Novel forming techniques of commingled fibres

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Novel forming techniques of commingled fibres

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**Abstract**

Lately it has become abundantly clear that the majority of today’s allegedly sustainable materials available on the market are merely postponing the problem of complete degradation by recycling them. Assume the recycling is successfully done, but is it the appropriate ecological solution?

With increasing awareness from organisations with approaches such as *cradle to cradle* design, a demand for fully degradable or recyclable products has surfaced. Research has recently increased in composites based on natural constituents either derived from natural sources or are specially made to be able to be biodegraded or recycled. This makes these materials environmental friendly because they can be reused as energy, soil or as starting materials. These resources for new materials can then be grown and composted at the end of their life cycle. This project is a stepping-stone toward the replacement of non-degradable material in products in all markets.

One of the most crucial factors for the success of replacing old and common ways in manufacturing is the creation of engineered manufacturing methods. These methods must be capable of producing products with identical geometries and to a similar or lower time and cost to make the method worth using.

More precisely, this thesis – done at Innventia AB – comprises testing of the concept of a potentially strong and competitive manufacturing method for a promising composite material. This composite is made from the bio-based polymer PLA (Poly-Lactic Acid) that is reinforced with cellulose fibres. Both components of the composite are derived from renewable natural resources.

Within the framework of a product realisation process, materials have been examined to find their processing potentials. To facilitate and secure a full spectrum of concepts, extensive research on manufacturing methods for related materials was conducted. The ideas for new manufacturing principles were screened, tested and evaluated before they could become complete concepts. When a few concepts had been created, they could be subject to further development and finally reduced or combined to one single concept. As a proof of the concept’s success, an object was designed and produced to demonstrate the ability of combining the composite and the newly developed method of manufacturing.
Sammanfattning
På senare tid har standarden av vad som är miljömässigt hållbart allt mer ifrågasatts. Många produkter under denna standard på marknaden satsar endast på återanvändning och ignorerar återinföring av materialet i naturens kretslopp. Förutsätt att återanvändning görs, är detta tillräckligt som en lämplig ekologisk lösning?

Med ökad medvetenhet från organisationer med metoder såsom cradle to cradle design, så har krav på fullt nedbrytbara eller återvinningsbara produkter dykt upp. Forskning har på senare tid ökat kring kompositer som är baserade på naturliga beståndsdelar. Beståndsdelarna kommer antingen från naturliga källor eller så är de särskilt tillverkade för att kunna bidra till en biologisk nedbrytningsprocess eller återvinning. Detta gör materialen miljövänliga eftersom de kan återanvändas som energi, jord eller som nytt material. Detta projekt är ett litet steg på vägen mot att ersätta icke nedbrytbara material i produkter på alla marknader.

En av de mest avgörande faktorerna för hur framgångsrikt det blir att ersätta gamla och traditionella metoder inom tillverkningsindustrin, är det innovativa nyskapandet av alternativa metoder. För att motivera att en metod har potential ska den kunna producera motsvarande produkter med identiska geometrier för högst samma kostnad och tid.

Närmare bestämt, denna avhandling – skriven för Innventia AB - omfattar utveckling och tillämpning av ett potentiellt, starkt och konkurrenskraftigt tillverkningskoncept för en lovande kompositmaterial. Kompositen är sammansatt av en bio-baserad polymer PLA (Polylaktid) som är förstärkt med cellulosafibrer och komponenterna tillhör förnyelsebara naturresurser.

# Table of contents

1. **INTRODUCTION** .................................................................................................................................................. 3  
   1.1. **BACKGROUND** .................................................................................................................................................. 3  
   1.2. **PURPOSE AND AIM** ........................................................................................................................................... 5  
   1.3. **CONSTRAINTS** .................................................................................................................................................... 6  

2. **THEORY** ................................................................................................................................................................. 7  
   2.1. **MATERIAL** .......................................................................................................................................................... 7  
   2.2. **MANUFACTURING** ............................................................................................................................................. 10  

3. **METHOD** .................................................................................................................................................................. 15  
   3.1. **MANUFACTURING CONCEPTS** .......................................................................................................................... 15  
   3.2. **PROCESS REFINEMENT** ..................................................................................................................................... 17  
   3.3. **PROOF OF PROCESS CONCEPT** ........................................................................................................................ 24  
   3.4. **SUMMARY OF METHOD** ..................................................................................................................................... 28  

4. **RESULTS** ................................................................................................................................................................. 29  
   4.1. **PROCESS CONCEPTS** ........................................................................................................................................... 29  
   4.2. **PROCESS REFINEMENTS** .................................................................................................................................. 40  
   4.3. **PROOF OF CONCEPT - PRODUCE A DEMONSTRATOR** .................................................................................... 54  
   4.4. **SUMMARY OF RESULTS** ....................................................................................................................................... 60  

5. **CONCLUSIONS** .......................................................................................................................................................... 63  
   5.1. **SPECIFICATION OF ACHIEVEMENTS** ................................................................................................................... 67  

6. **DISCUSSION/RECOMMENDATION** ....................................................................................................................... 69  
   6.1. **DISCUSSION** ......................................................................................................................................................... 69  
   6.2. **RECOMMENDATIONS FOR FURTHER WORK** ....................................................................................................... 69  

7. **ACKNOWLEDGEMENTS** ........................................................................................................................................ 71  

8. **BIBLIOGRAPHY** ......................................................................................................................................................... 73  

9. **ATTACHMENTS** ....................................................................................................................................................... 77
1. Introduction

1.1. Background

Bio-based polymers have been around for nearly 20 years without making a major impact [1], mostly due to their high cost compared to petroleum-based polymers. However, because of the rising oil prices and increasing awareness of the environmental issues, bio-based polymers may be on their way to become the more economical option, as an increasing amount of customers are willing to pay more for an environmental choice [2].

