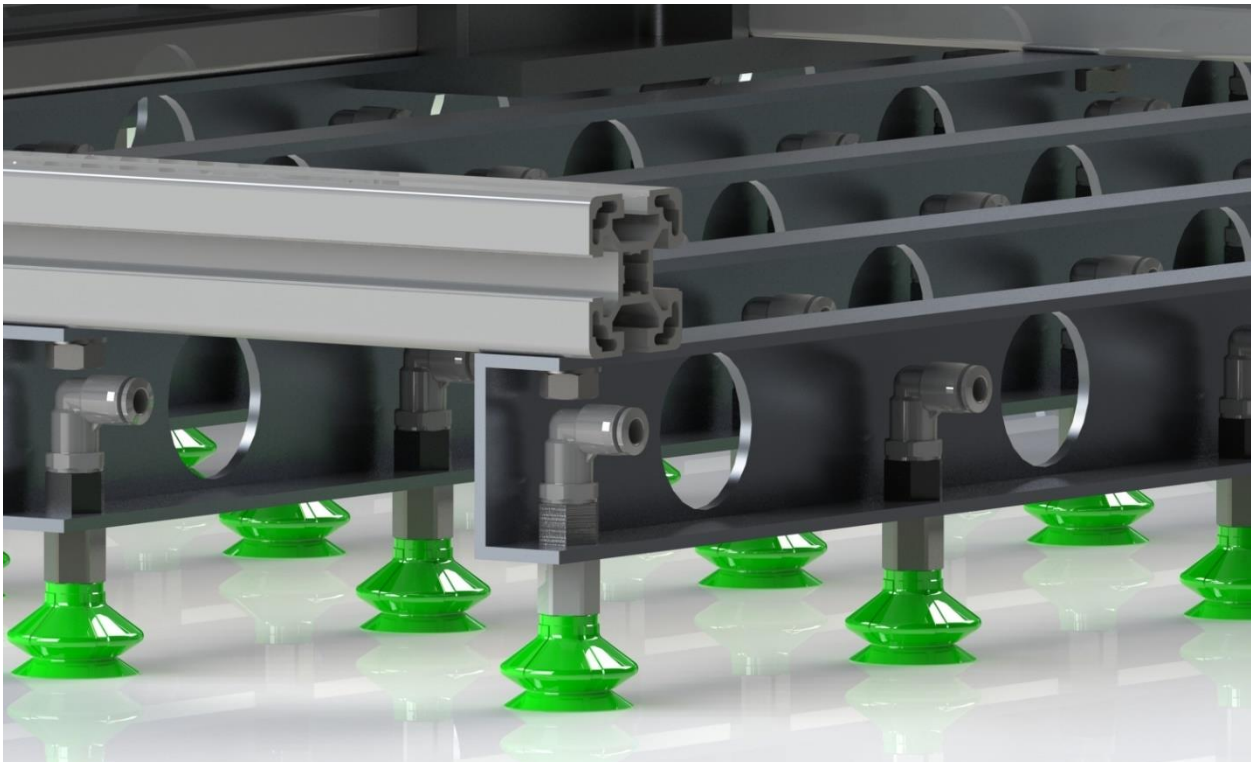


Figure 9. Final end effector design, suction cup assembly (location **A** from Figure 8).

The members at location **B** in Figure 8 are fastened together using standard corner braces, which are designed to be used with the 40mm T-Slotted framing. This junction is shown in Figure 10.

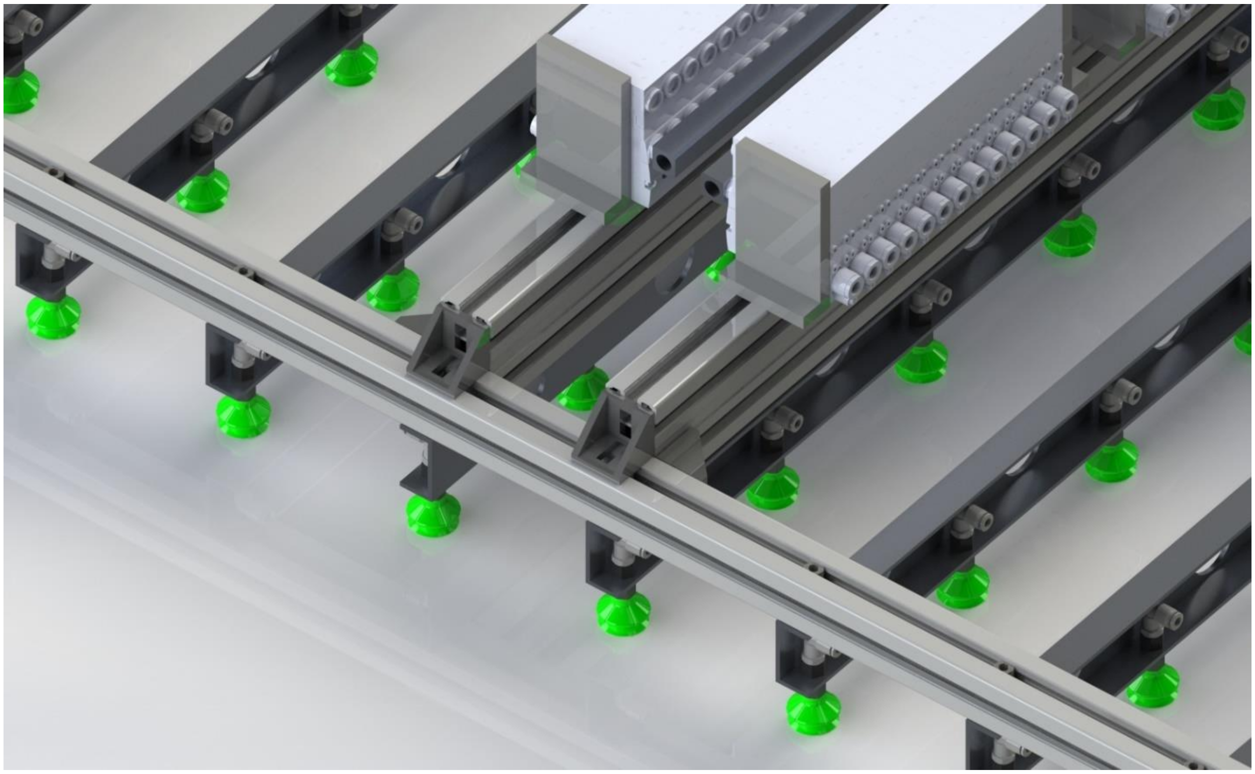


Figure 10. Location **B** from Figure 8.

At the center of the end effector (location **C** in Figure 8), the 6 structural T-Slotted beams are joined with a two-piece machined junction, shown in Figure 11. The junction grips the beams through both vertical and horizontal clamping force that are created with a series of bolts. Both upper and lower sections of the junction will be machined from aluminum 6061-T6.

The Interface Plate, labeled below, attaches directly to the robotic arm, allowing the end effector to be removed if necessary. The plate features a hole pattern that matches the bolt pattern at the end of the robotic arm. The plate will be machined from aluminum 6061-T6.

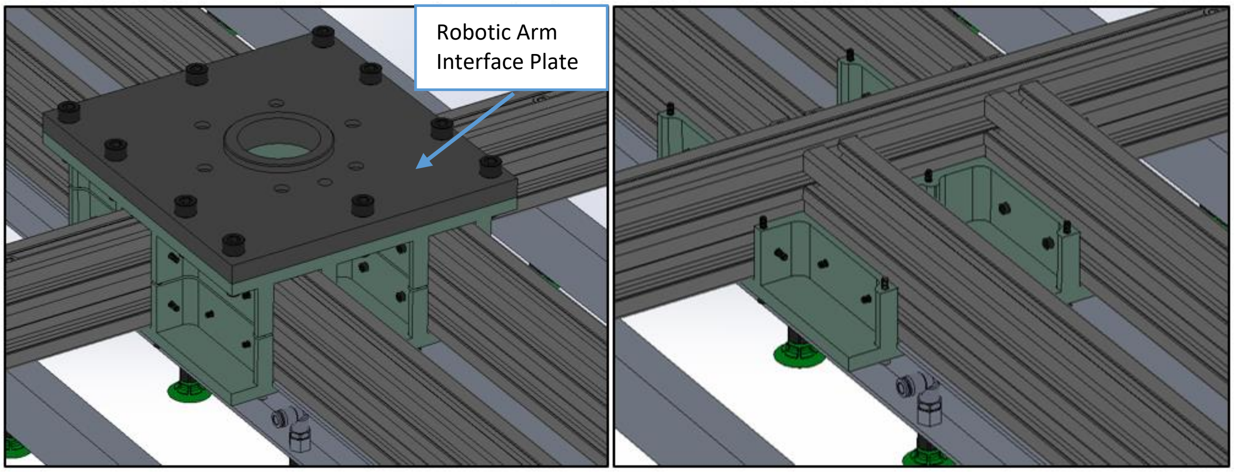


Figure 11. Centre junction of end effector (left). Centre junction partially hidden (right).

The compact vacuum generator terminals will be mounted directly onto the T-Slotted structural beams, as shown in Figure 8. From each of the ejectors, 6mm (outer diameter) plastic tubing will be run to each of the 130 suction cups.

Engineering drawings of the end effector components are available in Appendix G.

3.3 End Effector Summary

The final end effector design, shown in Figure 8, has the following characteristics:

- Structural frame built from T-Slotted aluminum beams
- Aluminum C-Channels used to support suction cups
- Center junction made from machined aluminum
- 10x13 grid of Schmalz suction cups, with 15cm centre-to-centre spacing
- 10 blocks of 13 compact vacuum ejectors from Schmalz
- Outer dimensions are 1.35x1.80mx0.20m
- Total mass = 52kg

The end effector will be fastened to the end of the robotic arm through its interface plate, which is located at the centre of the end effector.

4 Robotic Equipment

This section presents the final selections that were made for the robotic arm and rail systems.

4.1 Robotic Arm

The ABB IRB260, with a payload of 30kg, was selected for the preliminary design during the initial concept development phase. During the development of the end effector, it was determined that the mass of the end effector would be much greater than 30kg. The ABB IRB460, with a payload of 110kg, was selected to replace the IRB260 for our design [5]. The IRB460 is shown in Figure 12.

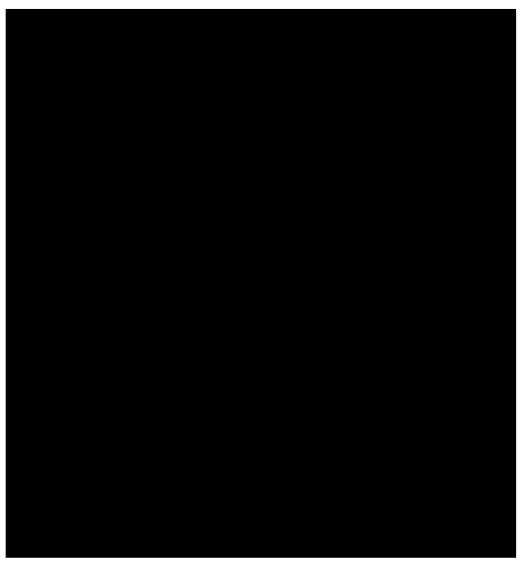


Figure 12. ABB IRB460, 4-axis robotic arm [5].

This robotic arm has a reach of 2.4m, which is an increase of 0.9m compared to the IRB260.

4.2 Robotic Rail

The Rollon 7th Axis Rail System was selected for the preliminary design during the initial concept development phase. However, after speaking directly with a representative from ABB, our team decided to replace the Rollon rail with the ABB IRBT4004 rail system, shown in Figure 13.

Figure 13. ABB IRBT4004, robotic rail system [6].

There are two reasons why the ABB IRBT4004 was selected. Firstly, since the robotic arm is also an ABB product, it will make the integration process, coding, and technical support much simpler. Secondly, we received quotations for an 18m length of both the Rollon and ABB rail systems. The Rollon rail was quoted at more than double the cost of the ABB rail.

5 Final Design

This section presents the overall layout of the final design, and several typical operation scenarios.

5.1 Layout

The IRBT4004 rail system lies on the floor, parallel to the cutting table, and with one meter between them. The IRB460 robotic arm and the ply collection table are mounted on separate vehicles on the rail. The height of the ply collection table and cutting table are both 36 inches from the floor. The layout of the design is shown in Figure 14 and Figure 15.

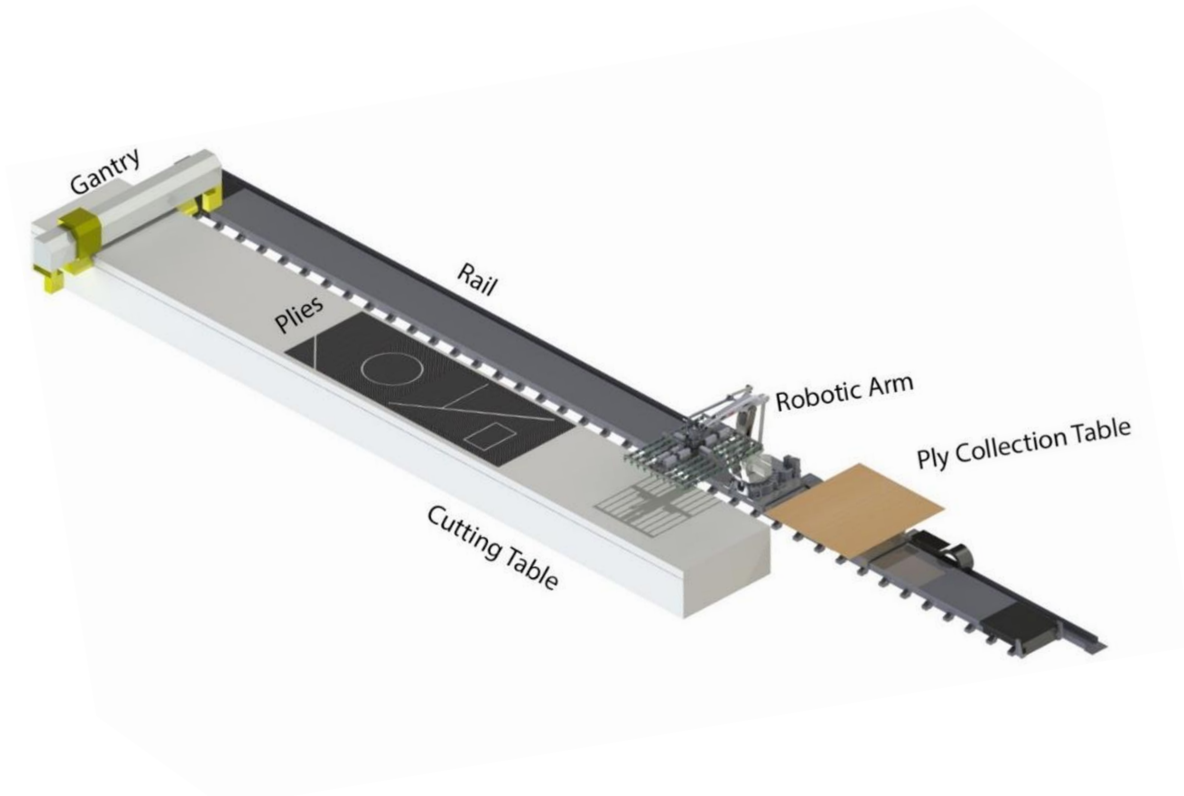


Figure 14. Overview of the layout of the final design.

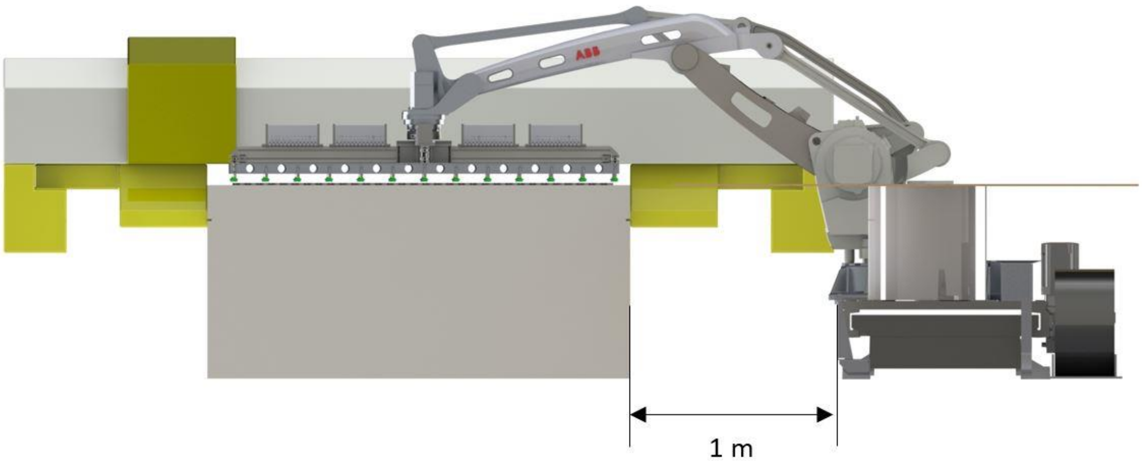


Figure 15. Related location between the rail and the cutting table.

An additional length of rail is required to allow the robotic arm to move off to the side while the cloth cutting gantry operates. With a 20m length of rail, there is an additional 5m length of rail past the end of the cloth cutting table, as shown in Figure 16.

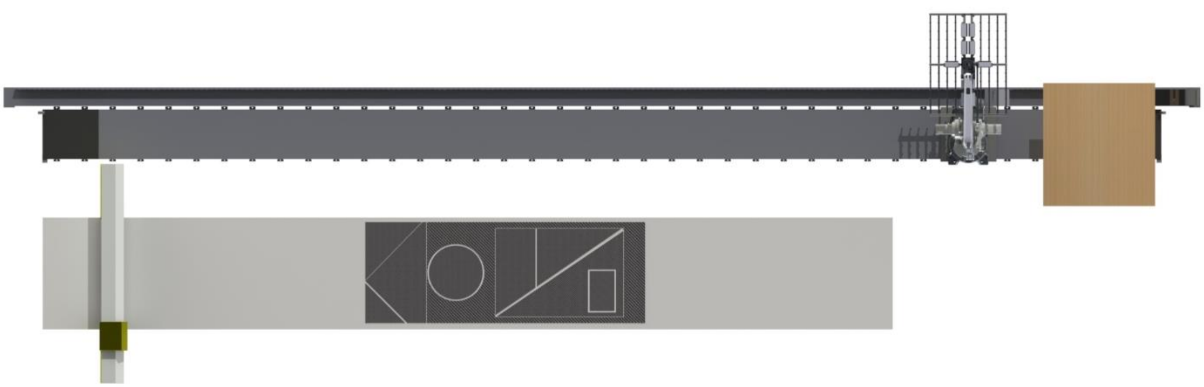


Figure 16. The location of the robotic arm when CNC cutting operation is in progress.

5.2 OPERATION

Once the ply collation operation starts, the rail system brings the robotic arm to the location of the next ply to be collected. The robotic arm will then position the end effector so that the ply is located within the grid pattern of suction cups, as shown in Figure 17 and Figure 18. The suction cup selection algorithm will then determine which suction cups are going to be activated based on the shape of the ply. The appropriate vacuum generators will be activated, allowing the ply to be gripped by the suction cups. Once the ply is gripped by the end effector, the arm will then lift the ply vertically off the table and rotate 90 degrees counter-clockwise to reach the ply collection table. The suction cups will then release the ply onto the collection table, as shown in Figure 19. The collection table is located on a rail platform, allowing it to maintain a constant distance from the robotic arm. The close proximity of the collection table helps reduce the cycle time of the process by reducing the required rail movements.

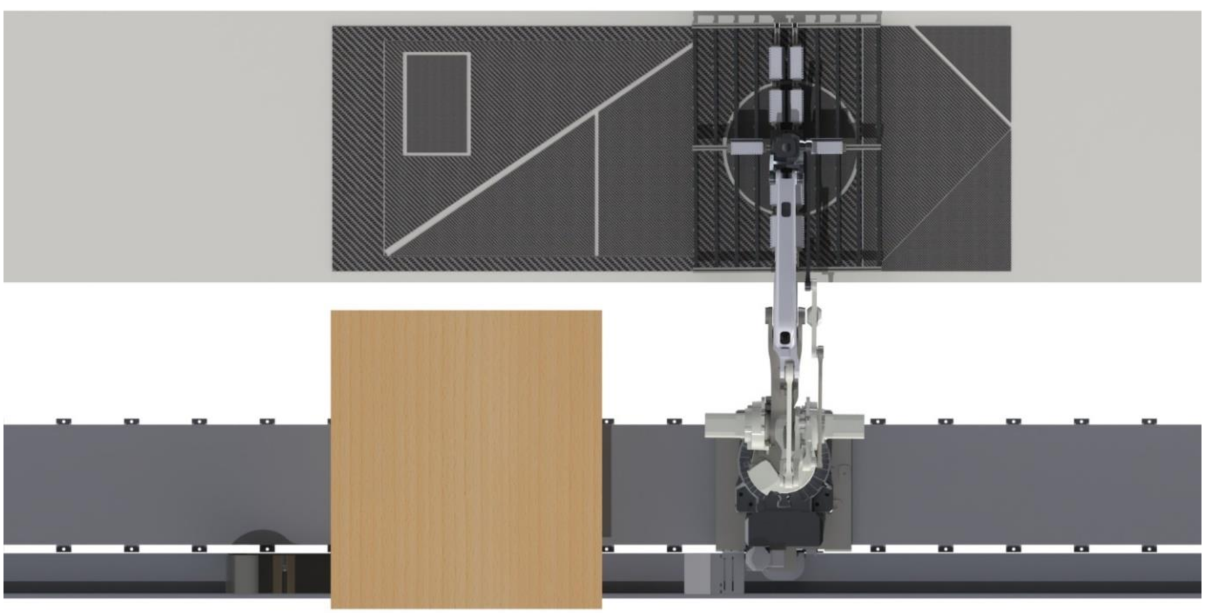


Figure 17. Robotic arm picking a ply from the cutting table (top view).

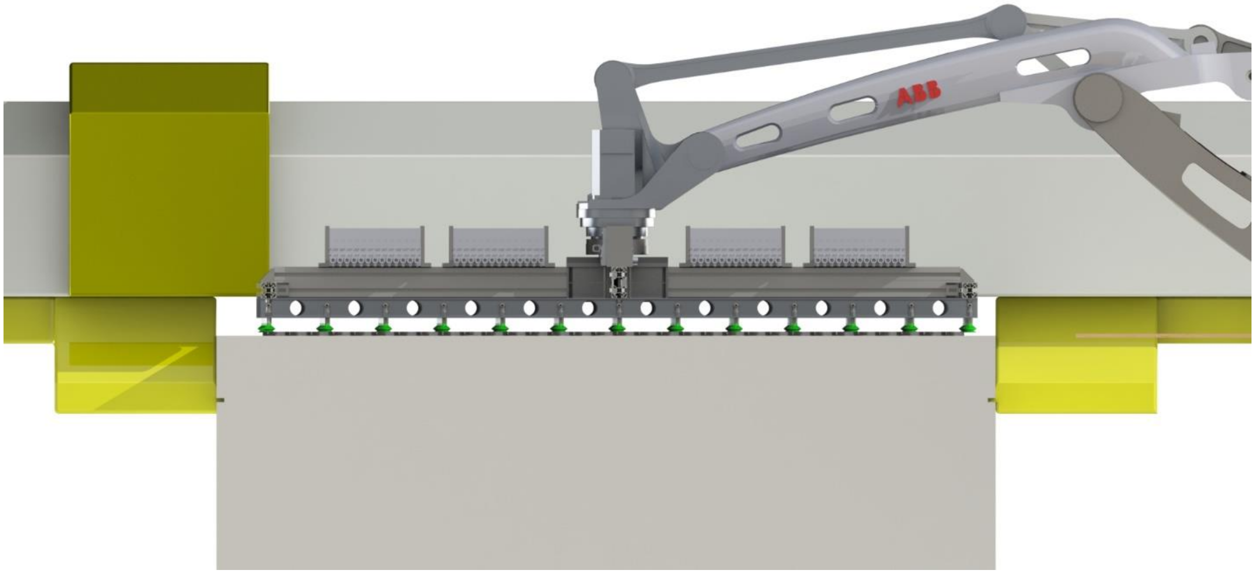


Figure 18. Robotic arm picking a ply from the cutting table (side view).

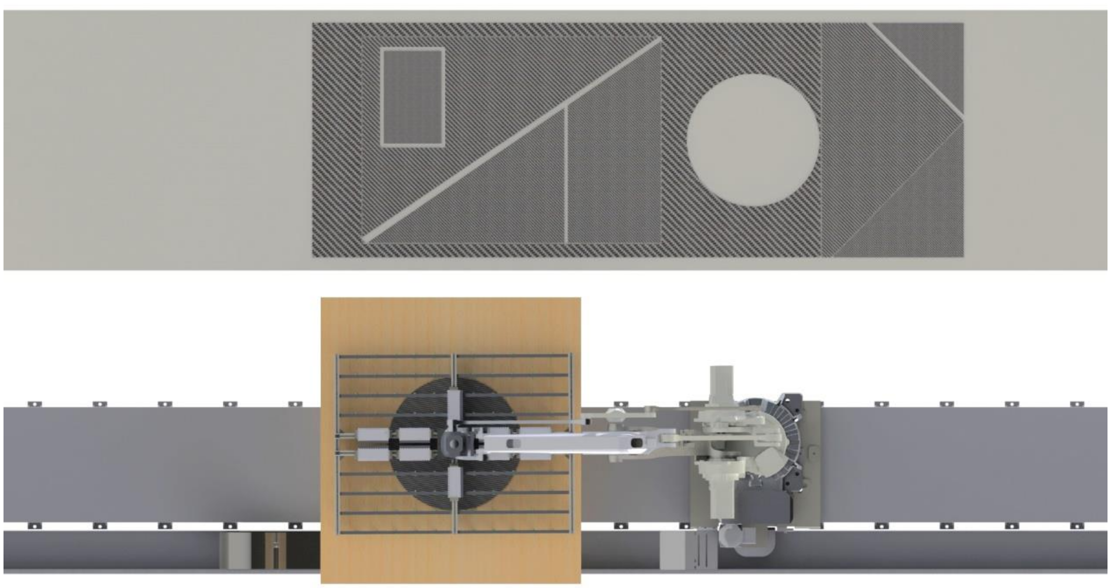


Figure 19. Robotic arm placing a ply on the collation table.

6 SIMULATIONS AND CODING

Several MATLAB scripts and functions were written to facilitate the evaluation of both the current ply collation process and the new automated process. These scripts simulate an entire collation cycle for a given kit size, and output the total collation time.

Additional code was also written to show that it is possible generate the robot movements and dictate which suction cups must be activated with an input of only the shape and position of the ply to be collected.

6.1 CURRENT MANUAL PROCESS CYCLE TIME

In the absence of current time studies, a script was created to simulate a collation job using the current process. The code has been summarised in the flowchart shown in Figure 20, and the entirety of the script can be found in Appendix D. The input for this code consists only of the number of plies in the kit. The code generates an array representation of the kit. An example of a generated kit of 100 plies is shown in Figure 21.

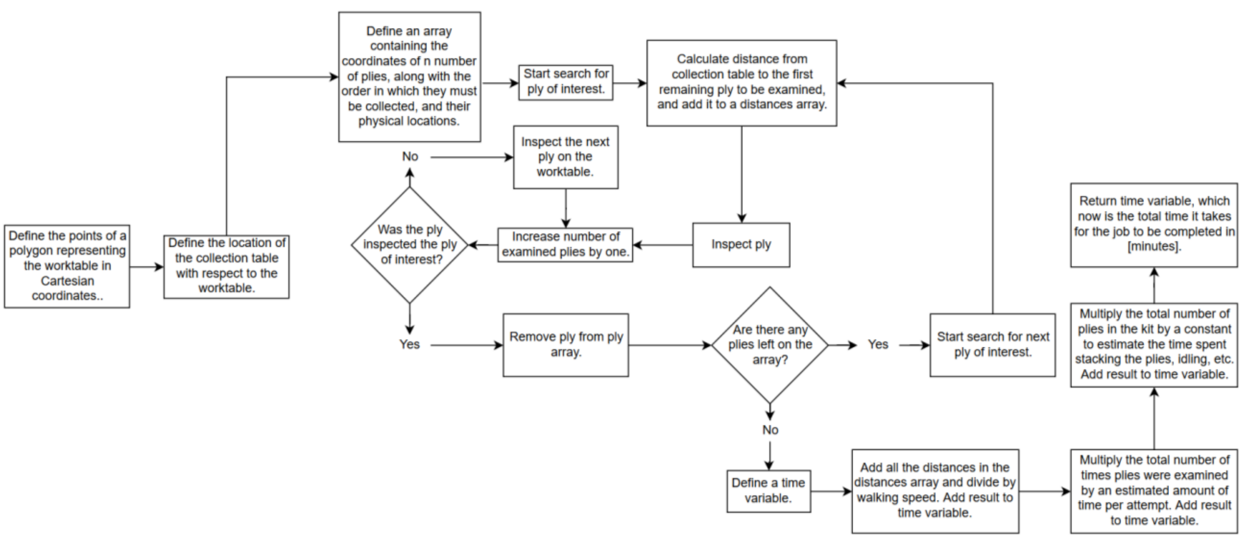


Figure 20. Flowchart for the current manual process simulation script.