One of the most important differences between today’s most common consumer product materials and bio-based materials is degradability. The misleading truth about petroleum-based polymers is that some actually do degrade, but only through UV-exposure in an oxygen-rich environment. This is called photodegradation [3]. In contrast, most bio-based materials degrade through biodegradation, which means microorganisms break down the organic matter. When broken down, the microorganisms will have created a more nutritious soil, supporting the growth of more resources for producing more bio-based material.

This thesis was contracted by and done at the company Innventia AB, based in Stockholm, Sweden. Innventia is active in the areas of research and development relating to pulp, paper, graphic media, packaging and biorefining.

MATERIAL

Engineers can now satisfy more specific and demanding needs of a wide range of applications with custom made composite materials. This is done by combining two or more materials with performance satisfying each critical parameter for the application in which they are needed. A composite is usually composed of fibres integrated in a matrix material, where the fibres reinforce the matrix material with their mechanical properties. A common reinforcement in composite materials is glass fibre. It is strong and stiff but not very sustainable.
In this project, cellulose fibres extracted from birch was used. They are sustainable, available to a low cost and when they are included in polymer-based composites, the composite can achieve similar properties to some with glass fibres (see Attachment 1). Cellulosic fibres have mainly been used by the paper and packaging industry. Due to production techniques, package designs using paper has either been limited to flat surfaces, such as the cardboard box or curved surfaces with constant thickness, e.g. the egg carton. Because of these limits in manufacturing, few products besides packages are created using the same manufacturing techniques as the ones used by the paper and packaging industry.

![Figure 1.1 Traditional egg carton.](image)

In the beginning of a product’s life cycle, raw materials are usually extracted through different processes. Some materials use non-renewable resources, such as oil or metals, while others such as wood is grown. Bio-based polymers are derived from renewable natural resources, which can be grown using the nutrition left behind by a fully degraded product made from bio-based materials. Almost all commercial polymers in use today are synthetic, derived from oil and are made from monomers, mainly consisting of carbon, hydrogen and oxygen. Nature’s own polymers are biotic, meaning they originate from living organisms. Most of these, such as wood, wool and leather, are renewable and can degrade.

In this project, the bio-based polymer PLA was used. PLA is made from lactic acid, which is made from dextrose by fermentation. Dextrose is made from cornstarch or cane sugar.
1.1.1. Manufacturing Process

It is often difficult to make paper sheets with a shape variable in all directions, due to the strong interactions between cellulose fibres. To achieve complex shapes, the cellulose can be formed in steps. One of the main steps is preforming which is where an approximate shape of the object is made. One way of doing this is by using a paper moulding technique. The mass is then referred to as “the preform” and it will be subject to further processing steps until a final shape can been achieved.

Now that composites made from bio-based materials are becoming more attractive, it is of more interest to study the possibilities of creating structurally strong materials using paper moulding techniques. Recently, a newly developed composite material, based on a mixture of cellulosic fibres and a bio-based polymer, has been processed to create innovative designs using a paper moulding process. One of these designs is the material sample, named The Kofes and shown in figure 1.2. This method is only capable of producing objects with a constant thickness and due to irregular fibre appliance, the objects will not be able to achieve a perfectly constant density. This makes the manufacturing method less suitable for more high end products.

![Figure 1.2 The Kofes, processed with paper pulp moulding, heating and pressing.](image)

1.2. Purpose and aim

This thesis is a stepping-stone towards introducing a bio-based composite in products for different markets. By creating modular innovations, old and common materials used in existing products can be replaced with new and sustainable
materials. Renewable composites offer more than just a way of replacing traditional, non-renewable materials. Their unique potential is also expected to give rise to entirely new products and markets. An approach to design that extends to the molecular level makes it possible to produce composite materials that are perfectly adapted to current and emerging market needs. Renewability, so far from being the defining factor, becomes one feature among many.

This thesis aimed to look at different methods to process the PLA-cellulose composite into preforms that can be consolidated in a step of shape correction. A further aim of the project was to show what could be accomplished using the material and the new manufacturing process through the design and development of a demonstrator object.

1.3. Constraints

Unless specified otherwise, the percentage of PLA and cellulose fibres used in the mix is precisely 60 wt% PLA, respectively 40 wt% cellulose. This material composition is derived from recommendations made by Innventia.

No optimisation of efficiency has been made when developing the manufacturing process, just construction and proof of the basic principles. However, the chosen concept is the one believed to have the greatest potential for improvement and implementation.

There is no connection between the demonstrator and a commercial market. It is merely an object suggesting one application in combination with the developed manufacturing process. Therefore, no contact has been made with any company to adapt the demonstrator for a specific purpose.

If certain required steps in the manufacturing process already exist, and if these are well developed, these will not be further developed unless required. Most development will be focused on steps in the manufacturing process that are new or have the most potential for improvement.
2. Theory

2.1. Material

According to a study made in 2007 by InsightExpress [4] in the United States, 72% of the American population was unaware that plastics are generally made from oil. The same study showed that 40% of the people questioned, believe the same plastics will degrade if discarded in the nature or in the sea. Plastic manufacturers in the United States consume approximately 2 million barrels of oil daily, which equals 10% of the nation’s total.

If the energy used to obtain cornstarch**, run the chemical polymerisation processes and the product manufacturing would originate from a renewable energy source, there would be barely any carbon footprint and the products would be fully carbon neutral**.

2.1.1. MECHANICAL PROPERTIES

2.1.1.1 Composite

In a polymer-based composite reinforced with fibres (see figure 2.1), it is mainly the fibres carrying the mechanical loads, which in this case is cellulose [5]. The fibres are protected from environmental factors and kept in place by the matrix material, the PLA. The matrix provides ductility, toughness and transmission of mechanical loads to the fibres. The properties of the composite are strongly dependent of the fibre-matrix material ratio, fibre length and fibre orientation. For further mechanical improvements, the presence of coupling agents can be considered to reinforce the bonds.

* Starch of the corn grain which can be used as a thickening or gluing agent when dissolved in water.

** A carbon footprint is the total set of carbon dioxide emissions caused by an organization or product.
The properties for moulded PLA and wood fibre in a 60-40 composition have been collected in Table 2.1 [6]. It has been found that the properties vary with the material composition. The examined compositions were 80-20, 70-30 and 60-40. In the case of 40 wt% cellulose fibres, compared to pure PLA, the tensile modulus increased significantly from 2.7 GPa to 6.3 GPa, which means the material becomes stiffer as the quantity of fibres increases. With 20 wt% cellulose fibres, the tensile strength reaches a maximum of 65.7 MPa and drops to 63.3 MPa with 30 wt% fibres. A further increment to 40 wt% cellulose fibres lowers the tensile strength to 58.7 MPa, which is below that of pure PLA (62.8 MPa). The impact strength decreases with the amount of cellulose fibres. From pure PLA to 60-40 PLA/cellulose, the impact strength decreases from 25.7 to 21.9 J/m.

Table 2.1 Data for PLA/cellulose composites as well as for pure PLA [6].

<table>
<thead>
<tr>
<th>Composition</th>
<th>PLA* – cellulose** composition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60 – 40</td>
</tr>
<tr>
<td>Tensile strength [MPa]</td>
<td>58.7 ± 3.1</td>
</tr>
<tr>
<td>Tensile modulus [GPa]</td>
<td>6.3 ± 0.9</td>
</tr>
<tr>
<td>Flexural strength [MPa]</td>
<td>114.3 ± 5.6</td>
</tr>
<tr>
<td>Impact strength [J/m]</td>
<td>21.9 ± 3.3</td>
</tr>
</tbody>
</table>

* Biomer L 9000, molecular weight, M<sub>w</sub> 20 kDa, M<sub>n</sub> 10.1 kDa, supplied by Biomer, Krailling, Germany

** 2010 MAPLE wood flour, supplied by American Wood Fibers, Schofield, WI
2.1.2. Thermal properties

2.1.2.1 PLA

Compared to other thermoplastics, the glass temperature of PLA [7] is relatively low and its range of service temperatures is narrow. However, this does not affect the amount of ways it can be processed [8]. PLA will be subject to thermal degradation when exposed to high temperatures. For example, colour changes in the material will quickly take place at temperatures over 200°C. When held 10°C above its melting point for a longer time, major molecular degradation will occur [9].

When subjecting PLA to heat with the presence of water, hydrolysis will take place [10]. This will cause a loss in the material’s mechanical properties. Furthermore, PLA is hygroscopic, which means it easily absorbs moisture from the air.

Due to the risk of having PLA reacting with water during processing, it is important that the preform is thoroughly dried before melting the PLA. Thermogravity analysis (TGA) [11] is a method for measuring mass change associated with moisture transition or degradation. The mass change is low from room temperature to 110 °C and is increased above 150 °C. A symptom of material degradation is when the material is shifting colour [12]. However, it can be beneficial to expose the material to temperatures between 170 °C and 185 °C for a shorter amount of time, since there can still be some moisture in the material even after it has been dried [13].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point</td>
<td>160-178°C</td>
</tr>
<tr>
<td>Glass temperature</td>
<td>56-58°C</td>
</tr>
<tr>
<td>Max. service temperature</td>
<td>45-55°C</td>
</tr>
<tr>
<td>Min. service temperature</td>
<td>-12°C</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.12-0.13 W/m·K</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>1.18e3-1.21e3 J/kg·K</td>
</tr>
<tr>
<td>Thermal expansion coefficient</td>
<td>126-145 μstrain/°C</td>
</tr>
</tbody>
</table>
2.1.2.2 Cellulose

The cellulose has the ability of creating strong fibre webs. By first commingling wood fibres in water followed by drying them completely, strong hydrogen bonds are created [15].

As cellulose creates its bonds during drying, it does not benefit from being exposed to the higher temperatures. However, if mixed with PLA, it becomes an unavoidable step in the material processing. While cellulose has a much wider range of possible service temperatures compared to PLA, it is important to notice the maximum service temperature of cellulose is approximately 50 °C lower than the melting point of PLA. This means that degradation of the cellulose will occur if mixed with PLA while it is being melted.

Table 2.3 Thermal properties for cellulose based paper [14].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. service temperature</td>
<td>77-130 °C</td>
</tr>
<tr>
<td>Min. service temperature</td>
<td>-273 °C</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.17 – 0.346 W/m·K</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>1.34e3 – 1.36e3 J/kg·K</td>
</tr>
<tr>
<td>Thermal expansion coefficient</td>
<td>5-20 µstrain/°C</td>
</tr>
</tbody>
</table>

2.1.3. ANALOGY

By using a material library software [14], the material properties of the 60-40 PLA cellulose composite could be compared to other materials. When comparing the materials mechanical properties, it was found in terms of strength and stiffness to be similar to polypropene, polystyrene with 20 % glass fibre content and polyethene with 30 % glass fibre content. This can be seen in Attachment 1.

2.2. Manufacturing

Composites consisting of a polymer mixed with a type of fibre have been used for almost every type of application possible [16] with few consisting production complications. However, these composites usually use fibres of glass or steel.
instead of cellulose. Cellulose-based products are most commonly paper, cardboard or textiles and since the cellulose reinforced PLA behave partly like paper until melted, it has the same production complications as paper or cardboard. Most commonly, paper has a constant thickness, is rarely thicker than one millimetre and has nearly no potential for plastic deformation. It also has to be mixed with water to allow the cellulose fibres to commingle [16]. None of these are properties of common polymers and they all make the production of a polymer-cellulose composite problematic. Manufacturing a shape containing variable thickness, while maintaining the same density, is difficult due to shrinkage when drying the composite.

There are numerous ways to process materials, though each way is most commonly adapted for a specific type of product. There is also no superior way to shape cellulose fibres into complex shape, such as injection moulding is for thermoplastics.

2.2.1. METHODS

In the paper making industry, the most common processing type for non-flat sheets is paper pulp moulding [17]. It utilises vacuum to draw paper pulp towards a tool with a fine meshed surface. This creates a preform that can be removed to be dried. In some cases a last step of shaping is done to correct the distortion caused by the drying.