The generated kit includes the coordinates for all nested plies, the order in which they must be collected, and their positions relative to the worktable. In the figure below, each square section represents a ply.

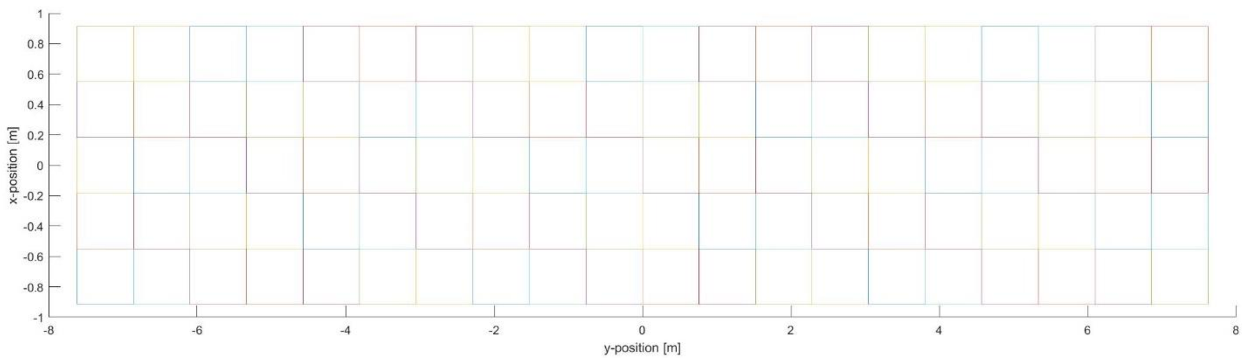


Figure 21. Example of a kit generated for the current manual process simulation.

The layout of the worktable and the collection cart was assumed to be configured as illustrated in Figure 22.

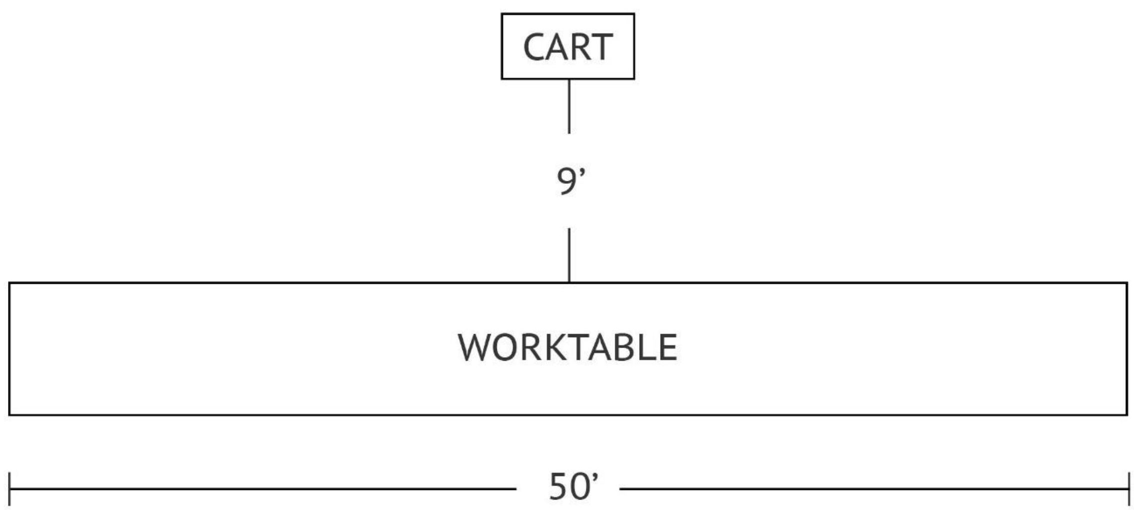


Figure 22. Worktable and cart layout.

Having defined the kit and the layout in which the simulation will take place, the script continues by starting to look for the next required ply by checking each of the remaining plies. The initial distance travelled from the cart to the worktable is recorded, as is the number of plies that are checked before arriving to the correct ply. Once the correct ply is found, the distance from its position to the cart is added to the total distance travelled, and the ply is removed from the kit array. This process is repeated until the last ply is found and collected. To calculate the total time spent in the collation process, the total distance travelled was divided by a walking speed estimated at 1.5 m/s. Added to this time is the product of the total number of times a ply was checked and the time spent checking each ply, which was determined to be approximately 0.97 s/attempt in the concept evaluation available in Appendix B.3. Finally, the total number of plies is multiplied by a coefficient of 4.5 s/part to account for any time spent stacking the plies, idling, or any other activity. This coefficient was also found during the concept evaluation phase and is available in Appendix B. The resulting time was taken as the cycle time for the current process.

The script was repeated 100,000 times for five different kit sizes to obtain an average and standard deviation for each of the cases. The results are shown in TABLE IV. Since the nesting order is randomized for each iteration, the results are best represented by an average time and standard deviation.

TABLE IV: SIMULATED COLLATION TIME AVERAGES FOR THE CURRENT MANUAL PROCESS

Number of plies	20	40	60	80	100
Average collation time [minutes]	4.470	12.215	23.102	37.372	54.701
Collation time standard deviation [minutes]	0.232	0.661	1.228	1.843	2.817

In addition to the table above, a plot of the simulated total collation time as a function of the number of plies in the kit has been generated and is shown in Figure 23. The collation time exponentially increases with the number of plies, because more plies need to be checked before the necessary ply is found.

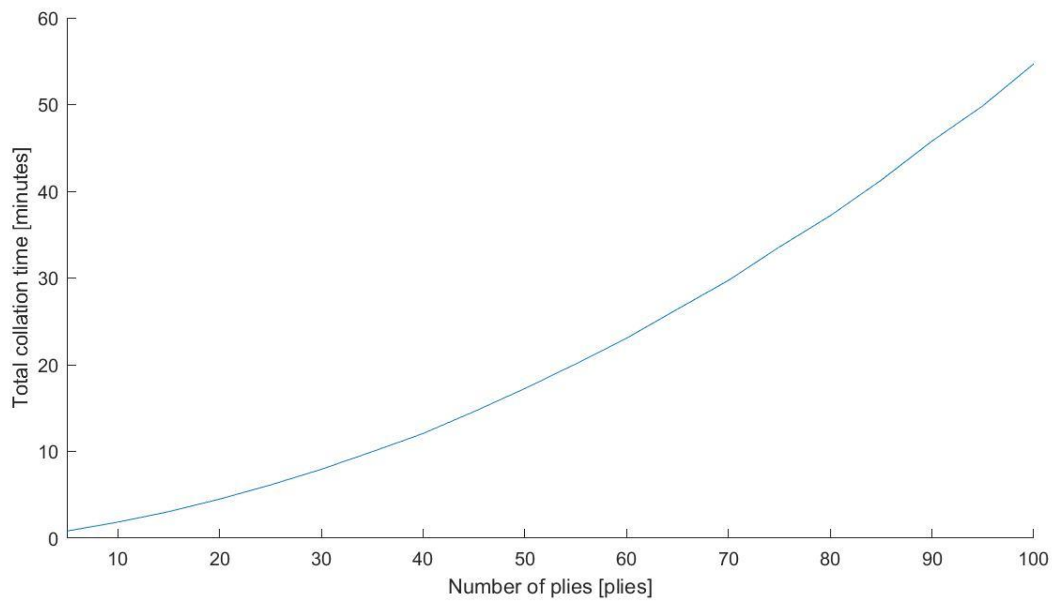


Figure 23. Total collation time in the current process as a function of kit size.

This simulation is an idealized version of the process, and as such further refinement would increase its accuracy. However, these results are consistent with the rough collation times the client has provided the team, so they will be taken to be reasonable estimates of the current process.

6.2 Automated Process Cycle Time

A script was written to simulate the collation process for the automated design presented in this report. The code has been summarised in a flowchart, presented in Figure 24. The full script can be found in Appendix D. The simulation starts by generating the layout shown in Figure 22 and creating an array representation of a kit similar to the one shown in Figure 21. Then, the travel time between the initial position of the end effector and the desired ply is calculated, along with the time it will take to move the ply from the worktable to the collection table. These two tasks can be done concurrently, so only the task that takes longest is counted towards the total collation time. The end effector's position is then changed to the location of the collected ply, from which it will have to move to the next ply until all the plies have been collected. The amount of time spent gripping and releasing the plies (roughly estimated at 2 s/ply) and the amount of time lowering and elevating the end effector (estimated at 0.5 s per each movement, based on robotic arm lifting axis angular velocity of 110^{o}/s [5]) are added to the total time. The resulting time was then taken as the cycle time for the automated process.

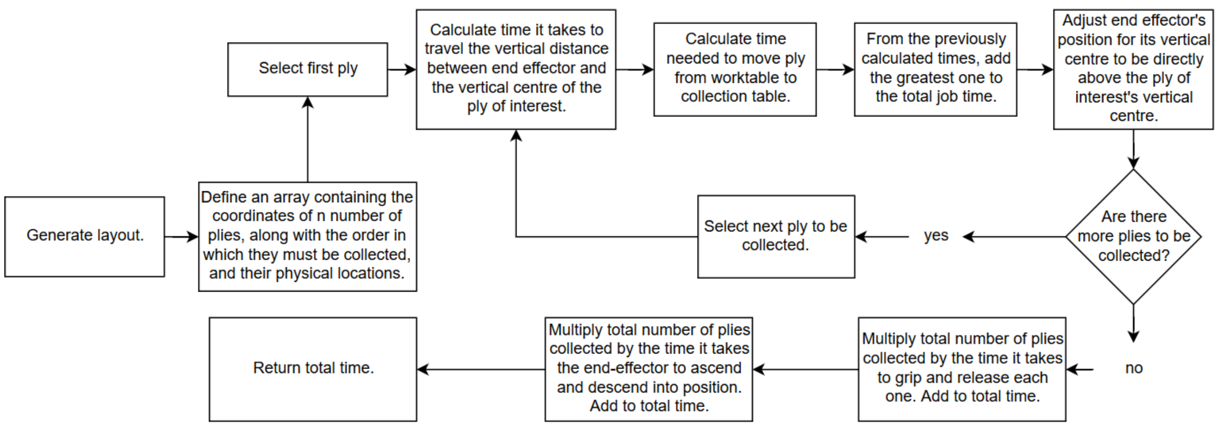


Figure 24. Flowchart for the automated process simulation script.

The process was repeated 100,000 times for five different kit sizes to obtain statistically significant data. The results are shown in TABLE V.

TABLE V: SIMULATED COLLATION TIME AVERAGES FOR THE AUTOMATED PROCESS

Number of plies	20	40	60	80	100
Average collation time [minutes]	2.3305	4.7037	7.0625	9.4131	11.7606
Collation time standard deviation [minutes]	0.124314	0.164041	0.20228	0.231604	0.265454

A plot of the simulated total collation time as a function of the number of plies in the kit for the automated process has also been generated, and is shown in Figure 25. The relationship is nearly linear in contrast to the to the current process' collation time plot shown in Figure 23. This is because the automated system does not need to spend any time searching for plies.

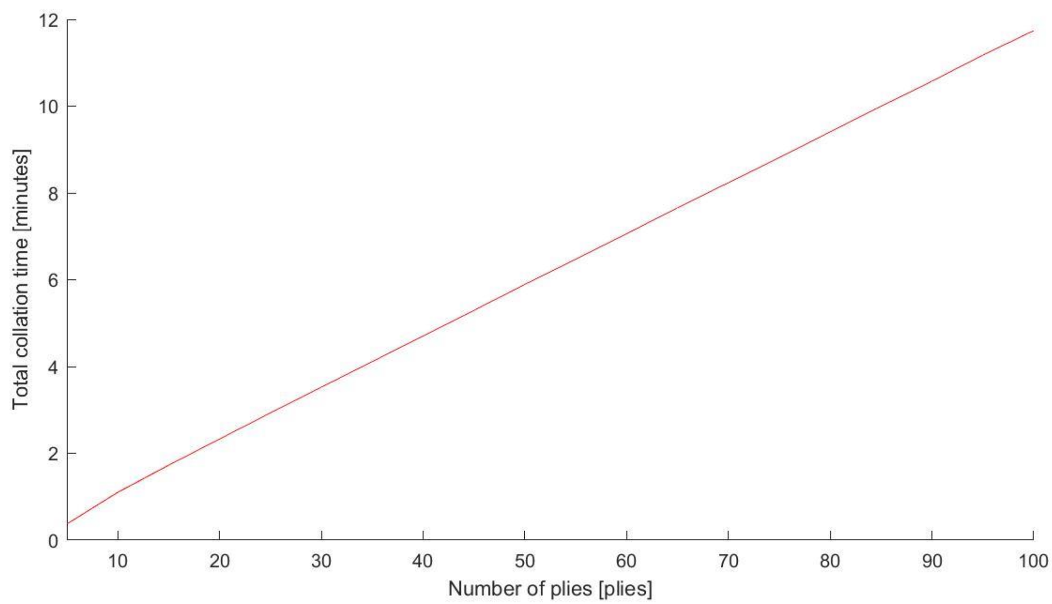


Figure 25. Total collation time in the automated process as a function of kit size.

Like the current manual process estimates, this simulation is idealized. However, an effort was made to incorporate as many factors as possible into the simulation, including the robot's acceleration and maximum speed, the time spent activating and deactivating the suction cups, and moving the ply from the worktable to the collection table. Therefore, the simulations results will be taken as an approximate representation of the real collation times that will result from the automated system's implementation.

6.3 SUCTION CUP SELECTION ALGORITHM

Given the location of a ply on the cutting table that needs to be collected, the system controller must place the end-effector completely over the ply. Additionally, only the suction cups that fall completely within the edges of the ply be activated. Activating the plies that do not lie entirely within the ply of interest would lead to the possibility of gripping other plies or even scrap material, which could lead to part damage. A proof-of-concept algorithm has been developed to simulate the desired behaviour of the end-effector.

The cup selection algorithm was initially written in MATLAB, but has been summarised in the flowchart shown in Figure 26. Once the dimensions of the worktable and the end-effector are defined, the only necessary input is the coordinates defining the edges of the ply. In MATLAB, this is given by a set of two arrays, one containing the x-coordinates for all the points defining the edge of the ply, and another one for their y-coordinates.

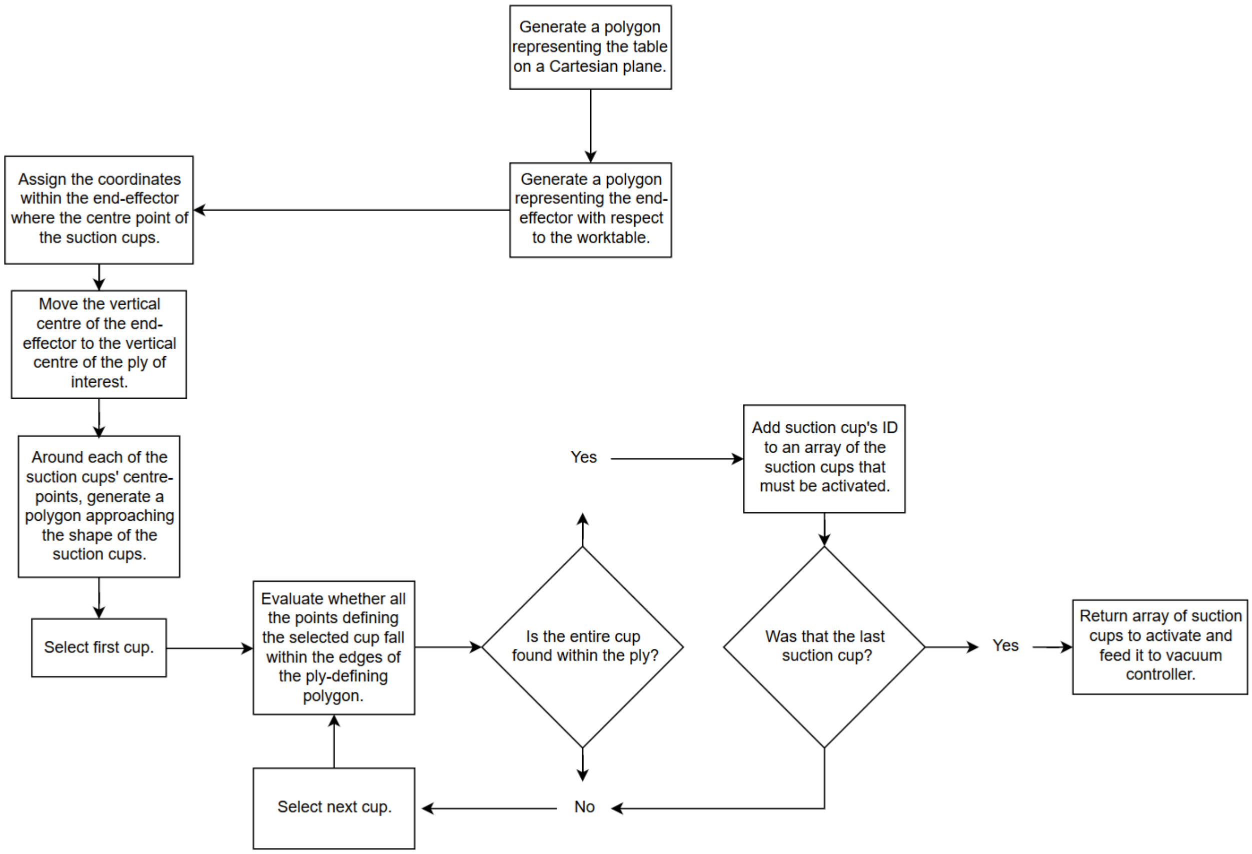


Figure 26. Flowchart for the cup selection algorithm.

Once the ply's coordinates are defined, the end-effector's coordinates are changed to align its vertical center with that of the. Each suction cup is then evaluated to determine if they lie entirely within the edges of the ply. If it does, then its ID is added to an array of the suction cups that must be activated. Otherwise, the algorithm jumps to the next suction cup and examines it. Once this process is complete, the algorithm returns an array containing the IDs of all the cups that must be activated once the end effector is placed over the ply.

The entire MATLAB code written for this proof of concept can be found in Appendix D. Additionally, this code generates a plot showing the worktable, the ply to be collected, the end effector, and the activated and inactive suction cups, as shown in Figure 27.

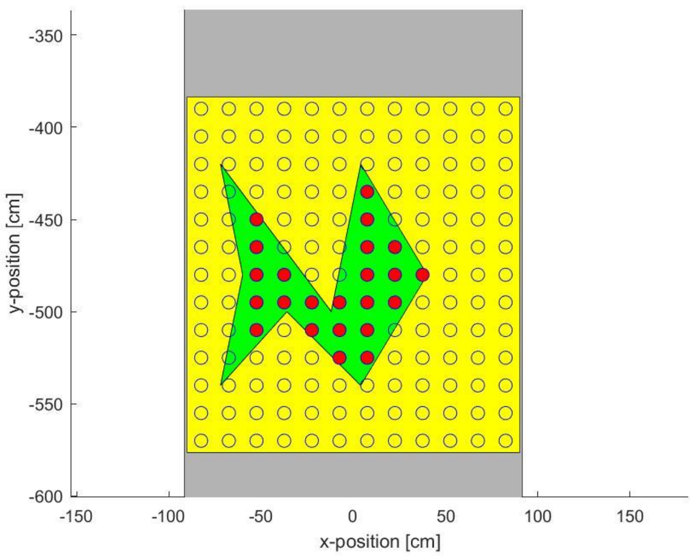


Figure 27. Cup selection plot generated by MATLAB code, where the grey area is the worktable, the yellow area is the end effector, the green area is the ply in question, and the red circles are the activated suction cups (not to scale).

Along with Figure 27, Figure 28 shows a simple graphical representation of the cup activation steps, where the controller places the end effector directly above the ply's vertical center, and activates only the suction cups found entirely within the ply of interest.

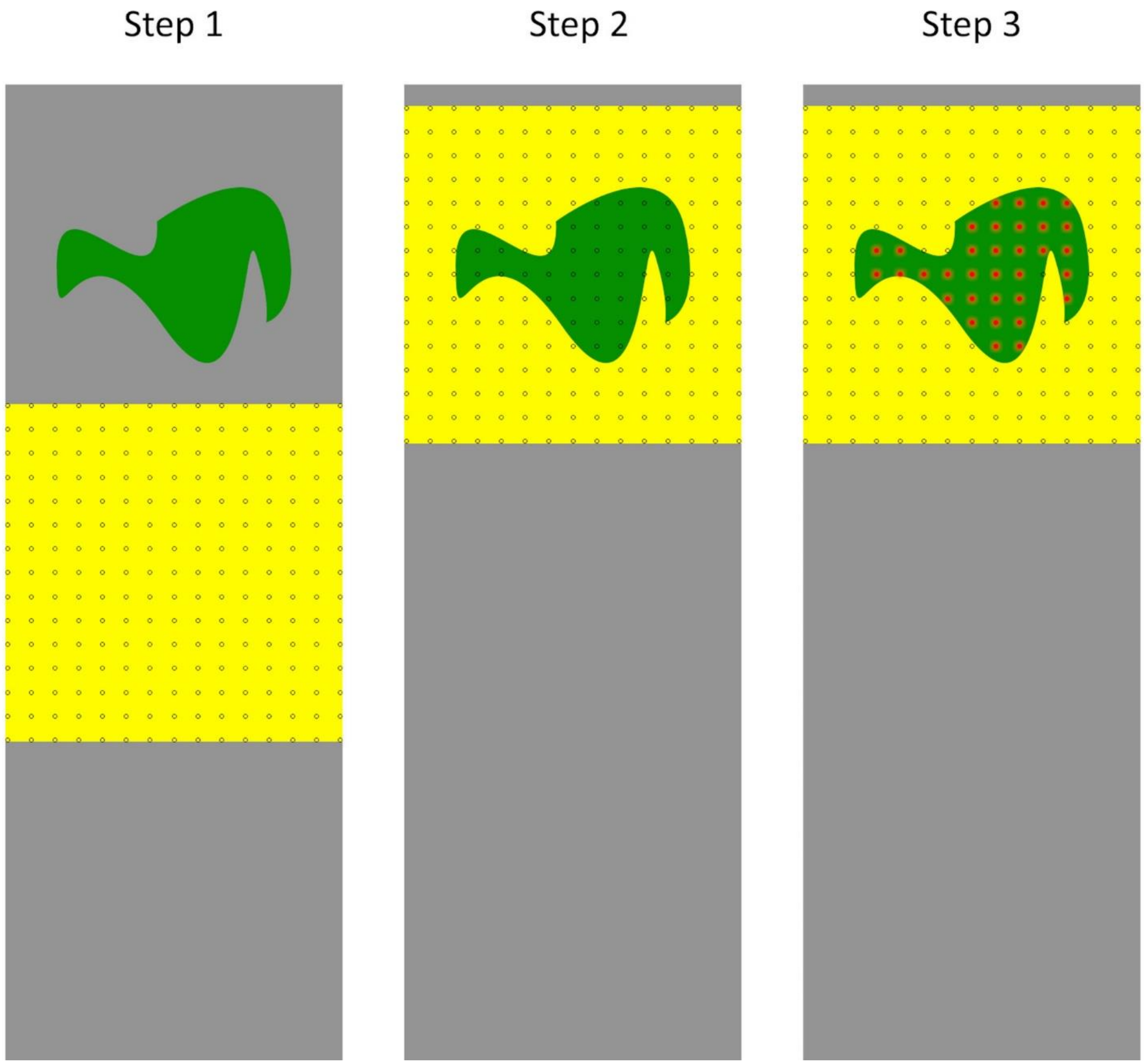


Figure 28. Graphical representation of the cup selection process, where the grey area is the worktable, the yellow area is the end-effector, the green area is the ply to be collected, and the shining red circles are the activated suction cups (not to scale).

With this proof-of-concept implementation of the cup selection algorithm, it is possible to obtain the necessary movements the robot must take as well as the suction cups that must be activated with only the ply's coordinates as the input. The method necessary to transform each ply into a set of coordinates from the dynamically generated nest has been deemed to fall outside of the scope of this report, and has therefore not been developed.

7 COST ANALYSIS

Cost analysis is a crucial factor in determining if the design achieves the project objectives. The design must achieve the goal of a sub-10-year payback period (ideally under 5 years) for an initial and non-recurring investment of under 2,000,000 CAD (ideally under 500,000 CAD). The cost analysis was based on the following assumptions:

1. The labour cost is 100 CAD per hour.
2. The operating collation time is 24 hours a day, 7 days a week, 4 weeks a month.

It is important to note that the values listed above do not represent the actual labour costs used by BCW. They are simply assumptions based on and the client's recommendations.

A bill of materials was created with the information obtained directly from suppliers and catalogs. In this section, a bill of materials is presented, and the total cost of all components will be considered the initial investment. The payback presented in 7.2 is based on the collation time reduction data obtained from the simulations in section 6.1 and 6.2, the initial investment, and recurring maintenance payments.

7.1 BILL OF MATERIALS

The bill of materials is shown in TABLE VI. The price for each component was determined either by requesting a quote from the supplier, or finding the price on the manufacturer's website. The bill of materials is separated into two main sections: The robotic equipment and the end effector. Appendix E for the full version of bill materials.

TABLE VI: SIMPLIFIED BILL OF MATERIALS

	Component	Part #	Qty	Unit Cost (CAD)*	Total Cost (CAD)*
Robotic Equipment	Robotic Arm	IRB460	1	[redacted]	
	Rail	IRBT4004	1		
	Guard Cell	-	1		
	Installation	-	1		
				Subtotal	**$201,381.00**
End Effector	Vacuum Generators	SCTMi	130	$571.50**	**$74,295.00**
	Control Cable	ASK B-M12-5 5000	10	$50.00	**$500.00**
	Cup + Nipple	SPB1 30 ED-65 G1/8-IG	130	$21.27	**$2,765.10**
	G1/8 M to F	0906	130	$1.56	**$202.80**
	G1/8 90deg 6mm Push Connector	MS6M-18G	130	$1.58	**$205.40**
	G1/8 Straight 6mm Push Connector	ME6M-18G	130	$1.08	**$140.40**
	Extruded Aluminum 4040 (10ft)	5537T102	2	$104.00	**$208.00**
	Extruded Aluminum 8040 (10ft)	5537T112	2	$181.00	**$362.00**
	Aluminum U-Channel (8ft)	9001K54	13	$50.00	**$650.00**
	Fasteners	-	1	$200.00	**$200.00**
	6mm tubing (100ft)	PU6MBLK100	1	$18.50	**$18.50**
				Subtotal	**$79,547.20**
				Total	**$280,928.20**

*All prices were originally listed in USD, and were converted to CAD at a rate of 1 CAD = 0.79 USD

**The unit cost for the vacuum generators was listed as CAD762, 25% off discount was assumed for bulk purchase

The total initial cost for all components is 280,928.20 CAD. This is the external cost. The design, manufacturing and installation cost (internal cost) for the end effector is not included in the bill of materials, since the end effector can be built by BCW. To calculate the internal cost, the following approximations for the fabrication of the end effector were made.

1. 100 CAD/hour labour cost (based on client's recommendation, does not represent actual labour cost at BCW)
2. 5-hour machining time

3. 12-hour assembly

The time for machining and assembly are estimates based on the team's best judgment, and therefore may vary from the actual values.

The total time for building the end effector is approximately 17 hours. With the labour cost of $100 CAD per hour, the internal cost is approximately 1,700 CAD. As a result, the initial investment is approximately 282,628.20 CAD, which is approximately 15% of the budget, and 56% of the ideal cost. TABLE VII shows a summary of total initial costs and budget.