![Figure 2.2 Tools for manufacturing Parupu, the paper pulp chair.](image)

A quite common production technique used for large surfaces, such as boat hulls, utilises a mixture of resin and glass fibres. These are simultaneously sprayed onto a
surface and then left to cure. This is called *Spray-up* [18] and does not require water like a cellulose based composite as the resin is in liquid form when leaving the spray nozzle. *Spray-up* methods can also be done with fibres mixed with a dry binder, which is followed by other production methods, i.e. *Resin Transfer Moulding (RTM)* [19].

There are many more production techniques similar or related to processing composites, polymers, cellulose, wood and fibres. Some which can be used as inspiration for creating a production technique concept for the PLA/cellulose composite. To emphasise the amount of ways there are to apply methods of manufacturing different materials, a list of techniques and their area of application can be seen beneath.

### 2.2.1.1 Processing composites

In manufacturing composites, the main families are *composite laminating*, *filament winding*, *3D thermal laminating*, *DMC* and *SMC moulding* [20].

- **Composite laminating**
  - Wet Lay-up
  - Pre-preg Lay-up
  - Resin transfer moulding

- **Filament winding**

- **3D Thermal laminating**
  - 3D laminating (3DL)
  - 3D rotary laminating (3DR)

### 2.2.1.2 Processing plastics

The main families of manufacturing methods for plastic materials are *thermoforming*, *injection-, compression- and blow moulding*. Less common methods of moulding are *rotation moulding*, *dip* moulding and *reaction injection moulding (RTM)* [21].
2.2.1.3 Processing wood and fibres

There are several methods for processing wood [22] but only a few for cellulose in slurry. These are paper pulp moulding and spray-up.

- Paper pulp moulding
- Spray-up
- CNC machining
Wood laminating
  - Kerfing
  - Solid wood lamination
  - Veneer lamination

Steam bending
  - Circle bending
  - Open bending

Spray-up is particularly well suited for fibres. The principle is used in dynamic sheet forming machines. It commonly uses a low percentage of different types of fibres, i.e. 1 wt% cellulose fibres, which it pumps through a pipe and out through a spraying nozzle. The nozzle oscillates vertically in the drum, spraying cellulose and water evenly onto a fine meshed net inside.
3. Method

3.1. Manufacturing concepts

To enable development of a successful manufacturing method, strong concepts were required. The purpose of these initial steps was to first develop promising manufacturing concepts, with the help from a set of tools. They went through an elimination of the weakest concepts, and continued by improvement of the strongest concepts. To make a final qualified decision on what concept to choose, a tool for objectivity was used.

3.1.1. DEVELOPMENT

Suitable methods were applied for initiating the process of creating concepts. These were all practised in a consequent and mostly objective manner. By targeting all the features and their importance, continuing with using a method for ensuring the generation of a wide range of concepts, potential solutions were revealed.

3.1.1.1 Specification of requirements

In general, this document [23] is created in the initial phase of a project by the developers and their employers. The document serves as a tool for pinpointing all the critical functions and their importance. Therefore, it shall consist of all the requirements that can be had on the final result. Each requirement must be labelled with a degree of importance. This is to be able to identify the most crucial objectives and in case of having to prioritise amongst them. The specification of requirements is also used to estimate the final result, as it will come to work as a reference document for benchmarking each concept. This is to ensure that the resulting concept will be one with the best fulfilment of the most important requirements or desired features.

3.1.1.2 F/M-Tree

This technique ensures that a maximum number of function variables are combined with a maximum number of means (tools) to generate a wide scope of possible concepts, built up and illustrated in a tree structure [24]. In practice, it starts by analysing and setting the fundamental function of the concept, the core
task. This is then branched off into several possible means of putting the function into practice. Each method is in its turn connected to another solving function with alternative practical means and their respectively functions. Most importantly, the tree had three top means of creating a product. The one that showed highest likelihood of succeeding were the mean of creating a preform that is shape corrected afterwards.

3.1.2. CONCEPTS

The process of generating different ideas for a specific goal is the most creative part of a project. By applying the tools mentioned above, in that order in which they appear, a maximum number of concepts could be generated.

3.1.3. EVALUATION

After having generated different production process concepts, these had to be screened, improved and evaluated to find the ones with most potential. The screening step is done to avoid excessive work by eliminating the weakest concepts first. The remaining are then passed on to a more elaborated decision matrix, which is used for both improvement and evaluation. After having performed these steps, a well-informed decision could be made.

3.1.3.1 Screening

The screening step [24] consists of a number of steps that each concept has to be checked against. The first step is to decide if the project group possesses enough knowledge of the technology utilised in the concept or if the technology used would be too difficult or expensive to perform basic experiments. A failure in passing this step would automatically eliminate the concept. The second step is only a test based on personal belief in the concept. While it is important there is belief in any concept subject to further work, a failure in passing the step would not automatically cause elimination. The third and fourth step, are based on earlier documented testing of the concept or testing of a process very similar to the concepts’ and if these tests were proven to be successful. A concept would only be subject to further work if it passed all tests. However, if there was strong belief in a concept, one failed test could be tolerated.
3.1.3.2 Decision matrix

With a number of concepts removed through the screening step, the remaining ones could be passed on to the decision matrix [25], where the specified requirements were listed in levels of importance. The rows in the matrix are made up of the requirements, which are based on the specification of requirements. The columns make up the different concepts that are being improved and evaluated, except from one column, which is dedicated to rank the importance of each requirement. Each concept was given an objective rating when estimating how it was believed to meet each requirement, which would lead to a total score. The concepts with a distinctly higher score would be the ones that went on for closer investigation. To be as consistent as possible, one approach of filling-in the matrix is to treat one requirement at a time, for all concepts.

3.2. Process refinement

After the thorough evaluation, a decision was made and the concept with the most promising manufacturing principle was chosen. The chosen concept for the manufacturing process is based on four mandatory steps – commingling, preforming, heating and shaping. It was then time for refining each one of these steps in to a complete concept. This was mostly done by analysing and performing tests.

The majority of the four steps were relatively finished. However, the step in most need of improvement was the second step, preforming. The core function of the preforming had been established. The question remained, with what means this would be realised through. There were two ways of doing this, free-form spray-up and rotational spray-up. Each sub concept needed exploration and further development before choosing one to apply in the complete manufacturing process.

In addition to the four steps, there was an alternative added after commingling, namely additives. It explored the possibilities for influencing properties and features in the material.
3.2.1. COMMINGLING

This is the first of four steps in the developed manufacturing process. It is where a certain amount of components are mixed to achieve the right composition in the material. The processing also enables a manageable material to be applied in an acceptable manner. Some factors had to be considered and adjusted.

The choice of material quality had to be consistent throughout the project, to ensure the results in performed tests could be reconstructed. Therefore, the PLA that came to be used was supplied from a single source*, labelled PL01 (produced and supplied 2005) and PL01 (produced and supplied 2008), with no other difference than the production and supply date. However, the batch produced in 2005 had showed signs of a slight degradation, though this was believed not to affect the process studies in substantial ways. The wood fibres were fully bleached hardwood fibres made from birch with the length of 5mm**. All water for commingling and preforming was deionised to eliminate impurities and eventual reactions with dissolved salts and minerals.

The commingling process was performed as follows. Firstly, the size of the batch was decided. A smaller batch would measure approximately 5 litres, while a larger batch would measure more than 30 litres. As paper pulp moulding commonly uses a high concentration of water [17], 99 wt% was suitable to be used as a starting point. Of the remaining 1 wt %, PLA and cellulose fibres was measured to 0.60 wt% and 0.40 wt% respectively, added to the deionised water and transferred to a fibre dissolver [26]. Depending on the size of the batch, the next step would be done all at once or a few litres at a time due to the small size of the dissolvers. The batch would be mixed with the dissolver for 500 – 1500 revolutions for a complete commingling.

3.2.2. ADDITIVES

This step is not included in the four steps of the manufacturing process. However, it can be used in conjunction as an additional step. Few materials are used in their original form, so the most common additives was taken into consideration, e.g.

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*N. I. Teijin Shoji Co., LTD, Japan.  
** Information given by the supplier
flame retardants as especially cellulose burns easily. The colour, surface or texture of the composite material may not be the desired one, thus coatings and surface treatment was taken into consideration as well.

Colouring agents that were used in the colouring trials were Sandoz Cartasol black dye and common red caramel colour.

3.2.3. Prefoming

The second step in the manufacturing process is preforming. This is where the material is formed into an approximate shape of the final result. It is a necessary step for the fibre composite since the fibres need to start bonding before proceeding with further processing. When forming the uncompressed structure of material, several things had to be taken into consideration.

3.2.3.1 Nets

The platform where the material is preformed, need to withhold material while allowing water to pass through. Therefore, a net is best suited. Four of many nets available at Innventia, each with different materials and mesh* sizes were tested for their ability to catch fibres sprayed onto them. This was done by pumping a 0.5 wt% mix of PLA and cellulose through a water pump [27] to a spraying nozzle to create an even flow and distribution. The water that passed through was collected and analysed for its concentration of fibres and their length.

3.2.3.2 Draining force

When preforming, it is essential to remove excessive volumes of water as fast and efficient as possible. This is important to enable well-defined transitions in the geometry. Therefore, two means for doing this were examined. Free-form spray-up has a draining force based on vacuum and rotational spray-up has one based on the centrifugal force.

Vacuum

As suggested in Free-form spray-up, a shaped net is being sprayed on one side while vacuum is being applied in a synchronised motion on the other side.

* The unit for measuring the size of the openings in a net.
Vacuum can be used both to force the material towards a meshed surface as well as removing the excess water. This could overcome problems such as large segments falling off the net due to friction, gravity or beam pressure being too powerful. To test this, a simple vacuum mouthpiece was constructed (illustrated in Figure 4.10). It was made from an elastic material to allow a tight fit against flat, as well as uneven surfaces. The mouthpiece was connected by tubing to the built in vacuum source at Innventia laboratories. Unfortunately, the vacuum strength of these was unknown. It also occurred a slight variation in strength from day to day depending on which laboratory was used. To avoid clogging the vacuum sources with too much water and pulp, separators were connected between the vacuum source and form.

The tests were performed in ways where the slurry was sprayed onto vertical and horizontal nets in different angles, directions and movements. Measurements were taken on the thickest areas that were achieved when spraying continuously.

Centrifugal force
As mentioned in Rotational spray-up, the draining force is retained through centrifugal force. This is done by rotating the net while spraying the preform on the inside, filtering the water from the material. The dynamic sheet former uses the same principle. Its motor rotates a net in a container. The centrifugal force compresses the pulp towards the net while draining it of water. To get a better understanding, experiments were done with a sheet former. It was used with slurry containing only a low concentration of the material (0.25-0.50 wt%). To find the right density in the material, different rotation speeds were examined. A cylindrical net that rotates around a vertical axis, can be sprayed either from the outside or from the inside. So, just for the sake of it, two set-ups for rotational spraying were made. The first one was spraying a rotating cylindrical net from the outside. In this case, the rotational force would have an undesired effect. This was done to study if the fibres would stick to the net, and if so, at what rotation speed the centrifugal force would detach the fibres from the net.

The second set-up was done in the dynamic sheet former, using a manually held spraying nozzle to spray the inside of a rotating cylindrical net. In theory, the
circumstances would now be right for using the rotational force as a draining force in. It was important to be able to achieve well-defined samples with largely varied thicknesses and short thickness transition lengths. Tests were carried out to examine the effect of combining different adjustments in water pressure, rotation speed, concentration and spraying distance.