TABLE VII: SUMMARY OF COSTS

Item	Cost (CAD)
External Cost	$280,928.20
Internal Cost	$1,700.00
Total Initial Investment	$282,628.20
Budget	$2,000,000.00

7.2 Payback Period

For the calculation of the payback period, the initial investment, the simulated current and automated collation times, and recurring maintenance costs were considered. Several assumptions were made to calculate the payback period:

1. The labour cost is 100 CAD per hour, with the annual inflation of 2% [7]. (based on client's recommendation, does not represent actual labour cost at BCW)
2. The current process operates 24 hours a day, seven days a week, four weeks a month.
3. The production amount for the automated process will remain the same as the current manual process (i.e. the runtime per day will be cut back to reach the same production level).

4. The labour cost will remain at 100 CAD per hour during the automated operation.
5. The operating cost (electrical power cost) for the robotic equipment will be 0.1671 cents CAD per hour. This is based on the electricity usage for a medium sized robot (100 kg payload) of 5 kW [7], and an electricity rate of 3.342 cents/kWh taken from Manitoba Hydro for General Service Large (non-residential and customer-owned transformation) [8]. An annual MB Hydro inflation rate of 3.5% is also taken into consideration [9].
6. The typical maintenance cost for robots is approximately 650 CAD per year for the first five years, which is mainly for lubrication and battery maintenance. On the fifth operating year, a cost of 6,500.00 CAD is predicted to replace worn parts. After that, the cost returns to its base value of 650 CAD per year. On year 10, approximately 38,000.00 CAD will be needed for the robots' refurbishment [10].

Since the cycle time for the automated process is significantly lower than the current manual process, as shown in TABLE VIII, the number of working hours for the automated process to reach the daily production is greatly reduced. The savings emerge from the reduction in hours spent collating per day.

TABLE VIII: CYCLE TIME FOR THE CURRENT METHOD AND THE AUTOMATED METHOD

# of plies per kit	20	40	60	80	100
Current Cycle Time (min) for 1 kit	4.47	12.22	23.1	37.37	54.7
Improved Cycle Time (min) for 1 kit	2.33	4.7	7.06	9.41	11.7

The following is a cost analysis for the production of 20 ply kits. Assuming the collation operation is performed 24/7, and neglecting the cutting time, the working hours of the current process for one month can be calculated as follows:

$$24\,\frac{\text{hr}}{\text{day}} \times 7\,\frac{day}{week} \times 4\,\frac{week}{month} = 672\ hours\ per\ month$$

The monthly cost for current manual process can then be calculated with the following equation:

$$100\,\frac{\text{CAD}}{\text{hr}} \times 672\,\frac{hr}{month} = 67{,}200\ CAD\ per\ month$$

The number of kits having 20 plies that can be produced in one month under the current process is:

$$\frac{60\ \text{min/hr}}{4.47\ \text{min/kit}} \times 672\,\frac{hr}{month} = 9020\ kits\ per\ month$$

The working hours needed for the automated process to produce the same number of kits as the current process is:

$$9020\,\frac{\text{kit}}{\text{month}} \div \frac{60\ \text{min/hr}}{2.33\ \text{min/kit}} = 350.3\ hours\ per\ month$$

The monthly labour cost for the automated process is:

$$100\,\frac{\text{CAD}}{\text{hr}} \times 350.3\ \frac{hr}{month} = 35{,}030.00\ CAD\ per\ month$$

The maintenance fee for the first five years is 650 CAD per year. The monthly payment is:

$$650\,\frac{CAD}{year} \div 12 = 54.20\ CAD\ per\ month$$

As previously discussed, the operating cost for the robot was assumed to be 16.71 cents CAD per hour, so the monthly payment for the operating cost is:

$$16.71\ cents\,\frac{CAD}{hr}\ \times 350.3\,\frac{hr}{month} = 58.54\ CAD\ per\ month$$

The Return on Investment (ROI) was calculated over a period of three years and is shown in TABLE IX.

TABLE IX: ROI CHART FOR COLLATION OF 20-PLY KITS

Month	Initial Costs	Robots Labour Costs*	Operating Costs**	Maintenance Costs	Monthly Cost (Robots)	Cumulative Robots Costs	Current Montly Costs*	Cumulative Current Costs	Cumulative Savings***
1	$282,628	$35,030	$58.54	$540.20	$318,257	$318,257	$67,200	$67,200	-$251,057
2		$35,088	$58.71	$54.17	$35,201	$353,458	$68,544	$135,744	-$217,714
3		$35,790	$59.88	$54.17	$35,904	$389,362	$69,915	$205,659	-$183,704
4		$36,506	$61.08	$54.17	$36,621	$425,984	$71,313	$276,972	-$149,012
5		$37,236	$62.30	$54.17	$37,353	$463,336	$72,739	$349,711	-$113,625
6		$37,981	$63.55	$54.17	$38,099	$501,435	$74,194	$423,906	-$77,529
7		$38,740	$64.82	$54.17	$38,859	$540,294	$75,678	$499,584	-$40,710
8		$39,515	$66.12	$54.17	$39,636	$579,930	$77,192	$576,776	-$3,154
9		$40,306	$67.44	$54.17	$40,427	$620,357	$78,736	$655,511	$35,154
10		$41,112	$68.79	$54.17	$41,235	$661,591	$80,310	$735,821	$74,230
11		$41,934	$70.16	$54.17	$42,058	$703,649	$81,916	$817,738	$114,088
12		$42,773	$71.57	$54.17	$42,898	$746,548	$83,555	$901,292	$154,745
13		$43,628	$73.00	$54.17	$43,755	$790,303	$85,226	$986,518	$196,215
14		$44,501	$74.46	$54.17	$44,629	$834,932	$86,930	$1,073,449	$238,517
15		$45,391	$75.95	$54.17	$45,521	$880,453	$88,669	$1,162,118	$281,665
16		$46,298	$77.47	$54.17	$46,430	$926,883	$90,442	$1,252,560	$325,677
17		$47,224	$79.02	$54.17	$47,358	$974,240	$92,251	$1,344,811	$370,571
18		$48,169	$80.60	$54.17	$48,304	$1,022,544	$94,096	$1,438,907	$416,363
19		$49,132	$82.21	$54.17	$49,269	$1,071,812	$95,978	$1,534,886	$463,073
20		$50,115	$83.85	$54.17	$50,253	$1,122,065	$97,898	$1,632,783	$510,718
21		$51,117	$85.53	$54.17	$51,257	$1,173,322	$99,856	$1,732,639	$559,317
22		$52,139	$87.24	$54.17	$52,281	$1,225,603	$101,853	$1,834,492	$608,889
23		$53,182	$88.99	$54.17	$53,325	$1,278,929	$103,890	$1,938,382	$659,453
24		$54,246	$90.77	$54.17	$54,391	$1,333,319	$105,968	$2,044,349	$711,030
25		$55,331	$92.58	$54.17	$55,478	$1,388,797	$108,087	$2,152,436	$763,639
26		$56,437	$94.43	$54.17	$56,586	$1,445,383	$110,249	$2,262,685	$817,302
27		$57,566	$96.32	$54.17	$57,717	$1,503,100	$112,454	$2,375,139	$872,039
28		$58,718	$98.25	$54.17	$58,870	$1,561,970	$114,703	$2,489,841	$927,872
29		$59,892	$100.21	$54.17	$60,046	$1,622,016	$116,997	$2,606,838	$984,822
30		$61,090	$102.22	$54.17	$61,246	$1,683,262	$119,337	$2,726,175	$1,042,913
31		$62,312	$104.26	$54.17	$62,470	$1,745,732	$121,723	$2,847,898	$1,102,166
32		$63,558	$106.35	$54.17	$63,718	$1,809,450	$124,158	$2,972,056	$1,162,606
33		$64,829	$108.47	$54.17	$64,992	$1,874,442	$126,641	$3,098,698	$1,224,256
34		$66,125	$110.64	$54.17	$66,290	$1,940,732	$129,174	$3,227,871	$1,287,139
35		$67,448	$112.86	$54.17	$67,615	$2,008,347	$131,757	$3,359,629	$1,351,282
36		$68,797	$115.11	$54.17	$68,966	$2,077,313	$134,393	$3,494,021	$1,416,708

*2% annual inflation is applied, and is divided by 12 to convert into monthly inflation rate

**3.5% annual inflation is applied, and is divided by 12 to convert into monthly inflation rate

***Cumulative Savings are calculated as subtracting Cumulative Robots Costs from Cumulative Current Costs

TABLE IX shows that the cumulative monthly savings reach a positive value between the 8th and 9th month from initial purchase. This represents the payback period. This figure also shows that the cumulative savings is predicted to reach approximately 1.5 million CAD at the end of the 3-year period. Figure 29 shows the cumulative monthly costs for both robotic process and current manual process over this period.

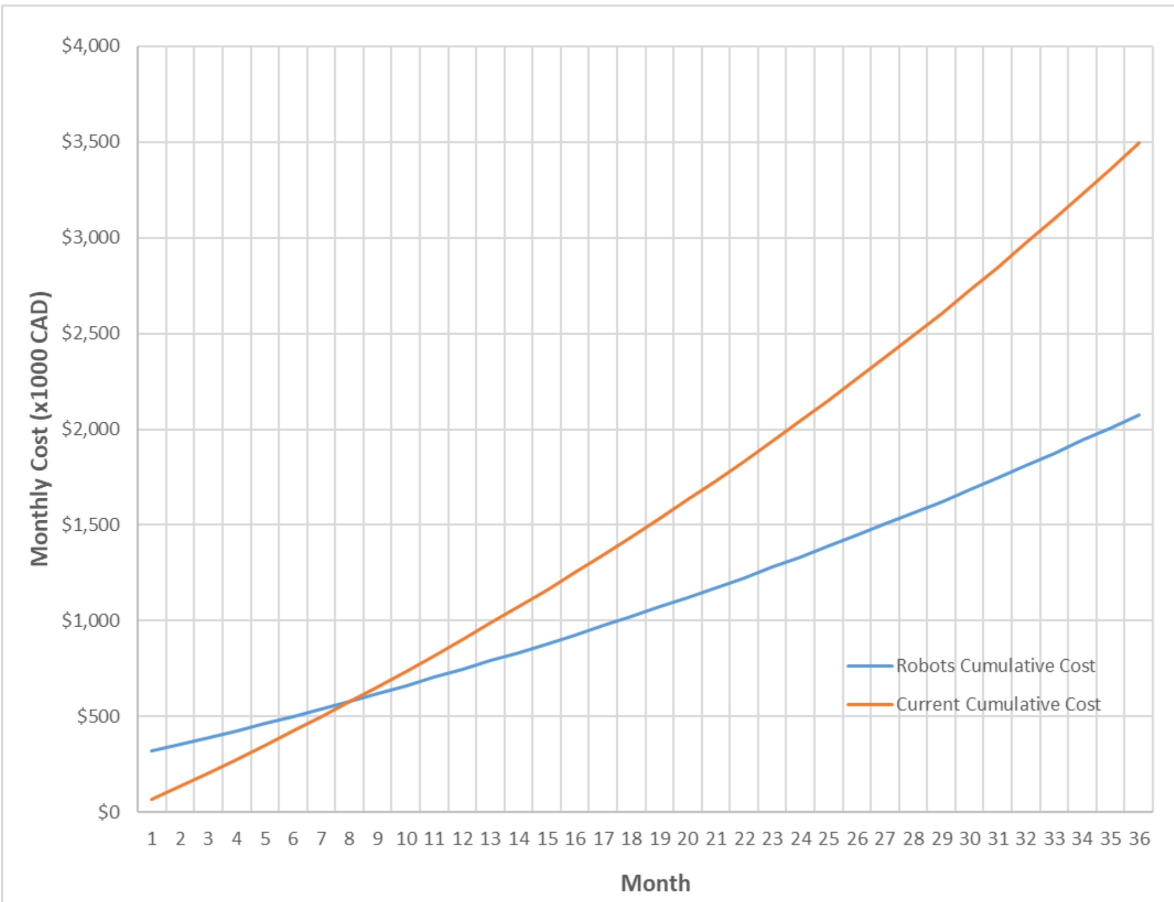


Figure 29. Cumulative monthly costs for robotic process and current manual process for collation of 20-ply kits.

Figure 29 shows that the break-even point lies between month 8 and 9, and the savings obtained from the implementation of the automatic process progressively increase over time.

Figure 30 illustrates the cumulative savings generated by the implementation of the automated design.

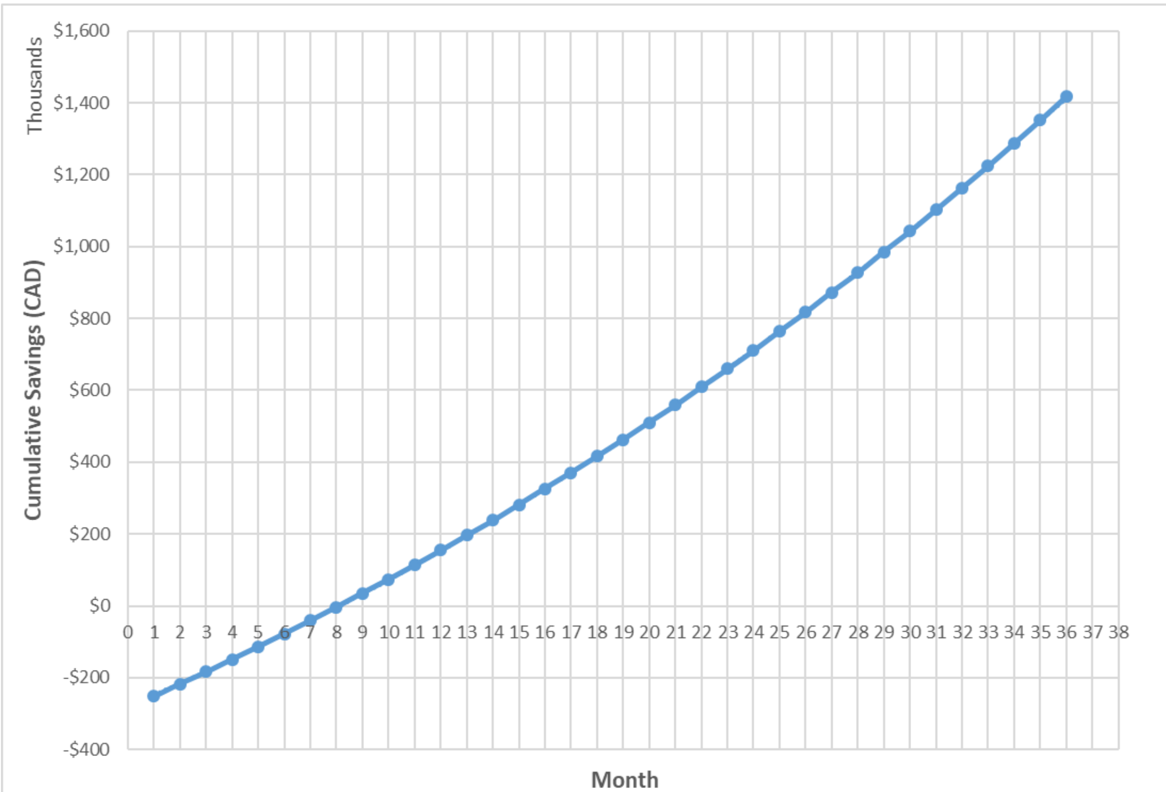


Figure 30. Cumulative savings generated by automatic process for collation of 20-ply kits.

Figure 31 and Figure 32 displays a long-term (10 years period) illustration of the costs for the two processes, and the cumulative savings gained from the automated design, respectively. Further details on the cost analysis is available in Appendix F.

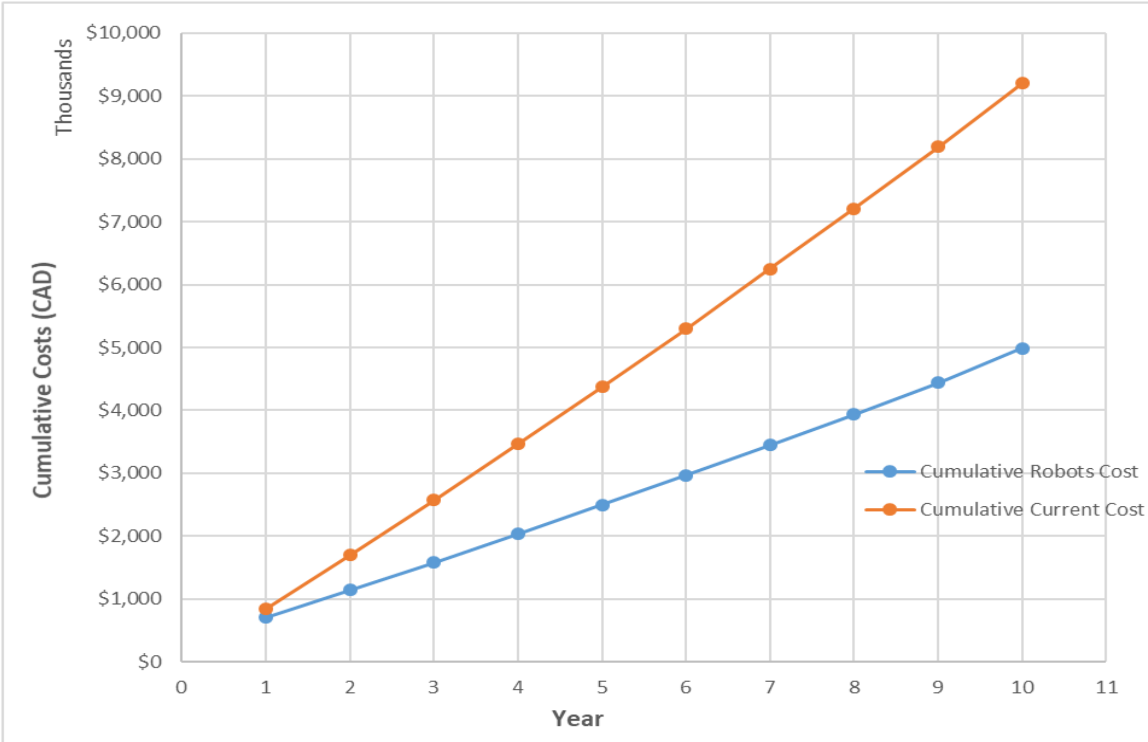


Figure 31. Cumulative costs of automated process and the current process for the collation of 20-ply kits.

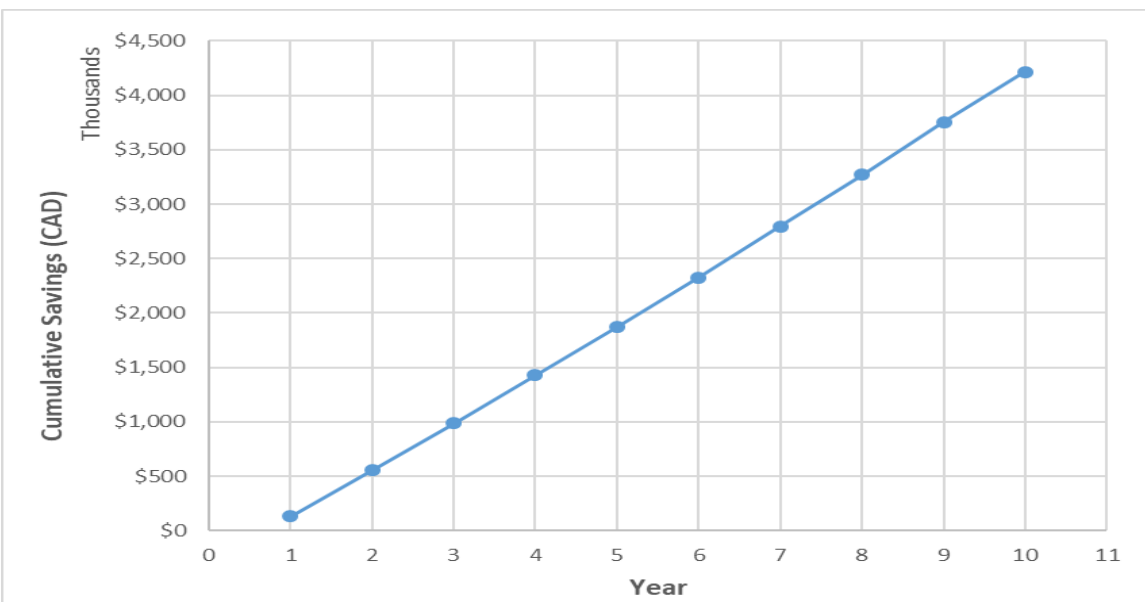


Figure 32. Cumulative savings generated by the automated process over a 10 year period.

It should be noted that the results obtained above only apply to the production of 20-ply kits, which is a relatively small kit size. If larger kits are produced, the savings are much higher. TABLE X summarizes the payback period and corresponding cumulative savings to produce kits with 20 plies, 40 plies, 60 plies, 80 plies and 100 plies. Additional details on these values are available in Appendix F.

TABLE X: SUMMARY OF PAYBACK PERIOD AND CUMULATIVE SAVINGS AFTER 3 YEARS FOR THE COLLATION OF 20-PLY, 40-PLY, 60-PLY, 80-PLY AND 100-PLY KITS RESPECTIVELY

# of Plies	20	40	60	80	100
Payback Period (Month)	9	7	6	6	6
Cumulative Savings after 3 years (CAD)	$1,416,708	$1,886,788	$2,141,419	$2,326,948	$2,351,073

The results of cost analysis show the initial investment is approximately 280,928.00 CAD, and the payback period may range from 6 to 9 months, depending on the average number of plies produced per kit. As details on the true production values at BCW have not been disclosed to the team, the calculated payback period is an estimate. However, the cost analysis is sufficient to prove that the ideal objective of a sub-5-year payback period for an initial cost of less than 500,000 CAD can be achieved.

8 RECOMMENDATIONS

Further improvements can be made to the design of the end effector presented in this report. The suction cups used in the team's design were selected based on the supplier's knowledge and recommendations. However, it would be prudent to build a small-scale end effector prototype that could be used to test different suction cups to determine whether they can correctly grip the plies without causing any damage.

End effector prototypes with different cup spacing and configurations could be tested to determine ply overhang with plies of different shapes. The prototype with the lowest ply overhang would have the least potential for ply damage. A prototype could also be used to estimate the robot's travel time, which would lead to a more concrete idea of the time savings this concept could bring.

The simulations conducted for this report consist of idealistic approximations for both the current manual collation method and the newly designed automated method. Ideally, time studies of the current method could be conducted to reach a more precise understanding of the benefits that the automated method would bring. It is also recommended that simulations of the automated process described in this report be conducted using RobotStudio – ABB's simulation software – to better predict the resulting collation times.

The algorithm for the suction cup activation presented in this report is only a proof-of-concept to determine the feasibility of the design. It is recommended that it be recreated in RobotStudio for the implementation of the new process. Furthermore, it is recommended that a method to transform the current dynamically nested kits' files into a format that allows for each ply's shape and location to be fed to the robot's controller.

Finally, the cost analysis presented in this report contains many estimates, such as the current operation costs per hour, potential maintenance costs for the new equipment, and others. Furthermore, the collation times used in the calculation of the costs and savings were obtained through idealized simulations. It is recommended that the true costs be obtained, and the cost analysis repeated with the new information. This will increase the certainty with which the decision of whether to implement this design or not can be taken.

9 CONCLUSION

The team was tasked with designing a method to improve ply collation times at Boeing Canada Winnipeg. For this process, pre-impregnated composite sheets are nested and cut with a CNC gantry system. The plies are then manually collated, in a specific order, and placed on a cart. This project's objective is to develop a method to improve the collation step of this process.

After completing the phases of problem definition and concept generation and selection, it was determined that the final design would be a fully automated solution consisting of three components: a mobility system, an arm, and an end effector. This concept was further developed and optimized.

First, the end-effector was designed. This process consisted of selecting appropriate suction cups, and a method to provide them with the suction power. In the final design, 130 suction cups are needed for the end effector, and the Schmalz SPB1 30 ED-65 G1/8-IG were selected. For the end effector to grip the plies individually without gripping any other plies or scrap material, the suction cups must be individually controlled. For this purpose, the *Schmalz Compact Terminal SCTMi* vacuum generation system was implemented, which consists of compact vacuum generators that can be mounted on the end effector itself.

The final end effector design consists of a structural frame built from T-slotted aluminium beams, and aluminum C-channels used to support the suction cups. There is a centre junction made from machined aluminum, which will be the attachment point for the 4-axis robot. The suction cups are arranged in a 10x13 grid, and the vacuum ejectors are arranged in 10 blocks containing 13 each. The outer dimensions of the entire structure are 1.35x1.80mx0.20m. Figure 33 presents the final design of the end-effector.

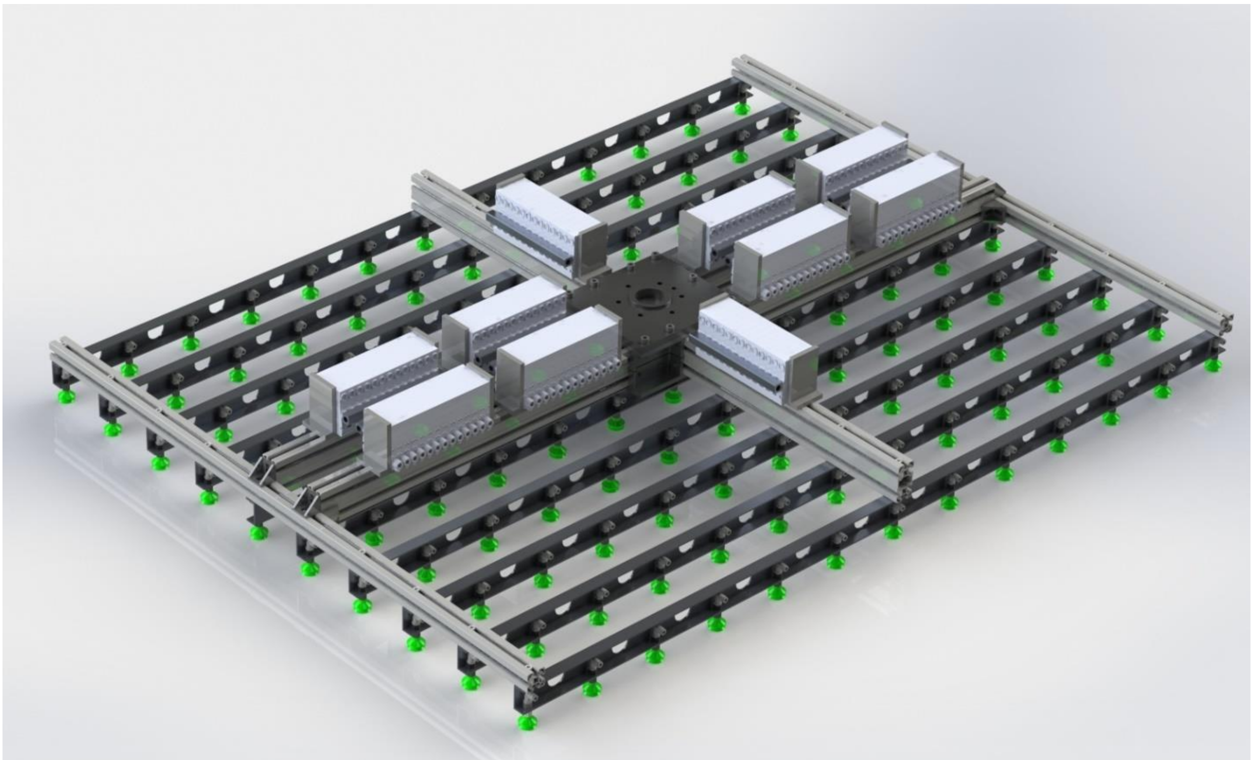


Figure 33. Final design of the end effector.

For the 4-axis robot, the ABB IRB460 with a payload of 110kg, was selected for the design. For the rail system, the ABB IRBT4004 rail system was selected. Since both are ABB products, it will make the integration process, coding, and technical support simpler.

Simulations were conducted through scripts written in MATLAB for the current process and the new process for jobs of different sizes. The cycle time improvement greatly increased as the job size did (measured in number of plies to be collected). For the largest kit size that was examined (100 plies distributed over the entire length of the worktable), the automated process reduced collation times by 78.5% (from 54.7 to 11.8 minutes).

The final design has a total initial cost of 282,628 CAD, a yearly operating cost of 2,756 CAD, and a yearly typical maintenance fee of 650 CAD. The payback period ranges between 6 to 9 months, depending on the ply kit size. These measures all fulfill the client's requirements, which were to achieve an ideal cost below 500,000 CAD and an ideal payback period below 5 years.

In conclusion, through the careful process of developing the design presented in this report, our team has successfully arrived at a solution to improve the collation time during the cloth cutting operation at BCW.