3.2.3.3 Spraying

The basic principle of the preforming step in the manufacturing concept is spraying. Different areas have been examined and further developed to create the most beneficial circumstances possible. Those areas were Equipment and Techniques.

Equipment

Since the spraying of fibres has proven successful in similar production processes or experiments, most aspects of the process had to be tested. This was done by setting up a test rig in a laboratory built for water handling. The rig consisted of a water pump capable of pumping fibres, a vacuum source, a spray nozzle and various tubing, connectors and containers, all seen in Figure 3.1. A small selection of spraying nozzles was available for use, though the one used, unless specified otherwise, was H1/4U-SS2504. This was a 1/4 inch stainless steel, flat spray nozzle with 25 ° spraying angle and 04 capacity size [28]. The capacity size is basically selected through desired litres/minute and pressure used. In this case, it is capable of 1.3 litres/minute at 2 bar and 1.8 litres at 4 bar, whereas a nozzle with the capacity size 09 would be capable of spraying 2.9 litres/minute at 2 bar pressure.

![Figure 3.1 The equipment used in spray-up experiments.](image)
The nozzles that were available for use* had been ordered during the original development of the dynamic sheet former. Nozzle 8 was an exception, which was ordered from a supplier** to make it possible to spray circular shapes with uniform fibre dispersion in difference to the flat spray nozzles.

During the initial testing, the spraying rig clogged up repeatedly both during start up and while running. Thus, the concentration of PLA/cellulose was adjusted to reduce the amount of clogging to only occur once in a few tests and only inside the spraying nozzle during start up.

**Techniques**

The spraying experiments started with examining the equipment where spraying pressure, distribution angles and spraying distances were tested. To ensure that a spraying technique could be used to spray onto nets of any shape and to ensure fibres would stay on them after being applied, both net orientation and the nozzle’s angle in relation to the net were taken into consideration and tested (as pictured in Figure 3.2). Other aspects taken into consideration were the movement and direction of the nozzle. When spraying on a static net with high pressure, the main problems were believed to be the increased friction between fibres and net as well as gravity affecting larger portions of applied fibre.

![Figure 3.2 The spray angle, α between the net and nozzle has a significant importance. The importance of β increases with larger portions of applied fibres.](attachment:2)

* See Attachment 2.
** Spraying Systems AB.
The initial material contact with the net has an effect on the spraying result. This is because the pressure from impact can vary. It can be relatively high or low depending on the beam pressure in combination with the direction and movement of the nozzle (see Figure 3.3). In the case of a high beam pressure, there is a risk that the beam will be strong enough to wash away the already applied fibres. In contrary, if the pressure would be too low the spray distribution angle of the nozzles could decrease [29].

![Figure 3.3 The relative movement of the nozzle in relation to the net can be decisive for the fibres to stick on to the net.](image)

3.2.4. Heating

The third step in the manufacturing process is divided into two phases, drying and melting. In the first phase, the preform is dried and the fibre bindings are completed. Since the PLA is hygroscopic, it is important to proceed to the next phase after drying so that the material will not absorb moisture. It is not before the second step is accomplished, that the preform becomes a fully integrated composite, as the PLA forms a matrix around the fibres. It is essential that the material have been fully dried before melting the PLA to keep it from reacting with water. Optimal treatment of PLA and cellulose fibres is desirable but the drying guidelines posted by *NatureWorks LLC* [10] were not followed strictly while designing the process.

In the first phase, the majority of the samples were left to dry in an oven over night or longer at approximately 40 °C. In the second phase, the temperature had
to be adjusted to melt the PLA without burning the cellulose fibres, while the production time should be kept as short as possible, but still creating products with full mechanical properties. A beneficial temperature and time combination was found by placing a number of samples in an oven and frequently examining changes. The changes could be deformation through melting or colour shifting caused by degradation. Temperatures equal to as well as higher than the melting point of PLA were tested.

3.2.5. SHAPING

The last step in the manufacturing process is shaping. This is done by conventional pressing where no incremental development of the method would take place. When pressing the preform it is done vertically in a pneumatic press. If required, the pressing tool in the press can be designed to press in variable directions. In this project however, the tool remained simple with a bottom and a top part.

Most of the tests were performed with rapid transfers of the preform from the oven to the shaping tool. The tool halves were used both at room temperature and heated to temperatures close to PLA’s melting point to achieve optimal material release and surface finish. The pressing tools were placed into a press and compressed with hydraulic pressures ranging from 40 – 400 bar.

3.3. Proof of process concept

The manufacturing concept is meant to produce objects in a material that is not yet used in the commercial industry. It is therefore a so-called radical innovation, first in line to fulfil its function. The process contains a number of operations that require several functions, which have been considered and solved in a methodical way of theories, calculations, and simulations through tests. To evaluate the conceptual manufacturing process thoroughly, an object was produced in the form of a demonstrator.
3.3.1. Development of demonstrator

With the main priority being the actual analysis of the manufacturing method, it was unlikely that a finished product could be developed within the time frame of the project and thus the product being made was in fact a demonstrator. The demonstrator was in this case an object that would demonstrate the potential of the manufacturing method in combination with the material. However, to preserve a design element in the thesis work, the demonstrator would be given added value by elaborating upon its design. This was done while keeping it in a simple shape, which could in fact have several purposes depending on the investigator. Shapes that are more complex would be possible, but it was not desired due to the increasing difficulties in net production and mould making. However, the simpler shape would not limit its ability to demonstrate the material’s capabilities.

The only restraints in designing the demonstrator were the parameters given by the material and manufacturing method experiments, as well as the maximum size possible to manufacture with the available laboratory equipment. Thus, the maximum width was constrained to what the pneumatic pressing tool allowed. The maximum height was set to 120 mm to allow the manufacturing mould to fit into the pressing tool. To follow a typical systematic design process, a large number of fast sketches were made with consideration taken to the high amount of limitations given by the material or manufacturing method. These were then objectively evaluated by judging their aesthetic appearance, their ability to demonstrate the possibilities of the material and manufacturing method as well as their possibility to be manufactured within the time frame of the project for a relatively low price.

3.3.1.1 Specification of demonstrator requirements

As previously noted, the method for setting the desired features and their rank were creating and filling out the specifications of requirements. This reference document came later to work as a buffer for benchmarking the concepts. By applying and going through these routines, the goals were ensured.
3.3.1.2 Concepts
With criteria from the required specifications and the ambition of showcasing the abilities of the process, concepts were generated. This was done through the creative process of iterating ideas into concepts.

3.3.1.3 Evaluation
After the basic concepts for the demonstrator had been formed, it was time to estimate and compare them. Many concepts evolved even further through enhancing them with new combined features from other concepts making them better alternatives.

A few of the strongest aspects considered and ranked were the relationship between the complexity of the object and risk for complications during manufacturing. Appearance was important and to hold a lateral capacity to imply potential future markets. Suggesting a sustainable choice in other fields may also be of great importance.

Similar to the development of the manufacturing process, the concepts had to pass through a simple screening before the iterative process of eventual further development followed by a last evaluation and decision.

3.3.2. Manufacturing
Each step had its own critical operation that had to be bridged with the best possible construction design. To put the process into practice, certain equipment was required. Structures needed to be fully conceptualised, manufactured and built.

3.3.2.1 Commingling
The necessities for the operation of mixing the compound were complete from before. See chapter 3.2.1 Commingling for the background details and how tests were performed.
3.3.2.2 Preforming

This operation required some innovative construction. The design needed to be done in a way where the formed net was docked to rotate in a fixated container surrounding it to collect water. The principle functions and line-up for the preforming equipment can be seen in Figure 3.4. Solutions (means) for the functions were designed and drawings for manufacture were made. Stainless net and waterproof bearing were ordered from suppliers*. Everything was sent to a contractor** for machining and assembling.

![Figure 3.4 The basic performing principle.](image)

3.3.2.3 Heating

Just as the commingling operation, all the prerequisites were available from before. See chapter 3.2.4 Heating for background details and how it was done.

3.3.2.4 Shaping

To accomplish a fully processed product, the preform needs to be defined with accuracy to achieve a smooth surface finish. A mould was needed to be machined according to drawings based on the demonstrator. The drawings were made and

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*Silduksfabriken i Jönköping AB

**TransemaAB
sent to a contractor* where the tool was made and assembled. See chapter 3.2.5 Shaping for the background details and how tests were performed.

3.4. Summary of method

The main objective was to create a manufacturing process that could produce three-dimensional objects from a PLA/cellulose composite. When this had been accomplished, the extensive task of proving the method successful remained. To achieve this, structured methods and routines were followed. During development of the manufacturing process, concepts were generated using a specification of requirements document and a F/M-Tree. The evaluation process was initiated by screening all irrelevant ideas followed by generating a decision matrix. The matrix was used to evaluate and improve the concepts and to facilitate an objective decision. One concept was chosen for further development. The concept is based on the four steps, commingling, preforming, heating and shaping. Preforming is based on a spray-up principle that initially had two different solutions, free-form spray-up and rotational spray-up. After some tests and analyses had been done, rotational spray-up was chosen for continued development. When the manufacturing concept had been sufficiently developed, it needed to be proven. An object demonstrating the potential of the manufacturing process in combination with the composite was needed. Concepts for the demonstrator were generated, evaluated and chosen, according to guidelines of product realisation [30]. The preforming and shaping steps required some equipment to be made. Thus, a construction for the preforming rig and pressing tool was dimensioned, drawn and outsourced for construction. With all equipment available, a demonstrator object could be produced.

* CNC-Process
4. Results

4.1. Process concepts

4.1.1. Development

The design process is seldom an exact science. The steps of generating concepts and having them evaluated are more usually cycles of bringing them back for improvement by intermingling them with features of other concepts. This is also the reason why the evaluation procedure often is included in the generation of the concepts process. The iteration process is continued until a concept that meet stipulated requirements is produced. Naturally, all tables presented with their performance were from the last improvement.

4.1.1.1 Specification of requirements

As there were no customers to create a manufacturing process for, the “specification of requirements” document was created during discussions with the initiator and tutor of the thesis, Dr. Fredrik Berthold. The goals of creating something new were combined with studies of similar materials and what these materials commonly are used for. These areas of interest could be combined to reach a conclusion of which objectives was desired to achieve. One of the most important objectives was the ability to achieve variable thickness with consistent density. At the same time, another objective was to create a uniform fibre dispersion and smooth surface.

See Attachment 3 for the complete specification of requirements.

4.1.1.2 F/M-Tree

To ensure an extensive generation of concepts, the F/M-Tree was thoroughly developed. Ideas were brainstormed as well as inspired by common and uncommon manufacturing methods to find methods, which could be used in the manufacturing of a composite material containing cellulose.
The main function was defined to simply “Making product” and the means of achieving this were:

- By creating a preform that will be dried and shape corrected.
- By using an additive that will eliminate or reduce the need of water.
- By using layer-based processes similar to rapid prototyping.

![Figure 4.1 Tree structure with main function (red) and three branching means (blue).](image)

Among these, the preforming method was believed to have the highest likelihood of fulfilling the main function and it was followed by the sub-functions:

- Making preform
- Melting matrix material
- Hardening and applying final shape

![Figure 4.2 Tree structure with one mean branching off to three sub-functions.](image)

The sub-functions received several methods in how to have them achieved, continuing to build up the tree which contains combinations for thousands of possible concepts.

For the complete F/M-Tree, see Attachment 4.

4.1.2. CONCEPTS

By combining the alternatives of functions and sub functions from the F/M-Tree, many concepts could be generated. Six of these concepts are presented in this...
thesis and all are ways to realise a theoretical production of a PLA/cellulose composite. These are Free-form spray-up, rotational spray-up, compression moulding with water distillation, (gelatinised) compression moulding, sheet pressing and paper pulp moulding. The concepts are all divided into four steps; commingling, preforming, heating and shaping.