10 References

[1] Fibre Glast Developments Corporation, "Prepreg 3K, 2x2 Twill Weave Carbon," Fibre Glast Developments Corporation, [Online]. Available: http://www.fibreglast.com/product/Prepreg_3K_2x2_Twill_Weave_Carbon_03101/PrePreg_Fabrics. [Accessed 30 September 2017].

[2] Canadian Centre for Occupational Health and Safety, "Noise - Occupational Exposure Limits for Extended Workshifts," 6 April 2016. [Online]. Available: https://www.ccohs.ca/oshanswers/phys_agents/exposure_ext.html. [Accessed 27 September 2017].

[3] Schmalz, "SPB1 30 ED-65 G1/8-IG," Schmalz, [Online]. Available: https://www.schmalz.com/en/vacuum-technology-for-automation/vacuum-components/vacuum-suction-cups/suction-cups-for-packaging/bellows-suction-cups-spb1-1-5-folds-55/10.01.06.03497. [Accessed 26 November 2017].

[4] Schmalz, "Compact Terminal SCTMi," Schmalz, [Online]. Available: https://www.schmalz.com/en/vacuum-technology-for-automation/vacuum-components/vacuum-generators/compact-terminals/compact-terminal-sctmi. [Accessed 26 November 2017].

[5] ABB, "ABB IRB460," ABB, [Online]. Available: http://new.abb.com/products/robotics/industrial-robots/irb-460. [Accessed 26 November 2017].

[6] ABB, "ABB IRBT4004," ABB, [Online]. Available: http://new.abb.com/products/robotics/application-equipment-and-accessories/robot-positioners-track-motion/irbt-4004-for-irb-4400. [Accessed 26 November 2017].

[7] R. Potter, "ROI Robot System Value Calculator," Robotic Industries Association, [Online]. Available: https://www.robotics.org/robotics-roi-calculator. [Accessed 28 November 2017].

[8] M. Hydro, "Commerical Rates," Manitoba Hydro, [Online]. Available: https://www.hydro.mb.ca/accounts_and_services/rates/commercial-rates.shtml#e-lgs. [Accessed 28 November 2017].

[9] M. Agriculture, "Guidelines for Estimating Solar PV Energy Production Costs 2016," October 2016. [Online]. Available: https://www.gov.mb.ca/agriculture/business-and-economics/financial-management/pubs/cop-agrienergy-solarpv.pdf. [Accessed 28 November 2017].

[10] T. M. Anandan, "Calculating Your ROI for Robotic Automation: Cost vs. Cash Flow," Robotic Industries Association, 19 March 2015. [Online]. Available: https://www.robotics.org/content-detail.cfm/Industrial-Robotics-Industry-Insights/Calculating-Your-ROI-for-Robotic-Automation-Cost-vs-Cash-Flow/content_id/5285. [Accessed 28 November 2017].

APPENDIX A: BACKGROUND INFORMATION

TABLE OF CONTENTS

LIST OF FIGURES

A.1 ULTRASONIC CUTTER CAPABILITIES

There are a wide variety of ultrasonic cloth cutting systems used in the composites industry. The model used for the cloth cutting process at BCW is the American GFM US-40, which will be useful for the concept development section of this report. This ultrasonic cutter uses a perforated suction table to hold the sheet of composite material flat on the table. The gantry, shown in Figure A.1, moves down the length of the table by riding on two rails on either side.

Figure A.1: American GFM US-40 cloth cutter [1].

The system has a maximum cutting speed and acceleration of 1 m/s and 2.5 m/s^2, respectively [1]. The table surface is approximately 15.2 m long, 2 m wide, and 0.9 m from the ground.

A.2 Composite Pre-impregnated Fabric Handling

The methods selected for handling the pre-impregnated (prepreg) fabric are crucial, particularly if the final design is to be automated. This is because the prepregs are more susceptible to damage in their uncured state. Based on the research conducted by Buckingham and Newell [2], the rigidity and the tack of the prepreg are the two critical issues when handling prepregs.

The tack of the prepreg is considered as the most important factor for automated prepreg handling [2]. The tack is defined as the ability for two adjacent prepregs to bond together [3]. The resin type, the fiber-to-resin ratio, the distribution of resin, and the temperature are factors that affect the tack of prepreg. These factors are particularly vulnerable when handled through direct contact, increasing the risk of damage to the prepreg [2]. Direct contact handling of prepregs could increases the risk of resin contamination and uneven resin distribution [4], as well as delamination and stretching. One widespread practice in the current composite industry is covering the prepreg surfaces with backing sheets during handling operation, which protects the tackiness of the prepreg as well as improving the rigidity [2].

Although the prepregs' vulnerability to damage makes handling them in an automation solution challenging [4], the coverage of backing sheets is able to substantially reduce the handling damage. All prepregs handled at BCW are covered by backing sheets on both sides, which allows the team to explore a wide variety of mechanical options for picking up the plies.

A.3 References

[1] A. GFM, "American GFM US-30 / US-40 ULTRASONIC CUTTING MACHINES," American GFM Corporatio , [Online]. Available: http://www.agfm.com/new/Cutting/US30.html. [Accessed 21 October 2017].

[2] R.O. Buckingham and G.C. Newell, "Automating the Manufacture of Composite Broadgoods," *Composites Part A,* vol. 27A, no. 3, pp. 191-200, 1996.

[3] O. Dubois, J.-B. Le Cam and A. Beakou, "Expeirmental Analysis of Prepreg Tack," Aubiere cedex, 2009.

[4] A. Bjornsson, J. E. Lindback, D. Eklund and M. Jonsson, "Low-cost Automation for Prepreg Handling - Two Cases from the Aerospcae Industry," *SAE International Journal of Material and Manufacturing,* vol. 9, no. 1, pp. 68-74, 2016.

APPENDIX B: CONCEPT SELECTION

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

B.1 CONCEPT SELECTION

In a previously written concept definition report, several concepts were generated and evaluated against each other to choose a concept to further develop. Criteria were developed to evaluate design concepts. The set of criteria is based on the list of target specifications. Each criterion was given a weight based on its importance relative to the other criteria. Finally, the methodology used in the concept evaluation process is discussed. It must be said that since the time of the evaluation presented in this section, major changes to the robot and end-effector have taken place. These changes are discussed in the main body of this report.

B.2 CONCEPT SELECTION METHODOLOGY

Criteria were developed to evaluate design concepts. The set of criteria is based on the list of target specifications. Each criterion was given a weight based on its importance relative to the other criteria. Finally, the methodology used in the concept evaluation process is discussed.

B.2.1 Criteria Development and Weighting

The criteria used for assessing concepts are derived from our customer's needs and target specifications. These criteria are shown in TABLE B-I.

TABLE B-I: DESCRIPTION OF CRITERIA USED TO ASSESS CONCEPTS.

Criterion	Description
Cycle time for small kit (3 m length)	As the kit length can range from 3 m to 15.2 m on the cloth-cutting table, the cycle time for collating the plies can vary drastically between kits.
Cycle time for large kit (15.2 m length)	As mentioned above.
Material Utilization	The nesting algorithm is currently designed for maximum material utilization to minimize waste. If the nesting is changed, material utilization may be reduced, consequently increasing long-term costs.
Risk of injury to technicians in immediate vicinity	As safety is always a priority in the manufacturing industry, meeting this criterion is crucial. The importance of safety has also been emphasized by the client.
Repetitiveness of task	With mundane, repetitive tasks, the worker is more prone to lose focus, which may lead to errors or reduced quality.
Comfort of design for technicians	This criterion involves the ergonomics of designs. A good ergonomic design can help technicians work more efficiently. In addition, a good ergonomic design can reduce the risk of injury for technicians.
Intuitiveness	It is preferred that new manual procedures are intuitive for technicians. This can greatly reduce required training, and reduce the risk of human error. For automated solutions, more intuitive processes and programming are preferred.
Risk of damage to prepregs	Since the prepregs are expensive and the process flow will be interrupted if damaging occurs, the damage to prepregs should always be avoided

Initial cost	The initial cost plays an important role in the calculation of payback period. Additionally, the company requires the non-recurring investment to be within two million CAD.
Payback Period	The payback period is a crucial factor in determining the success of this project. If the payback period is too long, the initial investment may not be worthwhile. Our client has specified an ideal payback period of five years, with an upper limit of 10 years.
Operating noise level at 3 m distance	High noise levels can be a safety risk to employees. Therefore, lower noise levels will be preferred.
Ease of installation	A complex installation procedure requires more time and labour, which results in the increase of initial cost.
Manufacturability	Manufacturability is critical to any design. No matter how perfect the design is in theory, the design will not be feasible if manufacturing is not possible.

A weighting matrix was used to compare each criterion against the others. Two criteria are compared, and one of the two is deemed more important than the other. This process is repeated for all criteria.

TABLE B-II presents the weighting matrix used to evaluate the criteria. In this table, the winner of the one-on-one comparison has its corresponding letter placed in the appropriate cell. Each criterion is given a total score, which is the number of times it has been deemed more important than another criterion. The relative weight of each criterion is determined by the ratio between its total score and the maximum possible score of 78. The total score and relative weight are shown in the bottom two rows of the matrix.

TABLE B-II: WEIGHING MATRIX.

Criteria	Criteria	Cycle time for small kit (3 m length)	Cycle time for large kit (15.2 m length)	Material utilization	Risk of injury to technicians in immediate vicinity	Repetitiveness of tasks	Comfort of design for technicians	Intuitiveness	Risk of damage to prepregs	Initial cost	Payback period	Operating noise level at 3m distance	Ease of installation	Manufacturability
		A	B	C	D	E	F	G	H	I	J	K	L	M
Cycle time for small kit (3 m length)	A		B	A	D	A	A	A	H	A	J	A	A	M
Cycle time for large kit (15.2 m length)	B			B	D	B	B	B	H	B	J	B	B	M
Material utilization	C				D	C	C	C	H	C	J	C	C	M
Risk of injury to technicians in immediate vicinity	D					D	D	D	D	D	D	D	D	D
Repetitiveness of tasks	E						F	E	H	I	J	E	L	M
Comfort of design for technicians	F							F	H	I	J	F	L	M
Intuitiveness	G								H	I	J	G	L	M
Risk of damage to prepregs	H									H	H	H	H	M
Initial cost	I										J	I	I	M
Payback period	J											J	J	M
Operating noise level at 3m distance	K												L	M
Ease of installation	L													M
Manufacturability	M													
		A	B	C	D	E	F	G	H	I	J	K	L	M
Total Score		7	8	6	12	2	3	1	10	5	9	0	4	11
Relative Weight		0.09	0.103	0.077	0.154	0.026	0.038	0.013	0.128	0.064	0.115	0	0.051	0.141

The risk of injury to technicians, risk of damage prepregs, and manufacturability were given the highest weight, and are therefore considered the most important criteria. The payback period and cycle times, for large and small kits, are also heavily weighted, and are therefore considered important criteria.

B.2.2 *Concept Evaluation Methodology*

In the previously written concept definition report, several design concepts were generated and evaluated against each other to select a concept that would be further developed in this report. This section provides the methodology that was followed, as well as the concepts that were generated and later selected as part of the concept selection phase.

As both manual and automated solutions were deemed acceptable, the team brainstormed a variety of concepts for both situations. During the brainstorming process, the team realized that it would be difficult to directly compare all concepts against each other.

To deal with this issue, the concept evaluation was broken into a series of smaller component-specific evaluations. First, the concepts were broken into two categories, one for manual concepts, and the other for automated concepts. The manual concepts and automated concepts were evaluated individually, then the winners from each category were evaluated against each other to determine the final concept.

The automated concept can be broken down into three independent components. Each component has a list of concepts generated and evaluated. The winning concepts from each of the three components come together to form the final automated design. The components are discussed in detail this section.

B.3 Manual Concept Analysis

To analyze the manual concepts. a method to estimate the amount of time spent for each part of the process was previously developed. The time spent was estimated for the following three categories:

- Time spent travelling between the cart and the worktable.
- Time spent searching for a specific ply.
- Time spent outside of searching and transporting the plies.

For the analysis, a case where 100 different plies need to be collected was examined. It was also assumed that the collation process takes one hour from start to finish, based on rough estimates provided by the client.

B.3.1 *Time Spent Travelling Between the Cart and the Worktable*

To estimate the current time spent travelling between the cart and the worktable (when transporting plies to the cart and returning to the table), the layout was assumed to be as shown in Figure B.1.

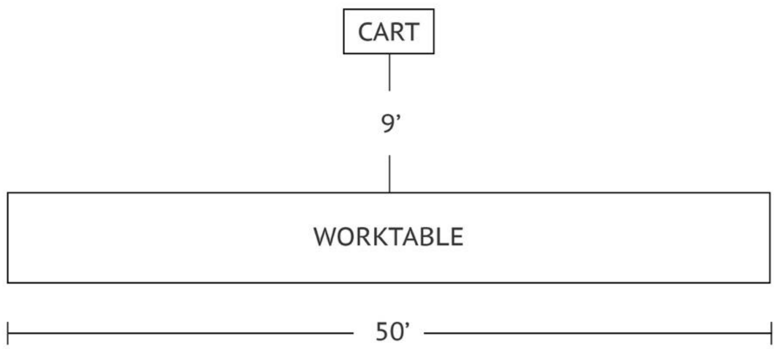


Figure B.1: Worktable and cart layout.

Assuming the technician can retrieve all the plies from one side of the worktable, then the average distance travelled between the cart and the worktable can be calculated as:

$$\bar{L} = \frac{\int_0^{25} (9^2 + x^2)^{\frac{1}{2}} dx}{25} = 16.11\ ft \tag{B.1}$$

The result of the integral above can also be expressed as:

$$\bar{L} = \frac{1}{2}\left(25\sqrt{x^2 + 81}x + 81 \sinh^{-1}\frac{x}{9}\right) \tag{B.2}$$

Where the variable x represents the nested kit's length, and assumes that the cart is placed 9 ft. away and in front of the middle of the kit.

The total time spent during this activity can then be estimated as:

$$T = 2\bar{L} * \frac{100}{\bar{\bar{v}}} \tag{B.3}$$

$\bar{v}$ is the average walking speed. A coefficient of 2 has been used above since each ply involves travelling both to and from the cart to the table. Assuming an average walking speed of 5 ft-s^{-1}, the total time is estimated at 644 seconds, or 10 minutes and 44 seconds. This then leaves 49 minutes and 16 seconds for time spent searching for the ply, in addition to any other potential activity. A reasonable estimate for the time spent outside of searching for the plies and transporting them must be made to proceed with the analysis, so it will be assumed that between five and ten minutes are spent in this this category for 100 plies (between 3 and 6 seconds per ply). This time can therefore be expressed as:

$$T_3 = 4.5n \tag{B.4}$$

B.3.2 Time Spent Searching for a Specific Ply

To estimate the time spent searching for the specific plies, the assumption will be made that the process can be reasonably modelled as analogous to finding a specific card from a deck of cards without replacement, where each attempt takes a certain amount of time to complete. The expected number of attempts can be computed as follows:

$$\bar{A} = 1\frac{1}{n} + 2\left(\frac{n-1}{n}\right)\left(\frac{1}{n-1}\right) + 3\left(\frac{n-1}{n}\right)\left(\frac{n-2}{n-1}\right)\left(\frac{1}{n-2}\right) + \cdots \tag{B.5}$$

Where $\bar{A}$ is the average number of attempts before finding the desired ply in a nest containing n plies. The equation can be rewritten as:

$$\bar{A}_n = \frac{1}{n}\sum_{k=1}^{n} k = \frac{n(n+1)}{2n} = \frac{n}{2} + \frac{1}{2} \tag{B.6}$$

To find the total number of attempts necessary to find n plies, the number of attempts must be calculated each time the total number of plies on the worktable decreases, and these must be added together. This can be represented as follows:

$$\bar{A}_T = \sum_{k=1}^{n} \frac{k}{2} + \frac{1}{2} = \frac{n(n+1)}{2*2} + \frac{1}{2} * n = \frac{n^2 + 3n}{4} \tag{B.7}$$

Substituting 100 into n in the equation above, one obtains:

$$\bar{A}_T == \frac{100^2 + 100}{4} + \frac{100}{2} = 2575\ attempts \tag{B.8}$$

The average time per attempt can be calculated as follows:

$$\bar{T}_A = \frac{2575}{T_T}, \tag{B.9}$$

where T_T is the total time spent searching for a ply. It was previously estimated that approximately 10 minutes and 44 seconds are spent while transporting the plies, and between 5 and 10 minutes are spent outside of searching and transporting the plies. This means the time spent searching for all the plies is between 44 minutes and 16 seconds and 39 minutes and 16 seconds. Consequently, the minimum average time per search attempt is then 0.91 seconds, and the maximum is 1.03 seconds. The average time per attempt will then be taken as 0.97 seconds.

B.3.3 Effect of Group Nesting

With the collation time estimate for the current process, it is possible to evaluate the effect that group nesting will have on the average time spent searching for the plies on the worktable. The average number of attempts needed to find all the plies can be calculated as follows:

$$\bar{A}_T = g \cdot \frac{\left(\frac{n}{g}\right)^2 + \frac{3n}{g}}{4} + \frac{\frac{n}{g}}{2} = \frac{n^2}{4g} + \frac{3n}{4}, \quad 0 < g \leq n \tag{B.10}$$

Where g is the number of groups into which the nest will be divided. It has been assumed that the groups' positions will be predetermined and it will not be necessary to search for their location.

The time spent in the search can then be obtained by multiplying the total number of attempts by the average time spent per attempt which was calculated earlier (0.97 seconds). Figure B.2 shows diminishing returns as the number of groups increases, approaching a search time of zero (where every ply is placed in its own group of known location, making searching unnecessary).

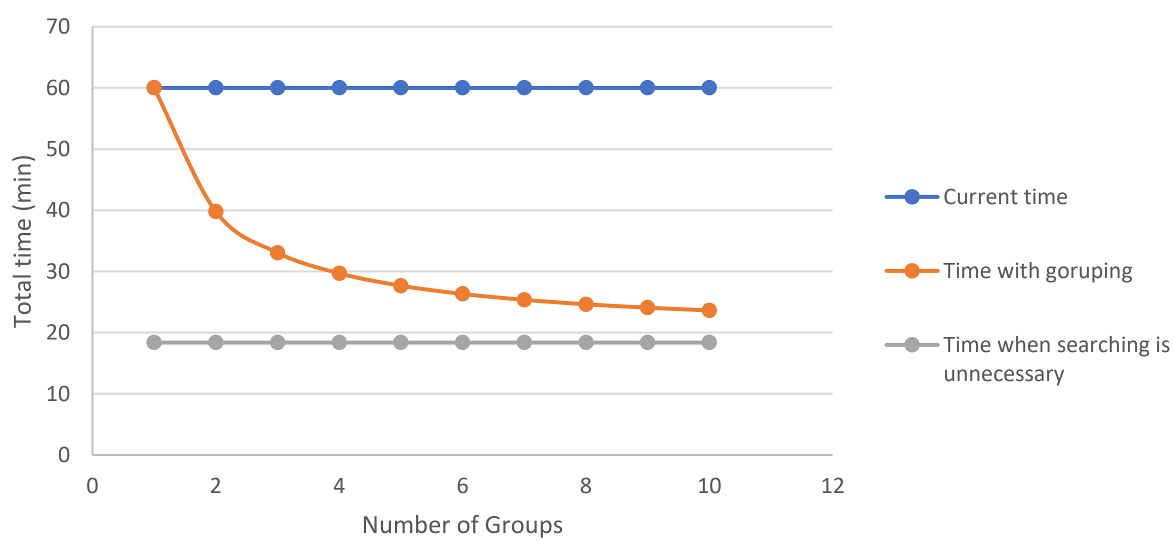


Figure B.2: Influence of nest grouping on total ply collation time.

As the number of groups increases, the nesting efficiency decreases, because the nesting algorithm has a smaller number of plies to nest. Due to this and the diminishing returns observed at high group numbers, it would be prudent to use a small number of groups when implementing this concept. Dividing the nest into two groups, for instance, could reduce collation times by 34%. This, again, would come at the cost of the extra material waste the grouping would cause.

If the sum of the labor and machine operation for one hour is $100, and the current amount of production per day is all that is needed, one can calculate the maximum possible savings by assuming the extra material cost is negligible. Using equation (B.9) and multiplying by the time per attempt, one can determine that dividing the nesting into 3 groups will lead to a search time of 11.3 minutes. Adding the time spent transporting the plies, as well as other activities, a total time of 29.7 minutes is obtained, which will be rounded to 30 minutes for simplicity's sake. The total collation time is cut in half, meaning 12 hours of work per day are saved. This is a maximum of $1200 per day, and $2,190,000 in five years.

B.3.4 Effect of Focus Light and Monitor Concepts

The focus light and monitor concepts were examined as one, since both work by directly showing the location of the next ply to the technician. As such, the time spent looking for specific plies is immediately reduced to zero. What remains in the case where there are 100 plies to be collected is the time transporting the plies to the cart and walking back to the next ply's location (10 minutes 44 seconds), and the time spent idling, stacking the plies, or any other activity (previously called activity 3 and assumed to last between 5 and 10 minutes for a 100-ply kit). As such, the total time is reduced to around 18 minutes and 44 seconds. This constitutes a 69.6% decrease to the total ply collation time, without any reduction to the nesting efficiency (and therefore no added waste). One can now estimate that up to $1680 can be saved per day, and $3,066,000 can be saved in five years using either one of these methods.

B.3.5 Accounting for Different Kit Sizes

To be able to apply the analysis conducted in this section to different cases with differing numbers of plies, a method to use the total ply number to estimate the nesting kit's length was developed.

If the number of plies is proportional to the square of the kit-length, that is:

$$n \propto L^2, \tag{B.11}$$

It can be assumed that, on average:

$$n = C \times L^2 \rightarrow L = \sqrt{n/C} \tag{B.12}$$

C is a coefficient to be determined. It is reasonable to relate the number of plies to the square of the length, as an increase in plies implies an increase in area. Since it was earlier assumed that a 100-ply kit had a length of 50 ft, it was possible to find the value of C. So:

$$L = \sqrt{n/25} = \frac{\sqrt{n}}{5} \tag{B.13}$$

With this relationship, it was possible to find the change to the collation time as it relates to the total number of plies to be collected in the job. The total collation times were calculated for the monitor and focus light concepts, the group nesting concept, and the current concept. This was done using equations (B.2), (B.4), (B.10), and (B.13). The results of these calculations are presented in Figure B.3.

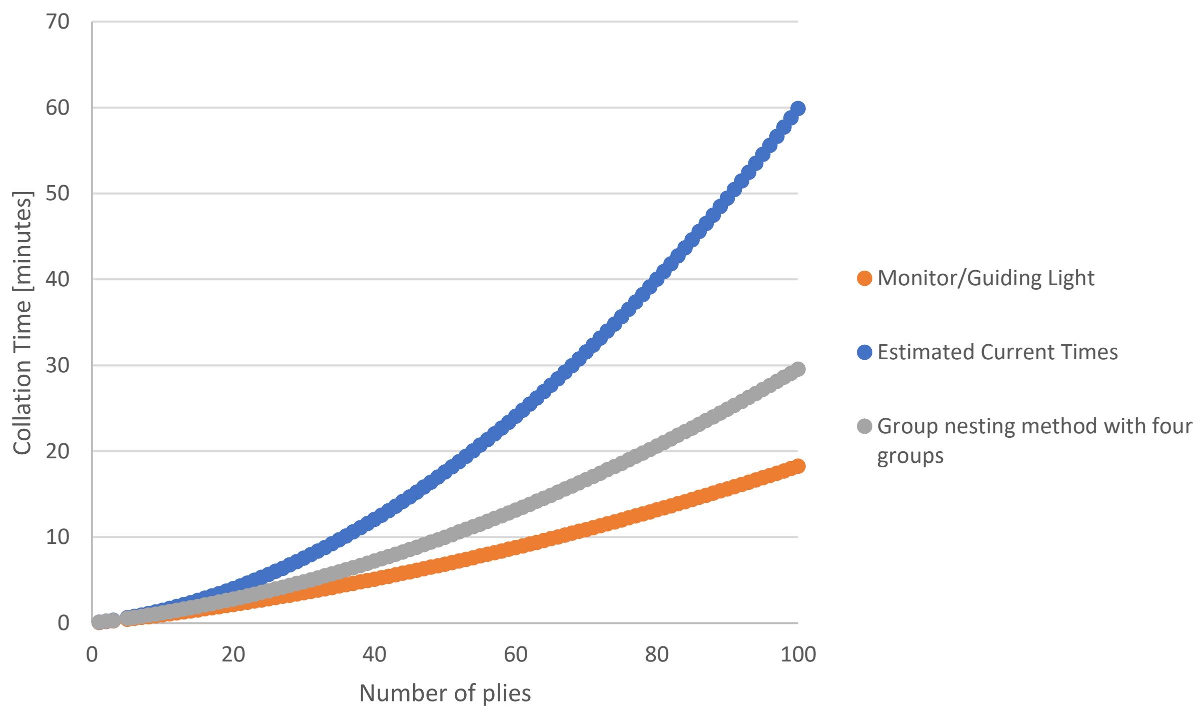


Figure B.3: Relationship between total collation times and total job size for the focus light/monitor concepts, group nesting with four groups, and the current process.

The improvement between the current process's collation time and the concepts evaluated in this section increases as the number of plies to be collected increases. The difference between the monitor/focus light concept and the group nesting method also increases with the number of plies, with the monitor/focus light concepts coming out ahead in terms of collation time reduction.

B.3.6 Manual Concept Scoring

The estimates for total collation time and savings over a five-year period obtained in the previous analysis section for the different concepts were only rough approximations, but they served as comparison points for the different concepts. A more thorough comparison was qualitatively carried out, and it is shown in TABLE B-III.

TABLE B-III: COMPARISON OF THE PERFORMANCE OF DIFFERENT MANUAL CONCEPTS ACCORDING TO SELECTED CRITERIA.

Criterion	Monitor	Group Nesting	Focus Light
Cycle time for small kit (3 m length)	Cycle time is the lowest and independent from kit size.	Cycle time is the lowest and independent from kit size.	Cycle time is slightly higher, and depends on the kit size.
Cycle time for large kit (15.2 m length)	Cycle time is the lowest and independent from kit size.	Cycle time is the lowest and independent from kit size.	Cycle time is much higher at large kit sizes.
Material Utilization	No increase in material waste.	No increase in material waste.	Grouping lowers nesting efficiency, increasing material waste.
Risk of injury to technicians in immediate vicinity	No increase from current levels.	No increase from current levels.	No increase from current levels.
Repetitiveness of task	No need to search repeatedly.	No need to search repeatedly.	Technician still needs to search for necessary ply every time.
Comfort of design for technicians	No extra walking due to searching.	No extra walking due to searching.	Technician still must walk around the table many times while searching.
Intuitiveness	Monitor shows where the ply is located on a layout of the worktable.	Focus light shows exactly where the ply is physically located.	Only the general location of the ply will be known.
Risk of damage to prepregs	No increase from current process.	No increase from current process.	No increase from current process.
Initial cost	Must buy monitor and set up a way for it to show the nested kit and the order of the plies to be collected.	The light/laser system must be purchased and installed. A controller must be made for it to be able to point to the correct location.	No purchases needed. Only need to make change to current nesting process.

Payback Period	The effect is the same as the focus light, but the cost is y much less.	The effect is the same as the monitor, but the cost is higher.	Low-to-no initial cost and high returns (albeit not as high as the other two concepts).
Operating noise level at 3 m distance	No increase.	No increase.	No increase.
Ease of installation	Requires only to be fed the nest and the location of the parts.	Must be installed above the table, a controller must be created, and the nest must be communicated to it.	No installation other than minor changes to nesting algorithm.
Manufacturability	Does not apply.	Does not apply.	Does not apply.

With the help of the qualitative analysis in TABLE B-III, the different concepts were scored in accordance to the scoring matrix presented in B.1.1 of this report.

TABLE B-IV presents the results obtained from this scoring.

TABLE B-IV: MANUAL CONCEPTS SCORING MATRIX.

Criteria	Relative Weight	Guiding Light	Monitor	Group Nesting
Cycle time for small kit (3 m length)	0.090	3	3	1
Cycle time for large kit (15.2 m length)	0.103	3	3	1
Material utilization	0.077	3	3	1
Risk of injury to technicians in immediate vicinity	0.154	3	3	3
Repetitiveness of tasks	0.026	3	3	1
Comfort of design for technicians	0.038	3	2	1
Intuitiveness	0.013	3	2	1
Risk of damage to prepregs	0.128	3	3	3
Initial cost	0.064	1	2	3
Payback period	0.115	1	2	3
Operating noise level at 3m distance	0.000	3	3	3
Ease of installation	0.051	1	2	3
Manufacturability	0.141	3	3	3
Total Score		**2.538**	**2.718**	**2.308**

Out of the three manual concepts, the monitor obtained the highest score in the concepts ranking matrix. The focus light concept was second, and group nesting ended at the bottom of the list. For this reason, the monitor concept passed this round of elimination and was later compared against the best of the automated concepts.

B.4 AUTOMATED CONCEPTS

In this section, various automated design concepts are discussed. When the team began brainstorming automated concepts, a wide variety of ideas were brought forward. These concepts ranged from simple cartesian gantry systems, to more complicated robotic arm and rail systems. It should be noted that use of robotic arm in picking and placing items is known as pick-and-place process in industry [1]. The team noticed that most of the automated designs that were generated could be separated into three independently functioning components:

- **The End Effector**: Mechanism that makes direct contact with the plies. It is used to grip the plies to pick them up and drop them off.
- **The Arm**: Method for reaching for the plies and holding the end effector.
- **The Mobility System:** Allows the arm and end effector to cover the full length of the cloth cutting table.

For each of the components above, multiple concepts are presented. The concepts for each component are interchangeable with the concepts of the other components. For example, a robotic arm may able to hold different types of material grippers, and may also be attached to different types of mobility systems.

The group of concepts for each component were evaluated individually to determine the best options for the end effector, arm, and mobility system. The three best components were then combined to form one automated design concept. The automated concept evaluation against the chosen manual concept will then be presented.

B.4.1 END EFFECTOR

This section presents the concepts for the end effector which is used to grip plies through direct contact during the pick-and-place process. Based on the research in Section A.2, safe handle of prepreg must meet the following essential criteria:

- The end effector must not cause any contamination, delamination, stretching, tear and permanent deformation of the plies.
- The end effector must be able to hold the plies firmly during the pick-and-place process.

There are several gripping technologies that have been developed to be applied as an end effector on the market. As such, the team decided that concepts for the end effector were to be selected and modified from current gripping technologies. The commercially available gripping technologies consist of three types, which have different operating mechanisms. The three mechanisms are pneumatic generated suction, material/surface attraction and mechanically introduced friction [1]. One concept for each mechanism type was selected by the team. These concepts were evaluated according to the weighted criteria, discussed in B.1.1. The most suitable concept was selected as the end effector component of the final automated design. Figure B.1 presents the concepts picked by the team.

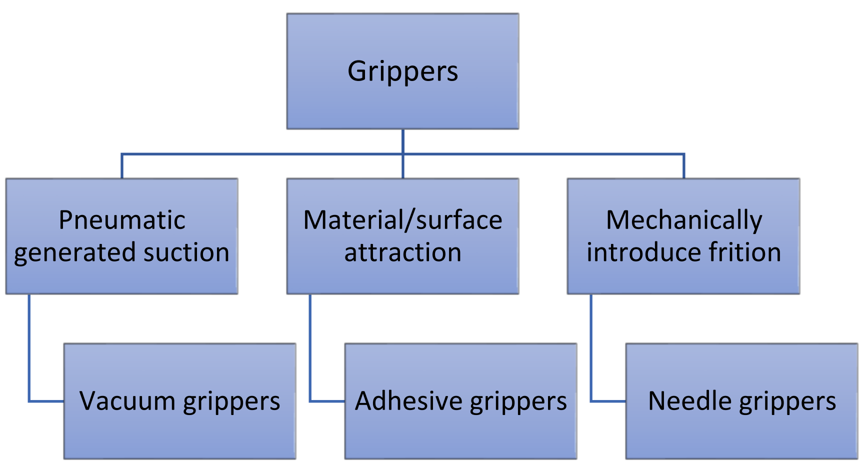


Figure B.4: Gripping technologies on current market, modified from [1].

B.4.1.1 Vacuum Grippers

For concept of vacuum grippers, the end effector will support a grid pattern of vacuum-powered suction cups, or “vacuum grippers”. The grid must be large enough to cover the largest plies of approximately 60”x80”. The grid must also support enough suction cups to allow some of the smaller plies to be picked up with multiple cups. Each suction cup would need to be controlled individually. This would allow only the necessary suction cups to be activated for a ply, without disturbing adjacent plies or the excess prepreg material. Figure B.5 hows an example of one type of commercially available suction cups.

Figure B.5: An example of suction cups on the market [2].

It should be noted that the roughness of the ply’s surface negatively affects the performance of vacuum grippers. To compensate for this, more suction power can be applied to the cups. However, the suction power should be carefully adjusted, since excessive power may draw some portions of the ply into the gripper causing permanent deformation [2]. In general, handling permeable materials like dry fiber fabrics requires high-powered vacuum grippers, while more airtight materials like prepreg can be handled by low-powered vacuum grippers [1].

B.4.1.2 Adhesive Grippers

If adhesive grippers are used, the cut ply would be picked up by an adhesive surface on the end effector. The adhesive zone would be arranged based on the various shapes of the plies to ensure they were lifted firmly without bending. This could require an assortment of quick-change end effectors to account for the variety of ply shapes.

The use of adhesion could provide better grip than the suction method. However, detaching the ply would require more effort, and could even require a mechanical removal device. Also, there would be an increased risk of damaging the ply when it is removed from the adhesive surface. Additionally, the adhesive would degrade over time, causing increased maintenance costs [2].

B.4.1.3 Needle Grippers

Needle grippers function by inserting multiple small needles into the ply. The needles enter the object at opposing 45-degree angles, providing a rigid contact between the gripper and the ply. Needle grippers are especially effective for handling the non-rigid materials like prepreg [3]. The number and the arrangement of gripping points would be similar to the arrangement discussed for vacuum grippers. Figure B.6 illustrates one type of commercially available needle grippers.

[redacted]

Figure B.6: An example of needle grippers on the market [5].

Although the act of needles penetrating the prepreg seems like it may cause damage, it has been proven by physical tests that the penetration does not reduce integrity of the prepreg's structure. However, needle grippers are known to cause objects to move unpredictably when being dropped off [2], which may cause difficulty when dropping the plies off.

B.4.1.4 End Effector Concept Scoring

TABLE B-V presents the concepts scoring results for the selection of the end effector. It should be noted that each concept was awarded a score of zero if their performance for a criterion is considered to be the same.

TABLE B-V: END EFFECTOR CONCEPT SCORING MATRIX

Criteria	Relative Weight	Vacuum Grippers	Adhesive Grippers	Needle Grippers
Cycle time for small kit (3 m length)	0.090	0	0	0
Cycle time for large kit (15.2 m length)	0.103	0	0	0
Material utilization	0.077	0	0	0
Risk of injury to technicians in immediate vicinity	0.154	3	3	2
Repetitiveness of tasks	0.026	3	1	3
Comfort of design for technicians	0.038	3	1	3
Intuitiveness	0.013	0	0	0
Risk of damage to prepregs	0.128	2	1	2
Initial cost	0.064	2	3	1
Payback period	0.115	3	2	2
Operating noise level at 3m distance	0.000	1	3	2
Ease of installation	0.051	0	0	0
Manufacturability	0.141	0	0	0
Total Score		**1.385**	**1.077**	**1.051**

The effect on the cycle time of the collation process was assumed to be the same for all three concepts. The material utilization in this case is identical for all three concepts as well, since the end effector does not affect the nesting program which controls the material utilization.

The price for one suction cup in the market is approximately 160 CAD [4], and the price for one needle gripper is approximately 920 CAD [5]. The adhesive grippers are relatively inexpensive. However, the degradation of the adhesive over time requires the frequent replacement of the adhesive surface. Also, the possibility of causing tear and transferring glue on the plies could lead to the high risk of damage to prepregs when using adhesive grippers.

The vacuum grippers received the highest score. They received the lowest score for the operating noise, but, since this criterion was given a weight of zero, they still performed better than the other concepts. This is because the vacuum grippers result in safe and effortless operation for technicians, as well as the relative low risk of material damage.

B.4.2 ARM

This section presents concepts for the arm component of the automated solution. The arm, which was not required to be an arm in the literal sense, serves to hold the end effector and provide a method of reaching the cutting-table from the base of the arm. In addition to the customer needs, the arm had to meet three basic functional needs. These needs were not used to evaluate the concepts in this section, they simply serve as minimum criteria for determining what concepts to consider. The three functional needs were as follows:

- The arm must be able to allow the end effector to reach the entire width of the table.
- The arm must be able to support the weight of the end effector.
- The arm must be able to remove the ply from the cutting table, once it has been grasped by the end effector, and relocate it onto a designated stacking location (within the arm’s reach).

There is a wide variety of industrial robotic arms available in the market. These robots vary in application, size, form, and cost. With throughput and quality being crucial for most manufacturing industries, these robotic arms are generally designed to operate quickly and precisely. Two of the concepts in this section are commercially available robotic arms.

In addition to the commercially available robotic arms, a custom made robotic arm was also considered as a concept. The final concept considered did not involve a robotic arm at all; it simply involved attaching the end effector directly to the downward-facing side of a gantry.

These concepts are discussed in greater detail in the following subsections. After each concept has been introduced, their evaluation using the weighted criteria discussed in Section B.2 will be presented.

B.4.2.1 ABB 6-Axis Robotic Arm

There are many companies that manufacture industrial robotic arms, offering similar products at similar price points. The team selected a robot from ABB for two reasons. Firstly, ABB is one of the leading companies in industrial robotic technology. Secondly, BCW has prior experience working with ABB robot systems and software, which would reduce any training and testing that may be necessary to implement a new robotics program.

The possibility of a 6-axis arm, which would allow excellent flexibility and positioning of the end effector, was examined. 6-axis robots allow the end effector to be oriented any direction in space.

Next, the team considered the required reach of the robotic arm. The arm had to be able to allow the end effector to reach the entire width of the table, as well as the cart where the plies will be stacked as they are picked up. Assuming the end effector would be at least the width of the table, 6 ft. (2 m) across, the robot had to be able to reach the centre of the table. The team also assumed that the base of the robot will be located 1.5 ft. (0.5 m) from the side of the table. Therefore, a minimum reach of 1.5 m would be required.

Finally, the team considered the maximum allowable payload of the robotic arm. For this selection process, the team initially assumed that the end effector will weigh no more than 25 lb (B.3 kg), and the ply being picked up will weigh less than 1 lb (0.5 kg).

By considering the weight, reach, and ABB's recommended applications for the arm, the team has chosen the IRB 2600, shown below in Figure B.7.

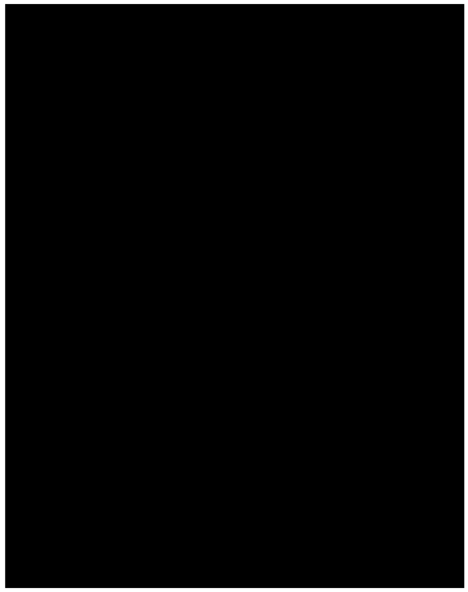


Figure B.7: ABB IRB 2600, 6-axis robotic arm [6].

The price of this robot is not publicly available, and the team was not able to receive a quote from ABB. However, RobotWorx, an authorized integrator and distributor of ABB robots, estimates that new industrial robots cost between $100,000 to $150,000 [6]. It was assumed that these values are in Canadian dollars, as the website does not specify.

Lastly, although the IRB 2600 was chosen for this concept, a different 6-axis robot could have been selected later if it were better suitable for the chosen Mobility System (Section B.4.3). For example, if the base of the robot were to be attached to a gantry system directly above the cutting-table, a robot of shorter reach could be preferred. Similarly, if the robot needed to be located further from the table than the assumed value of 0.5 m, a robot of longer reach could be required.

B.4.2.2 ABB 4-Axis Robotic Arm

In addition to the 6-axis robot already discussed, the team considered a 4-axis robot from ABB for this concept. For the selection of a 4-axis robot, the team used the same minimum criteria that was used for the 6-axis robot: the arm must have a minimum reach of 1.5 m and a payload of 11.8 kg.

By considering the weight, reach, and ABB's recommended applications for the arm, the IRB 260 was selected and is shown in Figure B.8. This root has a reach of 1.52 m and payload of 30 kg [7].

[redacted]

Figure B.8: ABB IRB 260, 4-axis robotic arm [7].

RobotWorx, an authorized integrator and distributor of ABB robots, provides some of the possible benefits and drawbacks of 4-axis robots when compared to 6-axis robots. 4-axis robots tend to be quicker and more precise than 6-axis robots of comparable size [8]. They also tend to be lighter and more economical due to their relative simplicity. The main drawback of 4-axis robots is their inferior versatility and limited movement when compared to 6-axis robots. However, since the plies in the collation process will generally be picked and placed in a horizontal orientation, the additional versatility of the 6-axis robot would not add any value.

B.4.2.3 Custom 2-Axis Robotic Arm

It would be possible to perform the pick-and-place operation with only two degrees of freedom. The first degree of freedom is a vertical axis at the base of the arm, allowing the arm to swing back and forth. The second degree of freedom is a horizontal axis at the base of the arm, allowing it to move up and down. Both axes would be motorized.

Figure B.9, below, shows a side and top view of the custom robotic arm and illustrates its movements. This figure is a simplified model of what the final product may look like.

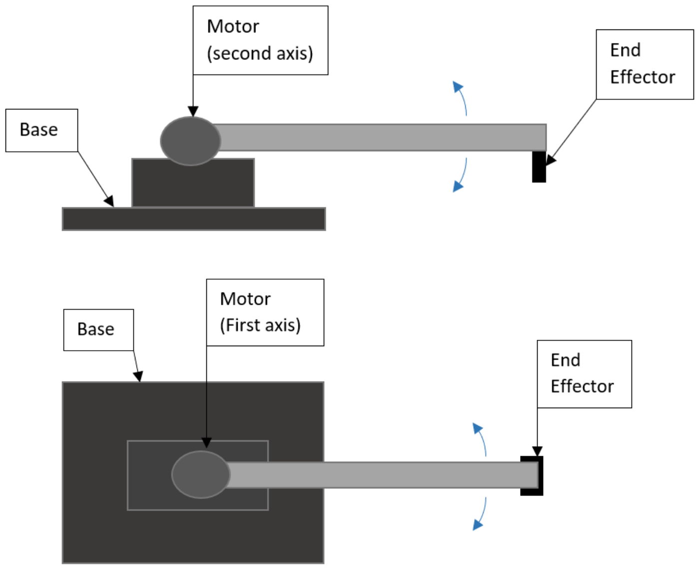


Figure B.9: Side view and top view of the custom 2-axis robotic arm (simplified model).

Since the cut-out plies are relatively light, the robotic arm would only need to be designed to lift light payloads. This would lower the amount of material required to fabricate the arm, and therefore reduce the cost. Additionally, the arm could be built from simple aluminum parts, eliminating the need for complex manufacturing methods. The major source of cost would be the two motors and the control systems that would be required to operate the robot.

This robot would not necessarily be as precise or versatile as the commercially available industrial robots. However, due to the relative simplicity of the pick-and-place operation, a high degree of precision and versatility may not add value. The speed of this robot would most likely be comparable to the speed of the commercially available options, but further research and testing would be necessary to confirm this.

B.4.2.4 End Effector Attached Directly to Gantry

The end effector could be attached to either the existing gantry, the American GFM US-40, or to a separate gantry. The selection of which gantry the end effector will be attached to will be discussed in Section B.4.3.

If the end effector is designed to cover the entire width of the table, this concept would function with only two degrees of freedom: vertical motion to raise and lower the end effector and linear motion to move the end effector down the length of the cutting-table. This would simplify the programming, lower equipment costs, and facilitate quicker movements.

A drawback of this design is the lack of movement versatility. Once the ply has been grasped by the end effector, the gantry must travel down the length of the cutting-table to place the ply into a designated collection pile. This repetitive back-and-forth motion down the length of the table will drastically increase the cycle time. In contrast, the robotic arm concepts previously discussed can place collected plies on a platform that is fixed to its base, reducing the need for this back-and-forth motion.

B.4.2.5 Arm Concept Scoring

The weighted criteria, discussed in Section B.2, were used to compare each concept, which were ranked from one to four, with four being the best and one being the worst. The score of each concept (one to four) was multiplied by the weight of the corresponding criterion. This product will then be summed for all concepts, and the design with the highest score will be determined the most suitable design.

For most of the criteria, the concepts are evaluated qualitatively. Additional details on how the concepts are evaluated are shown in TABLE B-VI. Criteria that has already been discussed in the sections B.4.2.1 to B.3.4 will not be discussed in further detail.

TABLE B-VI: COMPARISON OF THE PERFORMANCE OF DIFFERENT ARM CONCEPTS ACCORDING TO THE CRITERIA

Criterion	Rationale
Material Utilization	Since the existing nesting will be remain unchanged for all concepts, each concept was given a rank of four.
Risk of injury to technicians in immediate vicinity	Each of the automated concepts will be paired with safety boundaries, such as light curtains or physical barriers. Each concept was given a rank of four.
Repetitiveness of task	Each concept eliminates the repetitive tasks of the current manual collation process. Each concept was given a rank of four.
Comfort of design for technicians	The gantry concept was given a lower rank of three. This is due to the plies being placed onto the cutting table rather than onto a cart. This forces the technician to relocate the plies from the table onto the cart.
Payback Period	With the cycle times for each concept only varying slightly, the payback period was based purely on the initial cost. To achieve a more accurate estimate for the payback period, more accurate quotes and a detailed motion analysis for each concept would be required.
Manufacturability	The custom arm and gantry concepts were given a slightly lower score. This is because these concepts may require some custom components. In contrast, the ABB robotic arms are generally purchased as a complete unit, requiring no additional part fabrication.

TABLE B-VII shows how each concept scored for each criterion, and provides the total weight.

TABLE B-VII: ARM CONCEPT SCORING MATRIX

Criteria	Relative Weight	IRB 2600	IRB 260	Custom Arm	Gantry
Cycle time for small kit (3 m length)	0.090	3	4	2	1
Cycle time for large kit (15.2 m length)	0.103	3	4	2	1
Material utilization	0.077	4	4	4	4
Risk of injury to technicians in immediate vicinity	0.154	4	4	4	4
Repetitiveness of tasks	0.026	4	4	4	4
Comfort of design for technicians	0.038	4	4	4	3
Intuitiveness	0.013	4	4	3	4
Risk of damage to prepregs	0.128	4	4	4	4
Initial cost	0.064	1	2	3	4
Payback period	0.115	1	2	3	4
Operating noise level at 3m distance	0.000	4	4	4	4
Ease of installation	0.051	4	4	3	4
Manufacturability	0.141	4	4	3	3
Total Score		3.269	3.641	3.231	3.244

The IRB 260 received the greatest score and was therefore chosen as the most suitable concept. This means that the IRB 260 will be grouped with the best end effector and mobility system components to form the final automated concept.

B.4.3 MOBILITY SYSTEM

The mobility system is a design that allows the entire 50-foot length of the cutting-table to be reached by the arm and end effector assembly. The team brainstormed many ideas, from rail systems to free roaming wheel based robots. However, only the most feasible concepts were evaluated.

For all the following designs, it was assumed that the collection table, where the plies are to be stacked once they have been picked up, would be attached to the mobility system. This would reduce the need for the mobility system to travel back and forth to the collection table, as it would always be within the robotic arm's reach.

Following each concept's introduction, their evaluations using the weighted criteria are presented.

B.4.3.1 Existing Gantry

Making use of the existing gantry, the base of the robotic arm would be attached directly to cloth cutting gantry currently being used at BCW. The gantry is an American GFM US-40.

The team was not able to determine if it would be feasible to attach the robot directly to the US-40. However, it would be reasonable to assume that the US-40, which was primarily designed as a cloth cutting gantry, was not designed to support an additional 340 kg load.

Therefore, although this design would allow the robotic arm to reach the full length of the table, the gantry would require extensive reinforcement to support the weight of the IRB 260, and may not be possible at all. Consequently, this design would be difficult to implement and would most likely slow down the movement speed of the gantry.

B.4.3.2 Separate Gantry System

A separate gantry system would allow the base of the robotic arm to rest on it. This gantry would rest on rails that would run parallel to the length of the table, and lie on either side. This would allow the robotic arm to cover the full length of the table. There would be no need for the gantry to move across the width of the table or in the vertical direction. With the elimination of two degrees of freedom of the gantry, the system would be reduced to a simple rail system that runs directly above the cutting-table.

To support the 340-kg weight of the IRB 260, the gantry which would have to span at least 3 m to clear the cutting-table would need to be considerably robust. This added weight would decrease the speed of the gantry along the length of the table, and increase construction cost.

Due to the unique requirements of the gantry, it would be more suitable to manufacture a custom system rather than purchase a commercially available option.

B.4.3.3 Independent Rail System

If an independent rail system were to be implemented, the base of the robotic arm would rest on a rail system. The rail system would be located off to the side of the cutting-table, and would run parallel to its length. The robotic arm would be required to reach towards the table to allow the end effector to pick up the plies.

In contrast with the previous concepts, this design would allow the robotic arm to lie directly over the rails. This would allow the design to be much lighter and move more quickly. Additionally, this design would interfere less with the existing cloth-cutting gantry.

There are many commercially available industrial rail systems. For this concept, the team selected the SEV220-2 Seventh Axis, from Rollon Linear Evolution. A similar system from Rollon is shown below in Figure B.10. The SEV220-2 is capable of speeds of up to 4 m/s, can hold a maximum payload of up to 1200 kg, and is available in lengths of up to 46 m. In addition, the product information page for the SEV220-2 lists the IRB 260 as one of the recommended robots to pair with [9].

Figure B.10: Seventh Axis System from Rollon [9].

B.4.3.4 Series of Static Mounting Points

Until this point in the concept selection process, the team explored concepts that involve moving the base of the robot along the length of the table. An alternative to this method would be a series of robotic arms along the length of the table.

For this design to succeed, there would need to be enough robots to cover the entire range of the table. With the IRB 260's reach of 1.52 m, and a table length of 50 ft (15.2 m), an estimated value of over 10 robotic arms would need to be installed over the length of the table. To determine the actual number of robotic arms, further optimization would be required, but is not necessary for the concept evaluation.

It is also important to mention that, to stack all the plies in one single collection pile, a rail system would be required in addition to the series of robots. This rail system serves to bring the ply collection platform down the length of the table, allowing the robotic arms to stack the plies in the correct order.

Overall, this design would have a much higher initial cost, be much more difficult to program and install, and may see only small cycle time improvements.

B.4.3.5 Mobility System Concept Scoring

The weighted criteria, discussed in Section B.1, was used to compare each concept, which were ranked from one to four, with four being the best and one being the worst. The score of each concept (one to four) was multiplied by the weight of the corresponding criterion. This product was summed for all concepts and the design with the highest score was determined to be the most suitable design.

For most of the criteria, the concepts were evaluated qualitatively. Additional details on how the concepts are evaluated are shown in TABLE B-VIII.

TABLE B-VIII: COMPARISON OF THE PERFORMANCE OF DIFFERENT MOBILITY SYSTEM CONCEPTS ACCORDING TO THE CRITERIA

Criterion	Rationale
Material Utilization	Since the existing nesting will be remain unchanged for all concepts, each concept was given a rank of four.
Risk of injury to technicians in immediate vicinity	Each of the automated concepts will be paired with safety boundaries, such as light curtains or physical barriers. Each concept was given a rank of four.
Repetitiveness of task	Each concept eliminates the repetitive tasks of the current manual collation process. Each concept was given a rank of four
Payback Period	With the cycle times for each concept only varying slightly, the payback period was based purely on the initial cost. To achieve a more accurate estimate for the payback period, more accurate quotes and a detailed motion analysis for each concept would be required.
Manufacturability	Both gantry concepts were given a lower score. This is because these concepts may require additional reinforcements and material in order to support the weight of the robotic arm. In contrast, the series of robots, and separate rail systems are usually available as complete units, requiring only to be installed.

TABLE B-IX shows how each of the concepts have been evaluated for the weighted criteria.

TABLE B-IX: MOBILITY SYSTEM CONCEPT SCORING MATRIX

Criteria	Relative Weight	Existing Gantry	Separate Gantry	Separate Rail	Series of Robots
Cycle time for small kit (3 m length)	0.090	3	3	4	3
Cycle time for large kit (15.2 m length)	0.103	1	2	4	3
Material utilization	0.077	4	4	4	4
Risk of injury to technicians in immediate vicinity	0.154	4	4	4	4
Repetitiveness of tasks	0.026	4	4	4	4
Comfort of design for technicians	0.038	4	4	4	4
Intuitiveness	0.013	4	4	4	3
Risk of damage to prepregs	0.128	4	4	4	4
Initial cost	0.064	3	2	4	1
Payback period	0.115	3	2	4	1
Operating noise level at 3m distance	0.000	4	4	4	4
Ease of installation	0.051	2	3	4	1
Manufacturability	0.141	2	3	4	4
Total Score		**3.038**	**3.154**	4.000	**3.103**

The separate rail concept scored the highest, and will therefore be combined with the best arm and end effector to form a complete automated concept. This is discussed in the next section.

B.4.4 Final Automated Design

This section summarizes the preliminary automated concept. This section also provides detailed supporting performance calculations for the automated solution. The results from this analysis were used, in part, to evaluate the automated concept against the manual concept.

At the beginning of Section B.4, it was specified that the automated solution would be split into three components: the end effector, arm, and mobility system. In sections B.4.1 to B.4.3, concepts for each of these components were presented and weighed against each other. The final design selected for each component is shown in TABLE B-X.

TABLE B-X: SELECTION OF EACH COMPONENT FOR FINAL AUTOMATED DESIGN

Automated Design Component	Final Design Selection
End Effector Mechanism	The concept that has been chosen as the best option is the **suction cup gripping method**. The detailed design of the end effector design will not be developed at this point.
Arm	The concept that has been chosen as the best option is the **ABB IRB 260**, a 4-axis robotic arm.
Mobility System	The concept that has been chosen as the best option is the separate rail system. Specifically, the model **SEV220-2 Seventh Axis**, from Rollon Linear Evolution, would offer excellent performance.

The preliminary automated design concept is a combination of these three components. Therefore, the preliminary automated design consists of a suction cup end effector, carried by the IRB 260 robotic arm, which is attached to the SEV220-2 Seventh Axis linear rail system.

B.4.4.1 Robot Performance Analysis

A model was created for the calculation of the average time spent travelling between one ply pick-up point and another during the collating process. The average time per part can then be expressed as:

$$\overline{T} = \frac{0.5L}{v} \tag{B.14}$$

Where n is the total number of plies to be collected, L is the kit's length, and v is the velocity with which the robot travels parallel to the worktable.

The next time to be evaluated is the time it takes for the robot arm to reach the ply in question once it is within reach. For this estimate, it was assumed that a 4-axis industrial robot, viz. the IRB 260, would be used. The dimensions associated with this robot are listed in Figure B.11. The end effector as of this time has not been designed, and it could be made to reach further down.

Figure B.11: IRB 260 dimensions and range of motion [7].

If the base of the robot is located above the middle of the worktable at a height H above the location of the plies, it is possible to estimate the time it will take for the robot to reach a ply.

Taking the horizontal reach of the robot to be 1526 mm (L_1), the average rotation necessary to reach a ply assuming the robot starts at the middle of the table is computed as:

$$\bar{\theta}_1 = \sin^{-1}\left(\frac{W/4}{L_1}\right) = \sin^{-1}\left(\frac{914.4/4\ mm}{1526\ mm}\right) = 17.43° \qquad \text{(B.15)}$$

With a maximum base rotation speed [10] of 153°/s, the time spent on average on the base rotation is:

$$\bar{T}_1 = \frac{17.43°}{153°/s} = 0.11\ s \tag{B.16}$$

Since the plies all lie on the same plane, the positions for the vertical arm, the horizontal arm and the end effector could be held in place just above the plies, where the amount of time it takes to reach the ply once the end effector is above it is negligible. A certain amount of time will also be spent gripping the ply once the robot has positioned itself. It was assumed that this process takes on average one second per ply. At this point, the ply must be transported to a work surface that travels along the worktable with the robot arm. If this surface is placed in such a way that the robot's base must rotate, on average, 90°, then the time spent on this step will be:

$$\bar{T}_2 = \frac{90°}{153°/s} = 0.59\ s \tag{B.17}$$

The movement required for the other axes during this step is much smaller than that of the base, and since all the other axes move at an equal or greater speed [10], these other movements can be done concurrently within the same timeframe.

Finally, the robot must lay the ply on the surface. It was assumed this part will take one more second.

A summary for the analysis above for the case of a 50 ft.-long kit with 100 plies is provided in TABLE B-XI.

TABLE B-XI: ANALYSIS SUMMARY FOR A JOB WITH 100 PLIES IN A 50-FT. LONG KIT

Variables	**Kit length [m]:**	**15.24**
	Kit width [mm]:	**1828.8**
	Gantry velocity [m/s]:	**4**
	Number of plies:	**100**
	Base rotation speed [°s]:	**153**
	Maximum robot reach [mm]:	**1526**
	Average time to grip ply [s]:	**1**
	Average time to deposit ply [s]:	**1**
Results	**Average rotation angle to reach ply [°]:**	**17.43399**
	Average time for gantry to reach ply [s]:	**1.905**
	Average time for robot to reach ply [s]:	**0.113948**
	Average time to reach cart [s] per ply:	**0.588235**
	Total time spent on job [minutes]:	**7.678638**

Given that the average time for the robot to position itself above the desired ply was much lower than the average time for the gantry to reach it, the assumption was made that the robot's movement could be performed while the gantry reaches its destination, so this moment does not contribute to the average time spent on the job. The new summary is shown in TABLE B-XII.

TABLE B-XII: SIMPLIFIED ANALYSIS SUMMARY FOR A JOB WITH 100 PLIES IN A 50-FT LONG KIT

Results	**Average rotation angle to reach ply [°]:**	**17.43399**
	Average time for gantry to reach ply [s]:	**1.905**
	Average time to reach cart [s] per ply:	**0.588235**
	Total time spent on job [minutes]:	**7.488725**

With the equation (B.13) and the relationships established in this section, it was possible to evaluate the total collation times of both the current process and the automated concept. A plot of the collation times for the 4-axis robot arm at different job sizes can be found in Figure B.12.

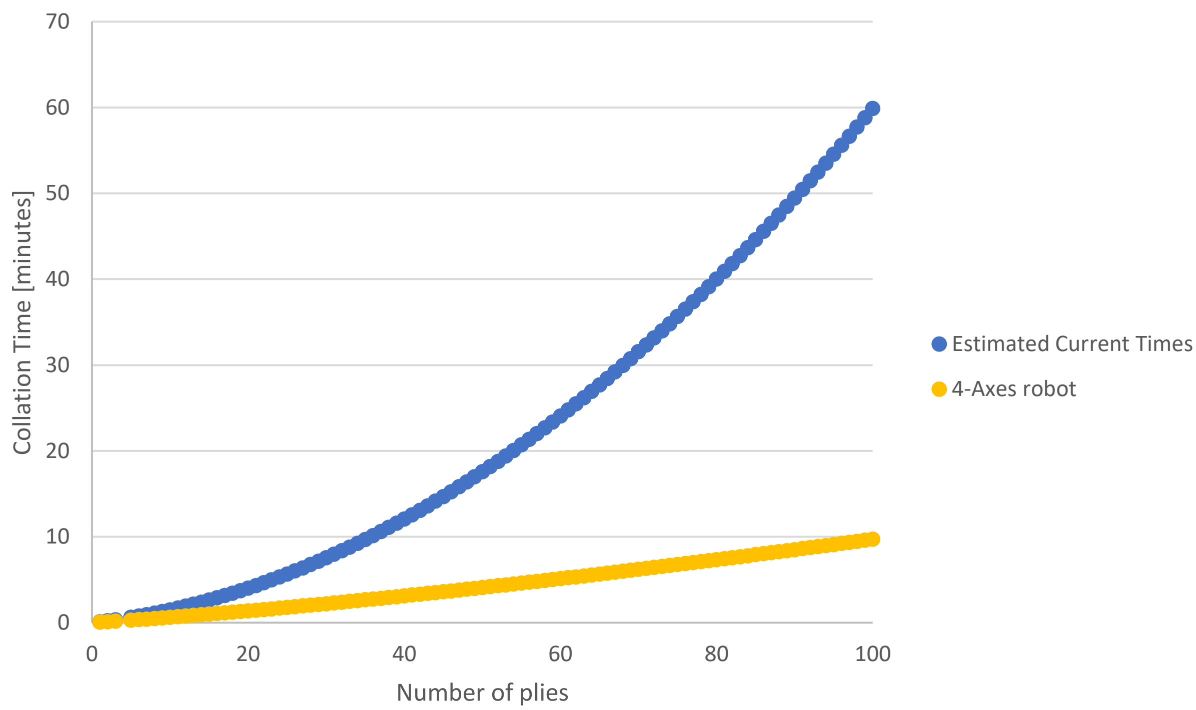


Figure B.12: Collation times as a function of total number of plies for the 4-axis robot arm.

There is a clear reduction in the collation time when comparing the current estimated times and the ones that would result from the 4-axis robot. This difference, however, is dependent on the job size, and increases rapidly as the number of plies increases. In the case of a 50-ft. long kit with 100 plies, the total collation time is reduced by 70%.

B.5 Automated vs. Manual Concept Evaluation

After selecting the best manual and automated concepts, both concepts were evaluated against each other. This section evaluates the two concepts against each other according to the weighed criteria discussed in Section B.2.

The chosen concepts were first compared on the estimated collation time for both small and large kids. Figure B.13 presents a comparison of the total collation times for the 4-axis robot, the monitor-assisted process, and the current process.

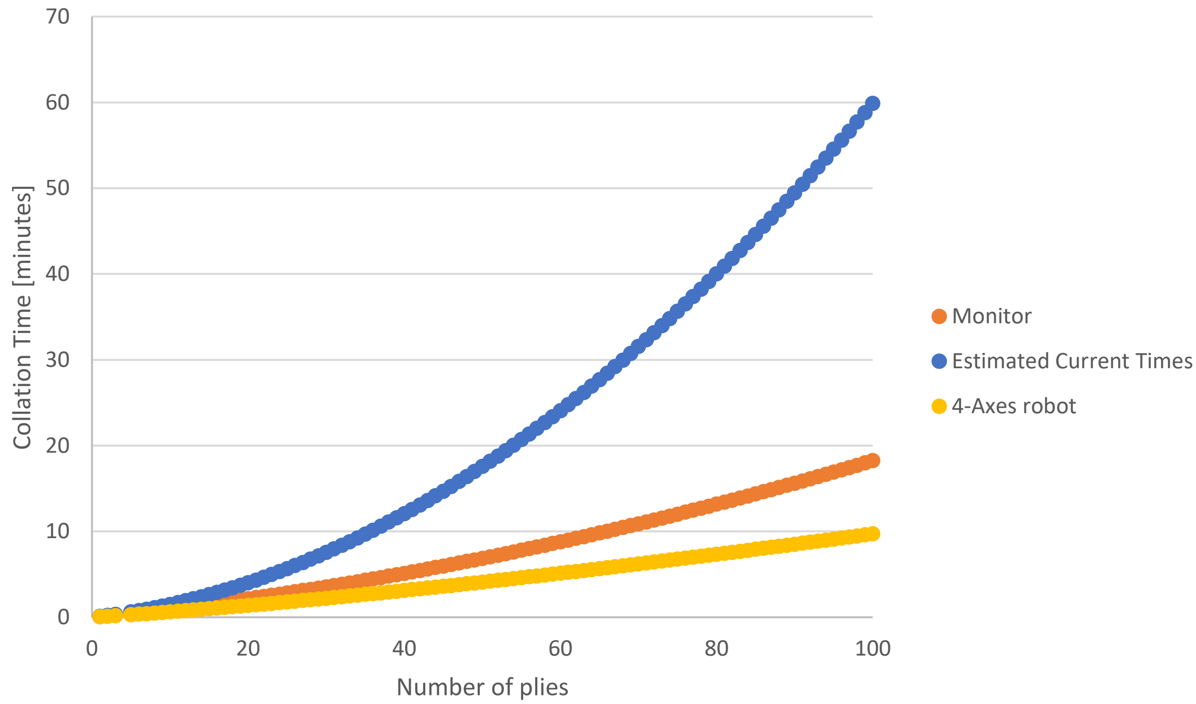


Figure B.13: Comparison of collation times for the selected automated and manual methods as a function of number of plies.

Clearly, the robot's collation time is shorter at every point in the plot Figure B.13.

A qualitative comparison between the monitor-assisted process and the 4-axis robot process was carried out and is presented in TABLE B-XIII.

TABLE B-XIII: COMPARISON OF THE PERFORMANCE OF THE CHOSEN MANUAL AND AUTOMATED PROCESSES ACCORDING TO SELECTED CRITERIA

Criterion	4-axis Robot	Monitor-Assisted Process
Material Utilization	No change.	No change.
Risk of injury to technicians in immediate vicinity	Low to no risk, as no technician is around the robot most of the time.	No increase to risk.
Repetitiveness of task	Zero repetitiveness.	High repetitiveness, as the technicians must travel back and forth for every ply.
Comfort of design for technicians	No technicians for this to apply.	Extensive walking can cause discomfort.
Intuitiveness	Does not apply.	Intuitive, but the technician must still map the layout to the worktable to find the plies.
Risk of damage to prepregs	The end effector will be designed to minimize risk of damage.	Human error can lead to damage.
Initial cost	More expensive than the monitor.	More economical than the robot.
Payback Period	Because of the high cost, the payback period will be longer than that of the monitor-assisted process.	Because of the low cost, the payback period will be shorter than that of the monitor-assisted process.
Operating noise level at 3 m distance	The robot would increase the noise during operation.	No increase.
Ease of installation	The robot involves installing a new base for the robot, programming it, debugging it, etc.	Requires only to be fed the nest layout and the location of the parts.
Manufacturability	Will be bought.	Will be bought.

The comparison above was used to quantitatively evaluate the two concepts as well. The results are presented in TABLE B-XIV.

TABLE B-XIV: FINAL SCORING MATRIX FOR THE 4-AXIS ROBOT AND THE MONITOR ASSISTED PROCESS

Criteria	Relative Weight	4-Axis Robot	Monitor-Assisted Process
Cycle time for small kit (3 m length)	0.090	3	2
Cycle time for large kit (15.2 m length)	0.103	3	1
Material utilization	0.077	3	3
Risk of injury to technicians in immediate vicinity	0.154	3	2
Repetitiveness of tasks	0.026	3	1
Comfort of design for technicians	0.038	3	1
Intuitiveness	0.013	3	2
Risk of damage to prepregs	0.128	3	2
Initial cost	0.064	1	3
Payback period	0.115	1	3
Operating noise level at 3m distance	0.000	2	3
Ease of installation	0.051	1	3
Manufacturability	0.141	3	3
Total Score		**2.538**	**2.282**

The automated process involving a 4-axis robot obtained a higher total score than that of the manual monitor-assisted process. As such, the 4-axis robot concept was selected for further development, which was carried out and presented in the main body of this report.

B.6 References

[1] A. Bjornsson, J. E. Lindback, D. Eklund and M. Jonsson, "Low-cost Automation for Prepreg Handling - Two Cases from the Aerospcae Industry," *SAE International Journal of Material and Manufacturing,* vol. 9, no. 1, pp. 68-74, 2016.

[2] R.O. Buckingham and G.C. Newell, "Automating the Manufacture of Composite Broadgoods," *Composites Part A,* vol. 27A, no. 3, pp. 191-200, 1996.

[3] "New Gripper Solutions for Non-rigid Objects," ROBOTNOR - Center for Advanced Robotics, [Online]. Available: https://robotnor.no/research/new-gripper-solutions-for-non-rigid-objects/. [Accessed 16 October 2017].

[4] "Suction Plates SPL POM-NBR," Schmalze Vacuum Technology Ltd., [Online]. Available: https://www.schmalz.com/en/vacuum-technology-for-automation/vacuum-components/vacuum-suction-cups/suction-cups-for-handling-composites/suction-plates-spl-pom-nbr. [Accessed 16 October 2017].

[5] "Needle Grippers SNG-V," Schmalze Vacuum Technologies Ltd., [Online]. Available: https://www.schmalz.com/en/vacuum-technology-for-automation/vacuum-components/special-grippers/needle-grippers/needle-grippers-sng-v. [Accessed 16 October 2017].

[6] RobotWorx, "How Much Do Industrial Robots Cost?," RobotWorx, [Online]. Available: https://www.robots.com/faq/show/how-much-do-industrial-robots-cost. [Accessed 21 October 2017].

[7] ABB, "ABB IRB 260," ABB, [Online]. Available: http://new.abb.com/products/robotics/industrial-robots/irb-260. [Accessed 21 October 2017].

[8] RobotWorx, "Speed vs Flexibility: 4-axis vs 6-axis robots," RobotWorx, [Online]. Available: https://www.robots.com/articles/viewing/speed-vs-flexibility-4-axis-vs-6-axis-robots. [Accessed 21 October 2017].

[9] R. L. Evolution, "Rollon Seventh Axis Leaflet," Rollon Linear Evolution, [Online]. Available: http://pdf.directindustry.com/pdf/rollon/leaflet-seventh-axis/5182-707724.html. [Accessed 22 October 2017].

[10] ABB, "Technical data for the IRB 260 industrial robot," 2017. [Online]. Available: http://new.abb.com/products/robotics/industrial-robots/irb-260/irb-260-data. [Accessed 22 October 2017].

APPENDIX C: END EFFECTOR DESIGN

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

C.1 END EFFECTOR DESIGN

This section shows details on the analytical and numerical stress analysis performed on the end effector.

C.2 ANALYTICAL STRESS AND DEFLECTION ANALYSIS

Figure C.1 shows the layout of the end effector members.

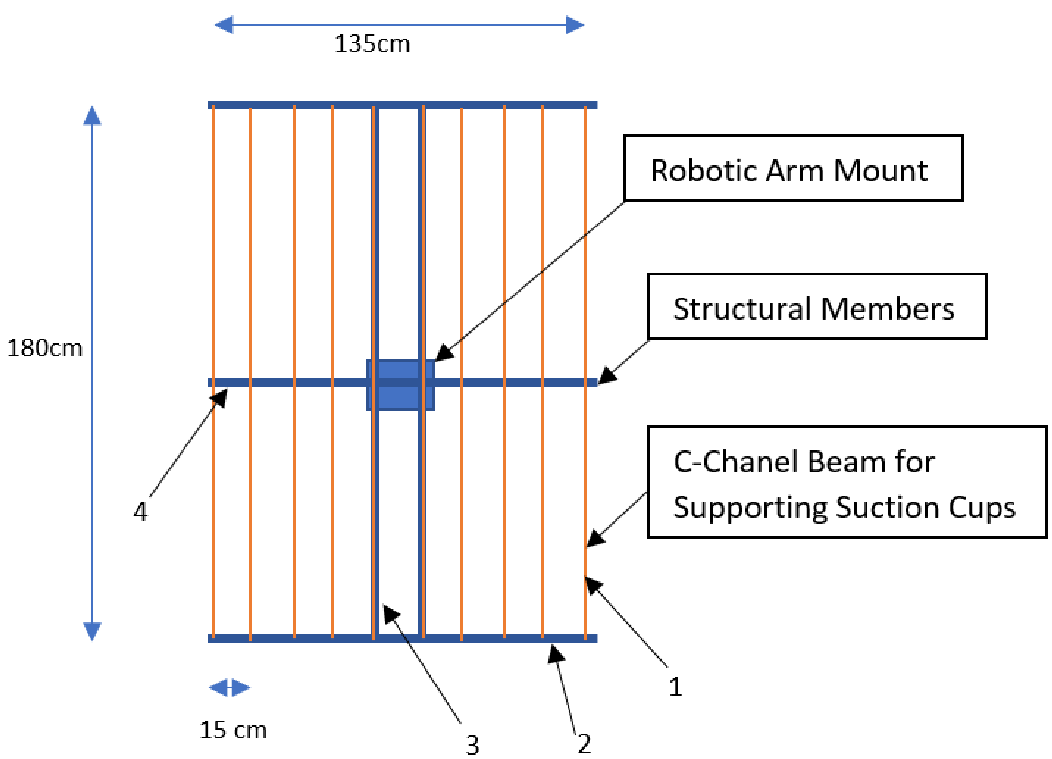


Figure C.1: Preliminary end effector design used for analytical stress analysis, bottom view.

For this analysis, beam theory is applied to individual members to calculate the deflection and stress. The deflection must be kept under 1mm to avoid issues with suction cup gripping.

Member 1 is a commercially available C-Channel with a height, width and wall thickness of 0.0508m, 0.0254m and 0.00375m, respectively. The material of the member is aluminum 6063 with the following material properties [1]:

- Density: 2700 Kg/m^3
- Modulus of Elasticity: 68.9 GPa
- Tensile Yield Stress: 214 MPa

Although the member will run the full length of the end effector, as shown in the figure above, it is fixed at its midpoint. Therefore, we can analyze half of the beam and consider it to be fixed at both ends. The moment of inertia about the neutral axis can be determined as follows:

$$I = \frac{1}{12}[(bh^3) - (b - t)(h - 2t)^3]$$

where *b, h, t,* and *I* are the base, height, thickness, and moment of inertia, respectively.

The only forces acting on the member are the body force and load from the suction cup weight. The load from the 5 suction cups located on the member will be simplified into a uniform distributed load and combined with the body force to acquire a net distributed load, *q*, acting on the member.

$$q = \frac{m + m_{cup} * 5}{L} * 9.81$$

where *m, mcup,* and *L* are the mass of the beam, mass of one cup assembly, and the length of the beam, respectively.

For a beam that has both ends fixed, the maximum moment *M* will be located at the midpoint and can be determined as follows.

$$M = \frac{q \cdot L^2}{12}$$

The point on the beam that experiences the highest bending stress will be at the same location as the highest moment. The maximum bending stress σ can be calculated as follows:

$$\sigma = \frac{M\left(\frac{h}{2}\right)}{I}$$

The maximum deflection *d* of the beam will also be at its midpoint and can be calculated as follows:

$$d = \frac{qL^4}{384\,E\,I}$$

where *E* is the modulus of elasticity of the material.

The results for the analysis on one C-Channel are shown in TABLE C-I.

TABLE C-I: ANALYTICAL RESULTS FOR MEMBER 1

	Magnitude	Units
Bending Stress	0.129	MPa
Deflection	0.002	mm
Mass (for a 1.8m length)	1.71	Kg

As shown in the results table above, the bending stress and deflection are very low. This means that a lighter C-Channel could be selected in the interest of reducing weight, however the functionality of the C-Channels is necessary to efficiently mount the suction cups.

The next member that was analyzed is member 2 from Figure C.1. T-slotted framing was chosen for this member due to its current usage at BCW as well as its high degree of modularity. For this member, a 40x40mm option was chosen. The beam is made of aluminum 6360 and has the following material properties [2]:

- Density: 2700 kg/m^3
- Modulus of Elasticity: 68 GPa
- Tensile Yield Stress: 160 MPa

Although this member spans 1.35 m in length, it is fixed at two points: 60 cm from both ends. Therefore, for the analysis, we will consider the beam to be 60 cm long and fixed at one end. The moment of inertia, *I*, of the cross section of this member was determined to be 13.8 cm^4 from the supplier's website [3]. The total distributed load was determined as follows.

$$q = \frac{m + m_{uc} + 14m_{cup}}{L}(9.81)$$

where m_{uc} is the mass of the full-length C-Channel

For a cantilever beam supported at one end with a uniform distributed load, the maximum bending moment is located at its fixed end, and can be calculated as follows.

$$M = \frac{qL^2}{2}$$

The maximum stress is also located at the fixed end and can be calculated as follows.

$$\sigma = \frac{M\left(\frac{h}{2}\right)}{I}$$

The maximum deflection is located at the free end and can be calculated with the following equation.

$$d = \frac{qL^4}{8E\ I}$$

The results for member 2 are shown in TABLE C-II.

TABLE C-II: ANALYTICAL RESULTS FOR MEMBER 2

	Magnitude	Units
Bending Stress	1.4	MPa
Deflection	0.093	mm
Mass (for a 1.35m length)	3.2	Kg

The bending stress and deflection are well below the yield stress and maximum deflection of 1mm. In the interest of reducing weight, a similar analysis was performed on a smaller T-Slotted beam with a height of 40mm and width of 20mm. However, the deflection at the end of the member increased to 1.4mm. Therefore, the original choice 40x40mm T-Slotted tube was selected for the design.

The next member that was analyzed is member 4 from Figure C.1. This member is also a T-Slotted Aluminum 6360 beam. However, this member has a height of 8cm, width of 4cm, and moment of inertia of the cross section of 15.4cm^4.

This beam is under similar conditions as the previous beam. However, it has a larger distributed load due to additional body force, number of cups, number of supported C-Channels. An additional factor that increased the distributed load is that this beam also supports one block of 13 vacuum ejectors, each having a mass of 0.195 kg. The results for the analytical calculations for beam 4 are shown in TABLE C-III.

TABLE C-III: ANALYTICAL RESULTS FOR MEMBER 4

	Magnitude	Units
Bending Stress	1.06	MPa
Deflection	0.035	mm
Mass (for a 1.35m length)	5.0	Kg

The final member that was analyzed is member 3 from Figure C.1. Member three has the same material properties and cross-section as member 4. However, the loading case differs from member 4. For the following analysis, two 0.9 m parallel lengths of member 3 will be simultaneously analyzed and treated as one beam. The beam is fixed at one end.

The total distributed load acting on this member can be calculated as follows:

$$q = \frac{2m + 52m_{vac} + 10m_{cup}}{L}(9.81)$$

where *m* and *mvac* are the mass of the member and mass of a single vacuum ejector, respectively.

There is also a point load located at the free end of the beam. This point load is the result of the weight of member 2, member 1, and the suction cups. The point load, *P*, can be calculated as follows:

$$P = \left(m_2 + 4m_1 + 16m_{cup}\right) * 9.81$$

where m1 and m2 are the mass of member 1 and 2, respectively.

The maximum moment, M_q, due to the distributed load can be calculated with the same method used for Member 2.

The maximum moment, M_P, caused by the point load can be calculated as follows:

$$M_P = P * L$$

Both maximum moments are located at the fixed end of the beam.

The maximum bending stress can be found with the same equation used for Member 2. In this equation, the sum of both moments, M_p and M_q, must be used in the place of M.

Finally, the deflection at the free end of the beam can be calculated as follows:

$$d = \frac{qL^4}{8EI} + \frac{PL^3}{3EI}$$

The analytical results for member 3 (a single member, not the pair of parallel members) are shown in TABLE C-IV.

TABLE C-IV: ANALYTICAL RESULTS FOR MEMBER 3

	Magnitude	Units
Bending Stress	2.69	MPa
Deflection	0.179	mm
Mass (for a 1.35m length)	3.3	Kg

C.3 Finite Element Analysis of the End Effector Structure

A finite element analysis was performed on the end effector to numerically calculate stress and deflection. Two aspects of the end effector were analyzed separately using SOLIDWORKS

Simulation: The C-Channels, and the centre beam junction at the robotic arm mounting point. The beam junction analysis also determines the beam deflection.

First, the stress and deflection of one of the C-Channels were simulated. The member was fixed at both ends and its midpoint, and was subjected to gravity (9.81m/s/s) and the mass of each suction cup assembly (21g) at their appropriate spacing. The results for Von-Mises stress and deflection were determined to be 1.5 MPa and 0.04mm, respectively, which are well below the yield stress and maximum defined deflection of 1 mm. In the interest of reducing weight, a pattern of twelve 40mm diameter holes were added to the beam. The results for the new stress and deflection are shown in Figure C.2 and Figure C.3, respectively. In these figures, the red, magenta and green arrows represent the gravitational force, suction cup load, and fixed geometry, respectively.

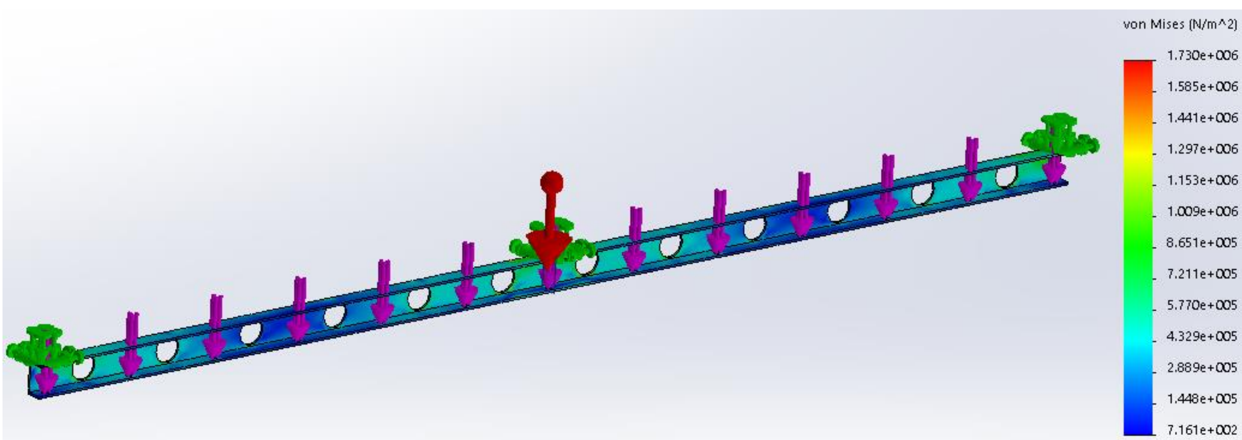


Figure C.2: Von Mises Stress for C-Channel with cut-outs.

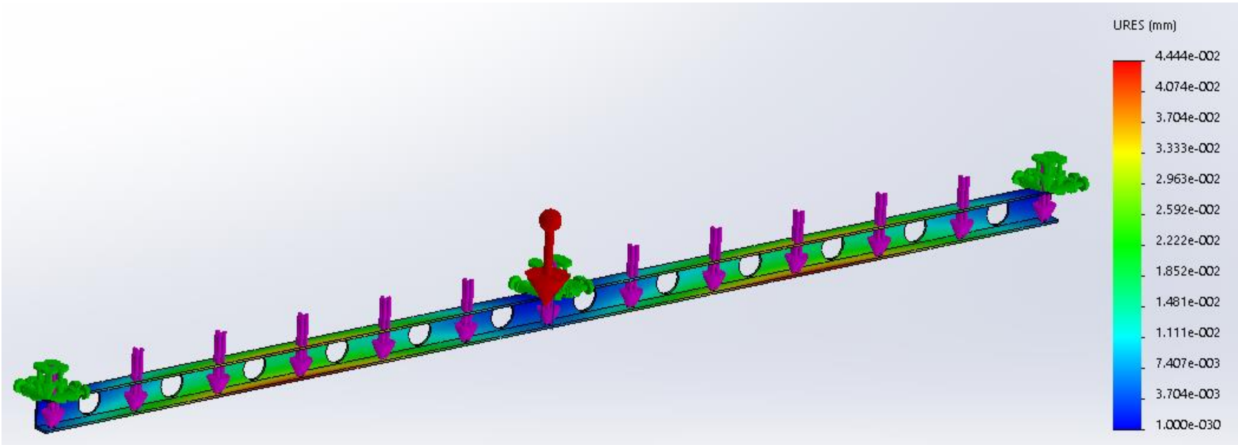


Figure C.3: Total deflection for C-Channel with cut-outs.

These figures show that the C-Channel's stress and deflection are still well below the yield stress and acceptable deflection. The cut-outs allowed for a weight saving of 1.4kg, for the total of 10 C-Channels to be used on the end effector. Each individual C-Channel, with the cut-outs, has a mass of 1.4 Kg.

Next, the structural members of the end effector as well as the central beam junction were analyzed. All end effector members, with the exception of the C-Channels and robot interface plate, were included in this analysis. The appropriate forces were applied to each member to represent the weight of the C-Channels, suction cups, and vacuum generators. A gravitational acceleration of 9.81m/s/s was applied. The upper junction plate was fixed at its mounting holes. The results Von-Mises stress and deflection are shown in Figure C.4 and Figure C.5, respectively.

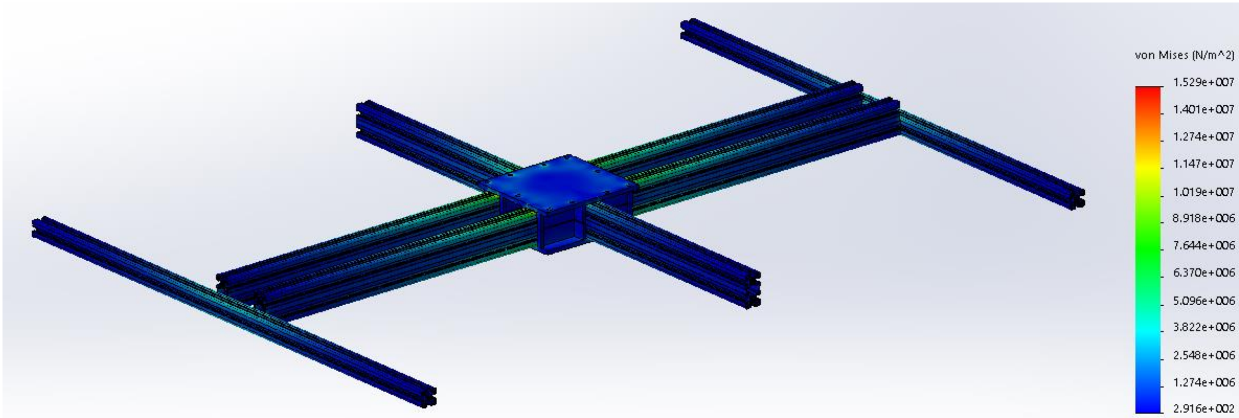


Figure C.4: End effector, structural members Von-Mises Stress.

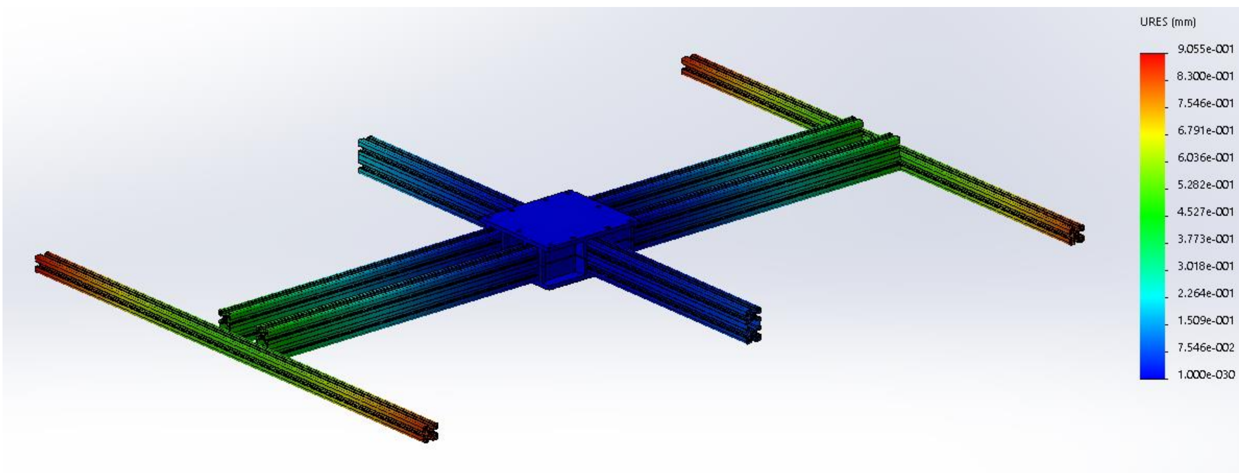


Figure C.5: End effector, structural members deflection.

The maximum deflection was determined to be 0.9mm, which is still below the defined maximum deflection of 1mm.

The maximum stress was determined to be 15.29 MPa, which allows for a factor of safety of approximately 10. The maximum stress is located on the upper junction plate, and is shown in Figure C.6.

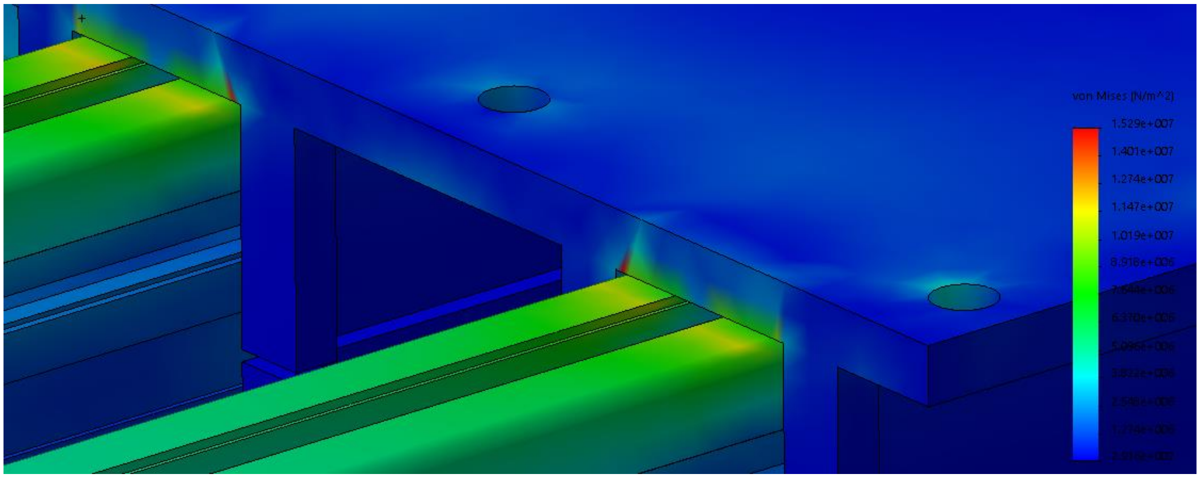


Figure C.6: End effector, location of maximum stress.

The numerical analysis performed in this section determined that the end effector is not likely to fail due to yielding. The maximum deflection of 0.9mm will likely not have a significant effect on the performance of the end effector, due to the suction cups’ ability to account for slight vertical misalignments when picking up plies.

C.4 References

[1] ASM, "Aluminum 6063-T6," ASM, [Online]. Available: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6063T6. [Accessed 27 November 2017].

[2] MakeItFrom, "6360-T6 Aluminum," MakeItFrom, [Online]. Available: https://www.makeitfrom.com/material-properties/6360-T6-Aluminum. [Accessed 27 November 2017].

[3] 80/20 Inc., "Deflection Calculator," 80/20 Inc., [Online]. Available: https://8020.net/deflection-calculator. [Accessed 27 November 2017].

APPENDIX D: MATLAB CODE

TABLE OF CONTENTS

D.1 MATLAB CODE

In this section, all the scripts and functions that were written in order to conduct simulations, or to show how the end effector can be activated, will be shown. The MATLAB code will be shown as it was written, with comments, and each script and function will be briefly explained.

D.2 FUNCTION: GENERATE KIT.M

Generates a matrix with the coordinates needed to define a certain number of plies.

This function takes three arguments:

- Length: A float representing the kit's length.
- Number: An integer representing the number of plies within the kit.
- Random: A Boolean value, where true will generate a kit were the ply order has been randomized, and false will generate one where the plies are organized in order from the bottom to the top.

The output of this function is a matrix of dimensions (12 x number), and each column contains the coordinates for one ply, as well as its row and column position in the entire kit. The first row contains the ply's row in the kit, the second row contains the ply's column in the kit, rows three through seven contain the x-coordinates of the ply's corners and rows eight through twelve contain the y-coordinates.

```
function [kit]=generate_kit(length, number, random)
    % Given a height and a number of kit, this will generate a kit with
    % the specified number of kit at the given length in [m].
    if (number <= 0) || (length <= 0);
        disp('The number entered must be an integer greater than 0.')
        disp('The length entered must be greater than 0.')
        return;
    end
    table_width = 1.8288;
    table_length = 15.24;
    part_width = table_width/5;
    rows = ceil(number/5);
    columns = 5;
    part_length = table_length/rows;

    kit = [];

    for v = 1:1:rows
       for u = 1:1:columns
           x_1 = -table_width/2;
           x_2 = -table_width/2+part_width;
           x_3 = -table_width/2+part_width;
           x_4 = -table_width/2;
           x_5 = -table_width/2;
           y_1 = -table_length/2 + part_length;
           y_2 = -table_length/2 + part_length;
           y_3 = -table_length/2;
           y_4 = -table_length/2;
           y_5 = -table_length/2 + part_length;
           if size(kit, 2) < number
             kit = [kit, [[x_1 x_2 x_3 x_4 x_5]+(u-1)*part_width, [y_1 y_2 y_3 y_4 y_5]+(v-
1)*part_length]'];
           else
               break;
           end
       end
    end
    % Adding values for the row and the column, for reference.
    for v = 1:1:size(kit, 2)
        x = mod(v, 5);
```

```
        y = ceil(v/5);
        if x == 0
            x = 5;
        end
        if y == 0
            y = 5;
        end
        kit(3:12, v) = kit(1:10, v);
        kit(1, v) = x;
        kit(2, v) = y;
    end
    % This randomizes the order in which the kit parts appear, similar to
    % the way the dynamic nesting distributes them.
    if random == true
        kit = kit(:,randperm(size(kit,2)));
    end
end
```

D.3 FUNCTION: MEAN_AUTOMATED_STATS.M

This function generates an array of collation times calculated using different randomly-generated kits. It is based on the flowchart presented in Figure 24, and it takes two argumenst:

- Number_of_parts: The number of plies that will be in the randomly generated kits.
- Sample_size: The number of collation times that will be generated and placed in the output array.

The kit length is calculated by assuming that a kit with 5 columns and 20 rows would span the entirety of the worktable. The code is commented to explain the steps taken.

```
function [ time_arry ] = mean_automated_stats(number_of_parts, sample_size)
% Collation job simulator.
% Written by: Rafael Hurtado
% Given a number of parts, this function generate an array of possible
% collation times of length sample_size, which can then be used to
%calculate a mean collation time and its standard deviation.
% 11/16/2017

table_width = 1.8288; %table width in m
table_height = 15.24; %table height in m
```

```
kit_length = (table_height/20)*ceil(number_of_parts/5);

% Assumed values:
suction_time    = 1; % The amount of time it takes the end effector to grip
                     % the ply in [s].
rail_speed      = 2; % The rail speed in [m/s].

angular_speed   = 400; % Robot's angular speed in [°/s]

angle_rotation = 90; % Angle of rotation to drop ply on collection table
                     % in [°]
height_change_time = 0; %Time the robot spends changing height when picking
                        % dropping plies.
acceleration = 2.5;       % Linear acceleration of rail system.



% Starting position for the end-effector.
start_pos = [0, 0];

% Vertical distance travelled to arrive to each of the kits
distance_arry = [];
time_arry = [];
times = [];
travel_times = [];
for u = 1:1:sample_size
    ver_dist = 0;
    time = 0;
    kit = generate_kit(kit_length, number_of_parts, true);
    for v = 1:1:size(kit, 2);
        part_y = kit(8:12, v); %y-coordinates of ply corners.
        vertical_centre = (min(part_y)+max(part_y))/2;
        % calculate distance between the vertical centre of the ply and
        % the center of the end effector.
        ver_dist = abs(vertical_centre - start_pos(2));
        travel_time = sqrt(2*ver_dist/acceleration);
        % the following branch is followed if there is enough time to go
        % past the maximum speed given the acceleration.
        if travel_time * acceleration > rail_speed;
           time_to_fs = rail_speed/acceleration; % time to achieve full speed;
```

```
            travel_time = time_to_fs + (ver_dist-(acceleration*time_to_fs^2)/2)/rail_speed;
        end
        travel_times = [travel_times, travel_time];
        % choose the highest between the travel time and rotation time, as
        % they can be done at the same time.
        time = time + max([travel_time, 2*angle_rotation/angular_speed]);
        % move end effector's position for the next calculation.
        start_pos(2) = vertical_centre;
        % calculate the total time.
        time = time + 2*suction_time + 4*height_change_time;
    end
    % Add current collation time to the collation time array. This array
    % will be the output once everything is finished.
    time_arry = [time_arry, time/60];
end


end
```

D.4 FUNCTION: CURRENT_STATS.M

This function generates an array of collation times calculated using different randomly-generated kits. It is based on the flowchart presented in Figure 20, and it takes the same arguments as *mean_automated_stats*.

```
function [ times ] = current_stats( number_of_parts, sample_size)
% Manual collation job simulator.
% Written by: Rafael Hurtado
% Given a number of parts, this function generate an array of possible
% collation times of length sample_size, which can then be used to
% calculate a mean collation time and its standard deviation.
% 11/16/2017

table_width = 1.8288; %table width in m
table_height = 15.24; %table height in m
kit_length = (table_height/20)*ceil(number_of_parts/5);
collection_table_pos = [-3.6576 0]'; % position of collation table in metres,
                                     % [0 0]' is the centre of the
                                     % worktable.
ply_length = kit_length/(number_of_parts/5);
% Assumed values:
```

```
walking_speed = 1.5; % Walking speed in [m/s].

attempts_array = [];
distances = [];
times = [];

for k = 1:1:sample_size
    kit = generate_kit(kit_length, number_of_parts, true);
    ordered_kit = generate_kit(kit_length, number_of_parts, false);
    attempts = 0;
    dist = 0;
    for v = 1:1:size(kit, 2)
        for u = 1:1:size(kit, 2)
            % First remaining ply's row position
            for z = 1:1:size(kit, 2)
               if ordered_kit(1, z) ~= 0
                   first_ply_row = ordered_kit(1, z);
               end
            end
            if ordered_kit(1:2, u) == kit(1:2, v)
                % this section 'removes' found plies from the ordered kit so
                % that they won't be counted again.
                fin_ply_row = ordered_kit(1, u);
                ordered_kit(1, u) = 0;
                y_dist_fin = abs(-table_width/2 + fin_ply_row*ply_length-ply_length/2);
                break;
            end
            if ordered_kit(1, u) ~= 0
                % if there is a ply to be looked at, that is counted as an
                % attempt. Otherwise, it's skipped over.
                attempts = attempts + 1;
            end
        end
        % y-distance to get to the first remaining plies starting from the
        % bottom of the kit.
        y_dist_init = abs(-table_width/2 + first_ply_row*ply_length-ply_length/2);
        x_dist = -table_width/2 - collection_table_pos(1);
        dist_init = (y_dist_init^2+x_dist^2)^(1/2);
        % dist_final is the distance from the picked up ply back to the
        % collection cart.
```

```
        dist_final = (y_dist_fin^2+x_dist^2)^(1/2);
        dist = dist + dist_init + dist_final;
    end
    times = [times, (attempts*0.97 + dist/walking_speed+number_of_parts*4.5)/60];
end
end
```

D.5 SCRIPT: CUP_SELECTOR.M

This script was written to determine which suction cups in the end-effector must be activated in order to grip a ply (whose edge is defined in coordinates) without gripping any material out of the needed ply. The flowchart on which this script is based can be seen in Figure 26.

```
% Suction cup controller for ply-collating end effector
% Written by: Rafael Hurtado
% 11/11/2017

% -------------------Table and end effector dimensions---------------------
% The dimensions of the table and the end effector
% must be assigned in this section.

table_width = 182.88; %table width in cm
table_height = 1524; %table height in cm

ee_height = 193; % end effector height in cm
ee_width = 180; % end effector width in cm

% Define the cöordinates of the 4 table corners
table_x = [-table_width/2, -table_width/2, table_width/2, table_width/2, -table_width/2]';
table_y = [-table_height/2, table_height/2, table_height/2, -table_height/2, -table_height/2]';

% Define the initial cöordinates of the end-effector.
ee_x = [-ee_width/2, -ee_width/2, ee_width/2, ee_width/2, -ee_width/2]';
ee_y = [-ee_height/2, ee_height/2, ee_height/2, -ee_height/2, -ee_height/2]';




% ----------------------------Ply definition------------------------------
```

```
% The position and shape of the ply to be picked up is to be defined in
% this section.

ply_x = [-36, -30, -36, -6, 2, 20, 2, -18, -36]'*2;
ply_y = [-270, -240, -210, -250, -210, -240, -270, -250, -270]'*2;

%ply_x = [-20, -20, 20, 20]';
%ply_y = [-20, 20, 20, -20]';

%--------------------------- Move end effector ----------------------------
% The end effector's y-centroid must be aligned with the vertical centre of
% the ply.

ply_v_center = (max(ply_y)+min(ply_y))/2;

n = 1;
while n < 6
    ee_y(n) = ee_y(n) + ply_v_center;
    n = n + 1;
end



%--------------------------Suction cups definition-------------------------
% The positions and geometries of the suction cups will be generated in
% this section.

radius = 1.5; % radius of the suction cups in cm.
cup_dist = 15; % distance between the centers of the suction cups in a row.
offset = 0; % offset between rows

% For odd rows:
num_spaces_odd = floor((ee_width - 2*radius) / cup_dist);

% x-cöordinates for odd rows:
odd_x = [];
for v = 0:1:num_spaces_odd
    odd_x(v+1) = (ee_width-num_spaces_odd*cup_dist)/2 + v * cup_dist;
    odd_x(v+1) = odd_x(v+1) - ee_width / 2; % center points horizontally
end
```

```
% x-cöordinates for even rows:
even_x = [];
for v = 0:1:num_spaces_odd
    a = odd_x(v+1) + offset
    if (a <= (ee_width/2-radius)) && (a >= (-ee_width/2+radius))
        even_x(v+1) = odd_x(v+1) + offset;
    end
end

% y-cöordinates for each row:
num_y_spaces = floor( ( ee_height- 2 * radius ) / cup_dist );
cup_y_1 = [];

for v = 0:1:num_y_spaces
    cup_y_1(v+1) = min(ee_y) + (ee_height - num_y_spaces * cup_dist) / 2 + (v) * cup_dist;
end

% Cöordinates for all the points:
final_cup_x = []
final_cup_y = []
for v=1:1:(length(cup_y_1))
    if mod((v+1), 2) == 0
        for u = 1:1:length(even_x)
            final_cup_x = [final_cup_x, even_x(u)];
            final_cup_y = [final_cup_y, cup_y_1(v)];
        end
    else
        for u = 1:1:length(odd_x)
            final_cup_x = [final_cup_x, odd_x(u)];
            final_cup_y = [final_cup_y, cup_y_1(v)];
        end
    end
end

%------------------- Find if entire cup lies inside ply ------------------
cup_x = []; % x-cöordinates of cups that fall entirely inside ply.
cup_y = []; % y-cöordinates of cups that fall entirely inside ply.
cup_numbers = [];

% Sketch a circle with same radius as cup.
```

```
L = linspace(0,2.*pi,100);
circle_x = (cos(L)')*radius;
circle_y = sin(L)'*radius;

for v = 1:1:length(final_cup_x)
    % Move the sketched circle over the centre of the cups.
    circle_x_x = circle_x + final_cup_x(v);
    circle_y_y = circle_y + final_cup_y(v);

    % Check if the entire perimeter of the circle falls inside the polygon.
    fits = inpolygon(circle_x_x, circle_y_y, ply_x, ply_y);
    if not(ismember(0, fits)) % if the fits array has any number other than zero
                              % then it there are points of the cup lying
                              % outside of the ply. The opposite is also
                              % true.
        cup_x = [cup_x, final_cup_x(v)];
        cup_y = [cup_y, final_cup_y(v)];
        cup_numbers = [cup_numbers, v];
    end
end

hold on
fill(table_x, table_y, [0.7 0.7 0.7]);
fill(ee_x, ee_y, 'y')
fill(ply_x, ply_y, 'g')
scatter(cup_x, cup_y, 60, 'filled', 'r')
scatter(final_cup_x, final_cup_y, 60, 'bo')
axis equal
hold off
```

APPENDIX E: BILL OF MATERIALS

LIST OF TABLES

TABLE E-I: BILL OF MATERIALS

Component	Manufacturer	Part #	Qty	Unit Cost (CAD)	Total Cost (CAD)	Comments	Source
Robotic Arm	ABB	IRB460	1	[redacted]			
Rail	ABB	IRBT4004	1	[redacted]			
Guard Cell	ABB	-	1	[redacted]			
Installation	-	-	1	[redacted]			
Vacuum Generators (182 units)	Schmalz	SCTMi	130	$571.50	**$74,295.00**	4x16, 2x14, 2x13	e
Cintrol Cable	Schmalz	ASK B-M12-5 5000	10	$50.00	**$500.00**	1 cable per generator block	f
Cup+Nipple	Schmalz	SPB1 30 ED-65 G1/8-IG	130	$21.27	**$2,765.10**	Bellows Suction Cup	g
G1/8 M to F	Legris	0906	130	$1.56	**$202.80**	Connects to cup	h
G1/8 90deg 6mm Push Connector	AutomationDirect	MS6M-18G	130	$1.58	**$205.40**	Connects to G1/8 F to M	i
G1/8 Straight 6mm Push Connector	AutomationDirect	ME6M-18G	130	$1.08	**$140.40**	Connects to Vacuum Generator	j
Extruded Aluminum 4040 (10ft)	McMaster Carr	5537T102	2	$104.00	**$208.00**	Supports suction cups	k
Extruded Aluminum 8040 (10ft)	McMaster Carr	5537T112	2	$181.00	**$362.00**	End effector structure	l
Aluminum U-Channel (8ft)	McMaster Carr	9001K54	13	$50.00	**$650.00**	End effector structure	m
Fasteners	Mcmaster Carr	-	1	$200.00	**$200.00**	Various fasteners for end effector	n
6mm tubing (100ft)	AutomationDirect	PU6MBLK100	1	$18.50	**$18.50**	Pneumatic tubing for all suction cups	o
Total					**$280,928.20**		

TABLE E-II: URL OF EACH COMPONENT IN BILL OF MATERIALS

	URL
a	http://new.abb.com/products/robotics/industrial-robots/irb-460
b	http://new.abb.com/products/robotics/application-equipment-and-accessories/robot-positioners-track-motion/irbt-4004-for-irb-4400
c	https://www.robots.com/faq/show/how-much-do-industrial-robots-cost
d	https://www.robots.com/faq/show/how-much-do-industrial-robots-cost
e	https://www.schmalz.com/en/vacuum-technology-for-automation/vacuum-components/vacuum-generators/compact-terminals/compact-terminal-sctmi
f	https://www.schmalz.com/en/21.04.05.00080
g	https://www.schmalz.com/en/vacuum-technology-for-automation/vacuum-components/vacuum-suction-cups/suction-cups-for-packaging/bellows-suction-cups-spb1-1-5-folds-55/10.01.06.03497
h	https://www.alliedelec.com/legris-0906-10-13/R1039952/
i	https://www.automationdirect.com/adc/Shopping/Catalog/Pneumatic_Components/Push-to-Connect_G-Thread_Pneumatic_Fittings_(Thermoplastic)/Male_Elbow/ME6M-18G
j	https://www.automationdirect.com/adc/Shopping/Catalog/Pneumatic_Components/Push-to-Connect_G-Thread_Pneumatic_Fittings_(Thermoplastic)/Male_Straight_(Hex_Body)/MS6M-18G
k	https://www.mcmaster.com/#5537t102/=1aejnrp
l	https://www.mcmaster.com/#5537t112/=1aejmf9
m	https://www.mcmaster.com/#9001k74/=1aekzq7
n	https://www.mcmaster.com/#standard-socket-head-screws/=1aekjhj
o	https://www.automationdirect.com/adc/Shopping/Catalog/Pneumatic_Components/Flexible_Pneumatic_Tubing_-a-_Hoses/Straight_Polyurethane_(PUR)_Tubing/6_mm/PU6MBLK100

APPENDIX F: ROI CHART

LIST OF TABLES

TABLE F-I: ROI CHART FOR COLLATION OF 40-PLY KITS

Month	Initial Costs	Robots Labour Costs	Operating Costs	Maintenance Costs	Monthly Cost (Robots)	Cumulative Robots Costs	Current Montly Costs	Cumulative Current Costs	Cumulative Savings
1	$282,628	$25,842	$43.18	$540.20	$309,054	$309,054	$67,200	$67,200	-$241,854
2		$25,885	$43.31	$540.20	$26,469	$335,522	$68,544	$135,744	-$199,778
3		$26,403	$44.17	$540.20	$26,987	$362,510	$69,915	$205,659	-$156,851
4		$26,931	$45.06	$540.20	$27,516	$390,026	$71,313	$276,972	-$113,054
5		$27,470	$45.96	$540.20	$28,056	$418,082	$72,739	$349,711	-$68,370
6		$28,019	$46.88	$540.20	$28,606	$446,688	$74,194	$423,906	-$22,782
7		$28,579	$47.82	$540.20	$29,167	$475,855	$75,678	$499,584	$23,728
8		$29,151	$48.77	$540.20	$29,740	$505,595	$77,192	$576,776	$71,180
9		$29,734	$49.75	$540.20	$30,324	$535,919	$78,736	$655,511	$119,592
10		$30,329	$50.74	$540.20	$30,920	$566,839	$80,310	$735,821	$168,982
11		$30,935	$51.76	$540.20	$31,527	$598,366	$81,916	$817,738	$219,372
12		$31,554	$52.79	$540.20	$32,147	$630,513	$83,555	$901,292	$270,779
13		$32,185	$53.85	$540.20	$32,779	$663,292	$85,226	$986,518	$323,226
14		$32,829	$54.93	$540.20	$33,424	$696,716	$86,930	$1,073,449	$376,733
15		$33,485	$56.02	$540.20	$34,082	$730,798	$88,669	$1,162,118	$431,320
16		$34,155	$57.14	$540.20	$34,752	$765,550	$90,442	$1,252,560	$487,010
17		$34,838	$58.29	$540.20	$35,437	$800,986	$92,251	$1,344,811	$543,825
18		$35,535	$59.45	$540.20	$36,135	$837,121	$94,096	$1,438,907	$601,786
19		$36,246	$60.64	$540.20	$36,846	$873,967	$95,978	$1,534,886	$660,918
20		$36,970	$61.85	$540.20	$37,573	$911,540	$97,898	$1,632,783	$721,243
21		$37,710	$63.09	$540.20	$38,313	$949,853	$99,856	$1,732,639	$782,786
22		$38,464	$64.35	$540.20	$39,069	$988,922	$101,853	$1,834,492	$845,570
23		$39,233	$65.64	$540.20	$39,839	$1,028,761	$103,890	$1,938,382	$909,620
24		$40,018	$66.95	$540.20	$40,625	$1,069,386	$105,968	$2,044,349	$974,963
25		$40,818	$68.29	$540.20	$41,427	$1,110,813	$108,087	$2,152,436	$1,041,623
26		$41,635	$69.66	$540.20	$42,245	$1,153,058	$110,249	$2,262,685	$1,109,627
27		$42,467	$71.05	$540.20	$43,079	$1,196,137	$112,454	$2,375,139	$1,179,002
28		$43,317	$72.47	$540.20	$43,929	$1,240,066	$114,703	$2,489,841	$1,249,775
29		$44,183	$73.92	$540.20	$44,797	$1,284,863	$116,997	$2,606,838	$1,321,975
30		$45,067	$75.40	$540.20	$45,682	$1,330,546	$119,337	$2,726,175	$1,395,629
31		$45,968	$76.91	$540.20	$46,585	$1,377,131	$121,723	$2,847,898	$1,470,767
32		$46,888	$78.45	$540.20	$47,506	$1,424,637	$124,158	$2,972,056	$1,547,419
33		$47,825	$80.02	$540.20	$48,445	$1,473,083	$126,641	$3,098,698	$1,625,615
34		$48,782	$81.62	$540.20	$49,404	$1,522,486	$129,174	$3,227,871	$1,705,385
35		$49,757	$83.25	$540.20	$50,381	$1,572,867	$131,757	$3,359,629	$1,786,762
36		$50,753	$84.91	$540.20	$51,378	$1,624,245	$134,393	$3,494,021	$1,869,777

TABLE F-II: ROI CHART FOR COLLATION OF 60-PLY KITS

Month	Initial Costs	Robots Labour Costs	Operating Costs	Maintenance Costs	Monthly Cost (Robots)	Cumulative Robots Costs	Current Montly Costs	Cumulative Current Costs	Cumulative Savings
1	$282,628	$20,533	$34.31	$540.20	$303,736	$303,736	$67,200	$67,200	-$236,536
2		$20,567	$34.41	$540.20	$21,142	$324,877	$68,544	$135,744	-$189,133
3		$20,978	$35.10	$540.20	$21,554	$346,431	$69,915	$205,659	-$140,772
4		$21,398	$35.80	$540.20	$21,974	$368,405	$71,313	$276,972	-$91,433
5		$21,826	$36.52	$540.20	$22,403	$390,808	$72,739	$349,711	-$41,096
6		$22,262	$37.25	$540.20	$22,840	$413,647	$74,194	$423,906	$10,258
7		$22,708	$37.99	$540.20	$23,286	$436,933	$75,678	$499,584	$62,651
8		$23,162	$38.75	$540.20	$23,741	$460,674	$77,192	$576,776	$116,101
9		$23,625	$39.53	$540.20	$24,205	$484,879	$78,736	$655,511	$170,632
10		$24,098	$40.32	$540.20	$24,678	$509,557	$80,310	$735,821	$226,264
11		$24,580	$41.12	$540.20	$25,161	$534,718	$81,916	$817,738	$283,020
12		$25,071	$41.95	$540.20	$25,653	$560,371	$83,555	$901,292	$340,921
13		$25,573	$42.79	$540.20	$26,156	$586,527	$85,226	$986,518	$399,992
14		$26,084	$43.64	$540.20	$26,668	$613,194	$86,930	$1,073,449	$460,254
15		$26,606	$44.51	$540.20	$27,190	$640,385	$88,669	$1,162,118	$521,733
16		$27,138	$45.40	$540.20	$27,723	$668,108	$90,442	$1,252,560	$584,452
17		$27,681	$46.31	$540.20	$28,267	$696,375	$92,251	$1,344,811	$648,436
18		$28,234	$47.24	$540.20	$28,822	$725,197	$94,096	$1,438,907	$713,710
19		$28,799	$48.18	$540.20	$29,387	$754,584	$95,978	$1,534,886	$780,301
20		$29,375	$49.15	$540.20	$29,964	$784,548	$97,898	$1,632,783	$848,235
21		$29,962	$50.13	$540.20	$30,553	$815,101	$99,856	$1,732,639	$917,538
22		$30,562	$51.13	$540.20	$31,153	$846,254	$101,853	$1,834,492	$988,238
23		$31,173	$52.15	$540.20	$31,765	$878,019	$103,890	$1,938,382	$1,060,363
24		$31,796	$53.20	$540.20	$32,390	$910,409	$105,968	$2,044,349	$1,133,941
25		$32,432	$54.26	$540.20	$33,027	$943,435	$108,087	$2,152,436	$1,209,001
26		$33,081	$55.35	$540.20	$33,676	$977,112	$110,249	$2,262,685	$1,285,573
27		$33,742	$56.45	$540.20	$34,339	$1,011,451	$112,454	$2,375,139	$1,363,688
28		$34,417	$57.58	$540.20	$35,015	$1,046,466	$114,703	$2,489,841	$1,443,376
29		$35,106	$58.73	$540.20	$35,705	$1,082,170	$116,997	$2,606,838	$1,524,668
30		$35,808	$59.91	$540.20	$36,408	$1,118,578	$119,337	$2,726,175	$1,607,597
31		$36,524	$61.11	$540.20	$37,125	$1,155,703	$121,723	$2,847,898	$1,692,195
32		$37,254	$62.33	$540.20	$37,857	$1,193,560	$124,158	$2,972,056	$1,778,496
33		$37,999	$63.58	$540.20	$38,603	$1,232,164	$126,641	$3,098,698	$1,866,534
34		$38,759	$64.85	$540.20	$39,364	$1,271,528	$129,174	$3,227,871	$1,956,343
35		$39,535	$66.14	$540.20	$40,141	$1,311,669	$131,757	$3,359,629	$2,047,960
36		$40,325	$67.47	$540.20	$40,933	$1,352,602	$134,393	$3,494,021	$2,141,419

TABLE F-III: ROI CHART FOR COLLATION OF 80-PLY KITS

Month	Initial Costs	Robots Labour Costs	Operating Costs	Maintenance Costs	Monthly Cost (Robots)	Cumulative Robots Costs	Current Montly Costs	Cumulative Current Costs	Cumulative Savings
1	$282,628	$16,907	$28.25	$540.20	$300,103	$300,103	$67,200	$67,200	-$232,903
2		$16,935	$28.33	$540.20	$17,503	$317,607	$68,544	$135,744	-$181,863
3		$17,274	$28.90	$540.20	$17,843	$335,449	$69,915	$205,659	-$129,790
4		$17,619	$29.48	$540.20	$18,189	$353,638	$71,313	$276,972	-$76,666
5		$17,971	$30.07	$540.20	$18,542	$372,180	$72,739	$349,711	-$22,468
6		$18,331	$30.67	$540.20	$18,902	$391,081	$74,194	$423,906	$32,825
7		$18,697	$31.28	$540.20	$19,269	$410,350	$75,678	$499,584	$89,234
8		$19,071	$31.91	$540.20	$19,643	$429,994	$77,192	$576,776	$146,782
9		$19,453	$32.55	$540.20	$20,026	$450,019	$78,736	$655,511	$205,492
10		$19,842	$33.20	$540.20	$20,415	$470,434	$80,310	$735,821	$265,387
11		$20,239	$33.86	$540.20	$20,813	$491,247	$81,916	$817,738	$326,491
12		$20,643	$34.54	$540.20	$21,218	$512,465	$83,555	$901,292	$388,827
13		$21,056	$35.23	$540.20	$21,632	$534,097	$85,226	$986,518	$452,421
14		$21,477	$35.93	$540.20	$22,054	$556,150	$86,930	$1,073,449	$517,298
15		$21,907	$36.65	$540.20	$22,484	$578,634	$88,669	$1,162,118	$583,483
16		$22,345	$37.39	$540.20	$22,923	$601,557	$90,442	$1,252,560	$651,003
17		$22,792	$38.13	$540.20	$23,370	$624,927	$92,251	$1,344,811	$719,884
18		$23,248	$38.90	$540.20	$23,827	$648,754	$94,096	$1,438,907	$790,153
19		$23,713	$39.67	$540.20	$24,293	$673,047	$95,978	$1,534,886	$861,839
20		$24,187	$40.47	$540.20	$24,768	$697,815	$97,898	$1,632,783	$934,968
21		$24,671	$41.28	$540.20	$25,252	$723,067	$99,856	$1,732,639	$1,009,572
22		$25,164	$42.10	$540.20	$25,747	$748,814	$101,853	$1,834,492	$1,085,678
23		$25,668	$42.94	$540.20	$26,251	$775,064	$103,890	$1,938,382	$1,163,317
24		$26,181	$43.80	$540.20	$26,765	$801,829	$105,968	$2,044,349	$1,242,520
25		$26,704	$44.68	$540.20	$27,289	$829,119	$108,087	$2,152,436	$1,323,318
26		$27,239	$45.57	$540.20	$27,824	$856,943	$110,249	$2,262,685	$1,405,742
27		$27,783	$46.48	$540.20	$28,370	$885,313	$112,454	$2,375,139	$1,489,826
28		$28,339	$47.41	$540.20	$28,927	$914,240	$114,703	$2,489,841	$1,575,602
29		$28,906	$48.36	$540.20	$29,494	$943,734	$116,997	$2,606,838	$1,663,104
30		$29,484	$49.33	$540.20	$30,073	$973,807	$119,337	$2,726,175	$1,752,368
31		$30,074	$50.32	$540.20	$30,664	$1,004,471	$121,723	$2,847,898	$1,843,427
32		$30,675	$51.32	$540.20	$31,267	$1,035,738	$124,158	$2,972,056	$1,936,318
33		$31,289	$52.35	$540.20	$31,881	$1,067,619	$126,641	$3,098,698	$2,031,078
34		$31,914	$53.40	$540.20	$32,508	$1,100,127	$129,174	$3,227,871	$2,127,744
35		$32,553	$54.46	$540.20	$33,147	$1,133,274	$131,757	$3,359,629	$2,226,354
36		$33,204	$55.55	$540.20	$33,799	$1,167,074	$134,393	$3,494,021	$2,326,948

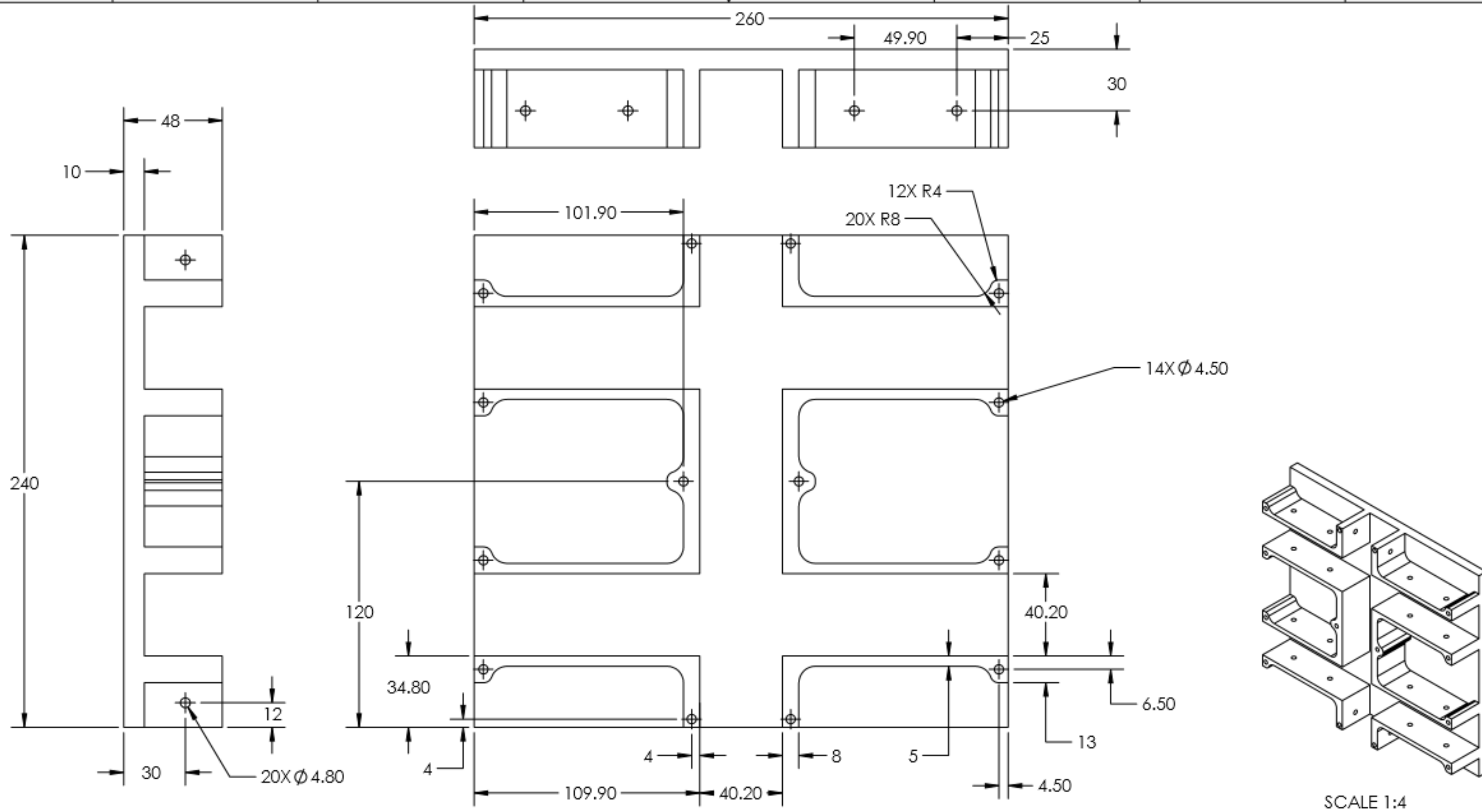
TABLE F-IV: CHART FOR COLLATION OF 100-PLY KITS

Month	Initial Costs	Robots Labour Costs	Operating Costs	Maintenance Costs	Monthly Cost (Robots)	Cumulative Robots Costs	Current Montly Costs	Cumulative Current Costs	Cumulative Savings
1	$282,628	$14,372	$24.01	$540.20	$297,564	$297,564	$67,200	$67,200	-$230,364
2		$14,395	$24.08	$540.20	$14,960	$312,524	$68,544	$135,744	-$176,780
3		$14,683	$24.57	$540.20	$15,248	$327,772	$69,915	$205,659	-$122,113
4		$14,977	$25.06	$540.20	$15,542	$343,314	$71,313	$276,972	-$66,342
5		$15,277	$25.56	$540.20	$15,842	$359,156	$72,739	$349,711	-$9,445
6		$15,582	$26.07	$540.20	$16,148	$375,305	$74,194	$423,906	$48,601
7		$15,894	$26.59	$540.20	$16,461	$391,765	$75,678	$499,584	$107,819
8		$16,212	$27.12	$540.20	$16,779	$408,544	$77,192	$576,776	$168,231
9		$16,536	$27.67	$540.20	$17,104	$425,648	$78,736	$655,511	$229,863
10		$16,867	$28.22	$540.20	$17,435	$443,083	$80,310	$735,821	$292,738
11		$17,204	$28.78	$540.20	$17,773	$460,856	$81,916	$817,738	$356,882
12		$17,548	$29.36	$540.20	$18,118	$478,973	$83,555	$901,292	$422,319
13		$17,899	$29.95	$540.20	$18,469	$497,442	$85,226	$986,518	$489,076
14		$18,257	$30.55	$540.20	$18,828	$516,270	$86,930	$1,073,449	$557,179
15		$18,622	$31.16	$540.20	$19,193	$535,464	$88,669	$1,162,118	$626,654
16		$18,994	$31.78	$540.20	$19,566	$555,030	$90,442	$1,252,560	$697,530
17		$19,374	$32.41	$540.20	$19,947	$574,977	$92,251	$1,344,811	$769,834
18		$19,762	$33.06	$540.20	$20,335	$595,312	$94,096	$1,438,907	$843,595
19		$20,157	$33.72	$540.20	$20,731	$616,043	$95,978	$1,534,886	$918,842
20		$20,560	$34.40	$540.20	$21,135	$637,178	$97,898	$1,632,783	$995,605
21		$20,971	$35.09	$540.20	$21,547	$658,725	$99,856	$1,732,639	$1,073,914
22		$21,391	$35.79	$540.20	$21,967	$680,692	$101,853	$1,834,492	$1,153,800
23		$21,819	$36.50	$540.20	$22,395	$703,087	$103,890	$1,938,382	$1,235,295
24		$22,255	$37.23	$540.20	$22,833	$725,920	$105,968	$2,044,349	$1,318,430
25		$22,700	$37.98	$540.20	$23,278	$749,198	$108,087	$2,152,436	$1,403,238
26		$23,154	$38.74	$540.20	$23,733	$772,931	$110,249	$2,262,685	$1,489,754
27		$23,617	$39.51	$540.20	$24,197	$797,128	$112,454	$2,375,139	$1,578,011
28		$24,090	$40.30	$540.20	$24,670	$821,798	$114,703	$2,489,841	$1,668,043
29		$24,571	$41.11	$540.20	$25,153	$846,951	$116,997	$2,606,838	$1,759,887
30		$25,063	$41.93	$540.20	$25,645	$872,596	$119,337	$2,726,175	$1,853,579
31		$25,564	$42.77	$540.20	$26,147	$898,743	$121,723	$2,847,898	$1,949,156
32		$26,075	$43.63	$540.20	$26,659	$925,402	$124,158	$2,972,056	$2,046,654
33		$26,597	$44.50	$540.20	$27,182	$952,584	$126,641	$3,098,698	$2,146,114
34		$27,129	$45.39	$540.20	$27,714	$980,298	$129,174	$3,227,871	$2,247,573
35		$27,671	$46.30	$540.20	$28,258	$1,008,556	$131,757	$3,359,629	$2,351,073

Appendix G: Engineering Drawings

This appendix presents the engineering drawings for the four custom machined parts for the end effector. The parts are displayed in the following order:

1) Main Beam Junction (Lower)
2) Main Beam Junction (Upper)
3) Robot Interface Plate
4) C-Channel



UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR INTERNAL THREADS AT ØMINOR

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

REV	DATE Y/M/D	DESCRIPTION		
			DWN	
			CKD	
			DWN	
			CKD	
			DWN	
			CKD	
			DWN	
			CKD	
			DWN	
			CKD	

MATERIAL

FINISH

DO NOT SCALE DRAWING

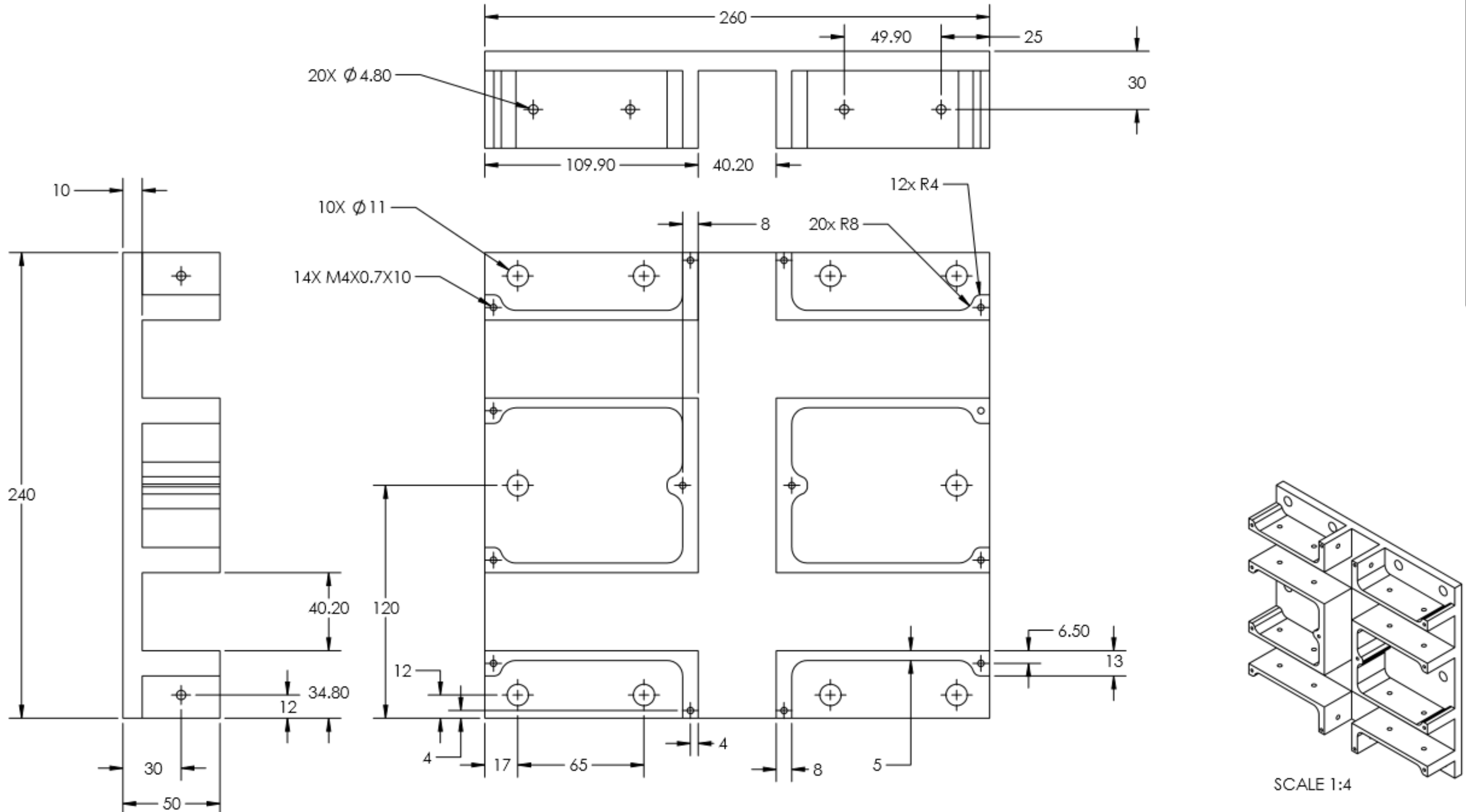
UNIVERSITY of MANITOBA

TITLE:

SIZE	DWG. NO.	REV
B	Main Beam Junction (lower)	1

SCALE: 1:2 | WEIGHT: N/A | SHEET 1 OF 1

DWG. NO. Main Beam Junction (lower) REV 1



DWG. NO. Main Beam Junction (upper) REV 1

REV	DATE Y/M/D	DESCRIPTION	
			DWN
			CKD
			DWN
			CKD
			DWN
			CKD
			DWN
			CKD
			DWN
			CKD

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS

FILLETS

BREAK SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR INTERNAL THREADS AT ØMINOR

SHARP

MATERIAL

FINISH

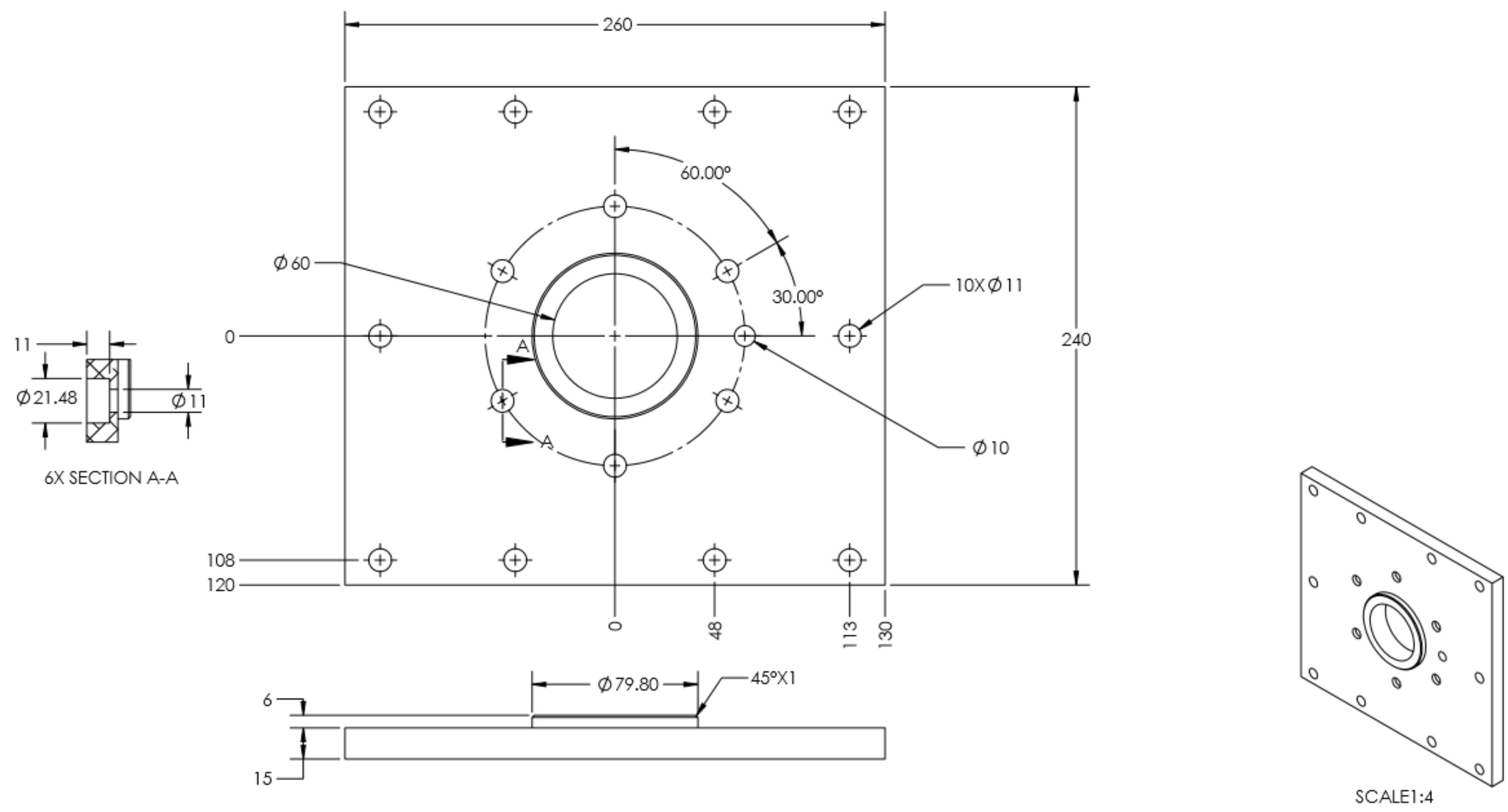
DO NOT SCALE DRAWING

UNIVERSITY OF MANITOBA

TITLE:

SIZE B | DWG. NO. Main Beam Junction (upper) | REV 1

SCALE: 1:2 | WEIGHT: N/A | SHEET 1 OF 1



			DWN	
			CKD	
			DWN	
			CKD	
			DWN	
			CKD	
			DWN	
			CKD	
			DWN	
			CKD	
REV	DATE Y/M/D	DESCRIPTION		

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR INTERNAL THREADS AT ØMINOR

MATERIAL

FINISH

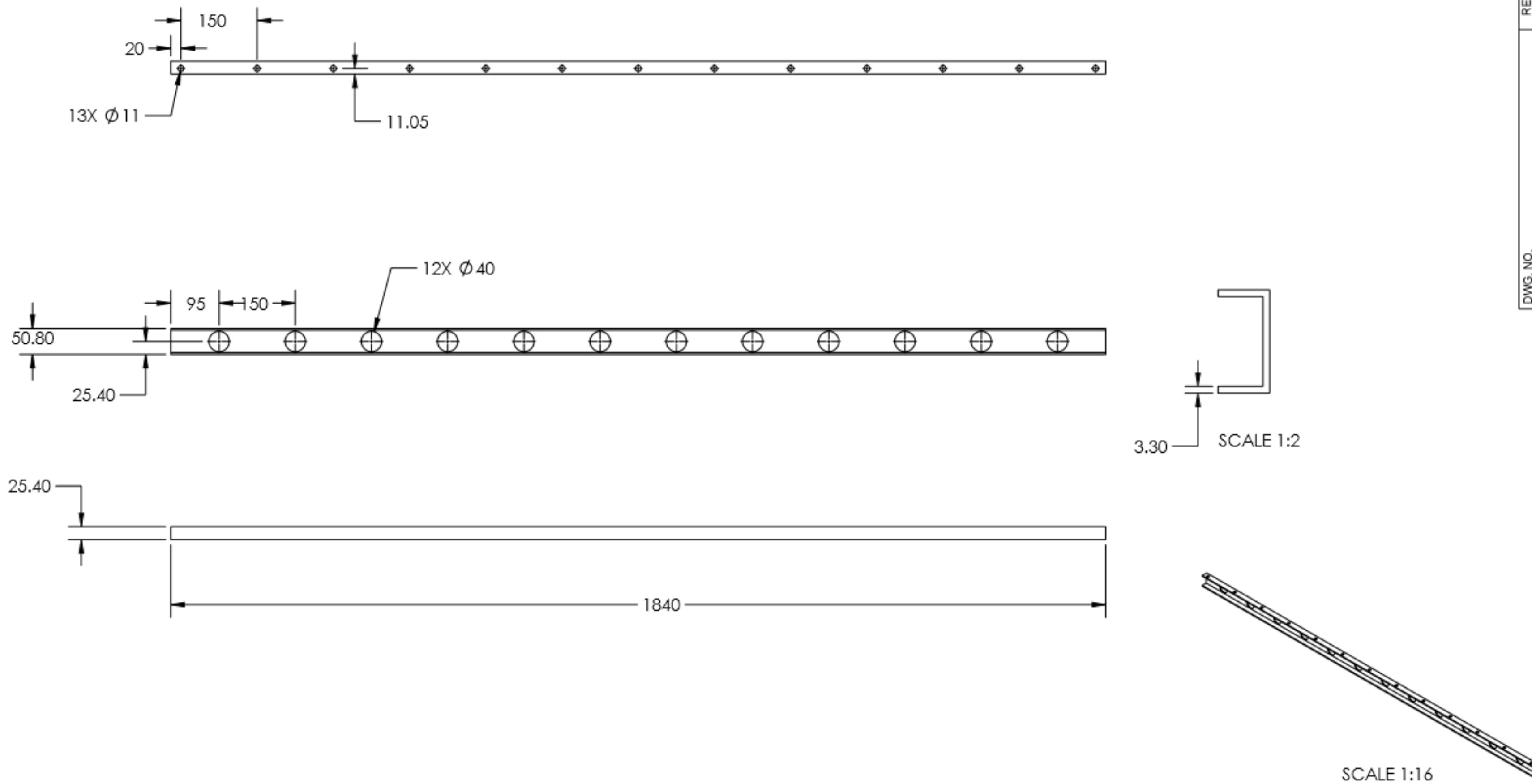
DO NOT SCALE DRAWING

UNIVERSITY OF MANITOBA

TITLE:

SIZE B | DWG. NO. Robot Interface Plate | REV 1

SCALE: 1:2 | WEIGHT: N/A | SHEET 1 OF 1



REV	DATE Y/M/D	DESCRIPTION

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ⌀MAJOR INTERNAL THREADS AT ⌀MINOR

MATERIAL

FINISH

DO NOT SCALE DRAWING

UNIVERSITY OF MANITOBA

TITLE:

SIZE B | DWG. NO. C-Channel | REV 1

SCALE: 1:8 | WEIGHT: N/A | SHEET 1 OF 1

DWG. NO. C-Channel REV 1