Additives of additional components, such as phthalates, deemed to lie outside the scope of this study. However, one concept making use of pre-gelatinised cornstarch was tested*.

Preforming was the step with the most need of improvement in comparison to the other three. In the context of demonstrating a method of manufacturing, the other steps are relatively complete as established industrial methods. Therefore, the concepts are primarily focused on the preforming step.

Commingling

To be able to produce a strong cellulose-based composite material, it will need to be treated with some amount of water to allow the cellulose fibres to commingle. To ensure this material has uniform fibre dispersion and an even density after further processing, the fibres are disallowed to aggregate and create clumps. Some measures can be taken to ensure fibres are distributed in a desired way in the finished material and this is described further in 4.2.1 Commingling.

Preforming

* See Attachment 5 for the achieved result.
Applying material to create an approximate shape of the final object is called preforming. This is where the six concepts differed most. See their concept description under this introduction.

*Heating*

Between transferring the preform from its tool to the shape-correcting tool, it needs to be dried as well as melted. The variables, time and temperature, of which the preform is exposed to is critical for the final result. See chapter 4.2.4 *Heating* for further description and settings.

*Shaping*

After being transferred from the oven in which the PLA is melted, the preform will be shaped by a tool split into one or more form halves to its final shape. All form halves are, if needed, treated with a release agent. To achieve the desired result this has to be done under specific pressure, temperature and time. See chapter 4.2.5 *Shaping* for further description and settings.

**4.1.2.1 Spray-up**

The Spray-up concept consists of two paths, *free-form* and *rotational*, and both share a main principle of preform-creation. The mass is sprayed to form a three-dimensional object on a fine meshed net. The net is used as a platform and has the shape of the lower part of the object to facilitate the incremental addition of material from the platform and up.

*Free-form spray-up*

This concept is based on spraying the dispersed fibres onto a net while using a vacuum mouthpiece, as shown in figure 4.1. The spraying nozzle (A) and vacuum mouthpiece (B) follow one another on opposite side of the net. The net does not have to be flat. In theory, it does not have any constraints as long as the nozzle and mouthpiece can follow the net’s shape in a synchronised movement.
As this technique showed enough potential for further development, the result from the early testing, as well as details relevant to the concept, are included under section 4.2 Process refinements.

**Rotational spray-up**

Unlike the *free-form spray-up* concept, the coordination of spraying the material onto the net is facilitated in a more controlled way. On the other hand, it requires the objects to be rotation symmetrical. The profile is rotated around the z-axis, which coincides with the direction of the force of gravity and the axis of symmetry. The spraying is done on the inside of the profile, making the pulp stick to the net through centrifugal force as well as by friction. Another alternative would be to spray onto the opposite side of the net, building up the material on the nets outside. In this case, the centrifugal force has to be counteracted by i.e. a strong vacuum as substitution for a centripetal force. In either case, the spray nozzle will only be allowed to move in the x-z plane.
Figure 4.2 Illustration showing the rotational spray-up concept and its coordination system.

As this technique showed great potential for further development, the results from early testing, as well as details relevant to the concept, are included under section 4.2 Process refinements.

4.1.2.2 Compression moulding with water distillation

The preforming is in this case done using compression moulding [31]. An amount of slurry with low concentration of material is poured into the female mould part. The male mould part is subsequently assembled creating a pocket with the slurry. The moulds are thereafter pressed together slowly to allow the water in the slurry to exit through the draining pipes in the bottom, i.e. the female mould part, until the preform has been compressed and the mould completely shut. The exits are placed to distribute a substantial uniform dispersion of the fibres and exclusions of water. The heating and shaping step are performed in the same way as the majority of the concepts.
4.1.2.3 (Gelatinised) Compression moulding

This concept is similar to the previous, but with a smaller volume of slurry. In this case, the cellulose fibres and PLA are mixed to the same weight as the one of the compressed finished result. Furthermore, the mix will contain a pre-gelatinised starch that will allow the fibres to flow throughout the moulds with an even dispersion.

One of the limitations with using water based slurry in which the components are mixed, is that existing production techniques based on viscous materials cannot be used without major modifications. Another problem with using water for shaping materials is the drying process.

The evaporation will lead to a weight decrease and in most cases a decrease in volume as well, which can lead to material contractions and wrinkles. To get around the downsides of water usage, inspiration was found in a patent which handles compositions of fibre reinforced starches and ways to process the mentioned composites [31]. Most of the material compositions in this patent contain a thickening agent, i.e. Stalok 400 that is a modified potato starch, which has been pre-gelatinised. As starches from potatoes and corn are both easily accessible and only have to be heated to a certain temperature to be gelatinised, an experiment was made mixing gelatinised Maizena (Corn starch) containing approximately 70 % water with a nearly dry 70/30 PLA-Cellulose mixture as seen in Figure 4.5 (The cellulose fibres are unbleached in this mixture).
4.1.2.4 Sheet pressing

The Sheet pressing method was inspired by the superforming process of metals, cavity forming [32] and the thermoforming process of plastics, pressure forming [33]. This was one potential method to be used when shaping the preform. Basically, the sheet is made through paper pulp moulding [17], which is dried, heated and pressed as shown in Figure 4.6.
4.1.2.5 Paper pulp moulding

Vacuum can be used both to force the material towards a meshed surface as well as removing excess water from a slurry. This was tested in numerous ways, to find pros and cons of a well-established related process. As stated, paper pulp moulding uses vacuum forms, moving vertically down into paper pulp slurry, drawing the pulp towards the net until it is fully covered and the pressure is insufficient to collect any more pulp (shown in Figure 4.8). In detail, the strength of the vacuum needs to reach a certain level to collect pulp as well as be able to hold it in place after the vacuum form has ascended from the slurry. Thus, tests were performed to ensure this could be achieved.
A small flowerpot was used to make a simple male and female mould in plaster. This would be used to see how well it could reproduce a copy of the pot through pressing a preform. The result can be seen in Figure 4.9.

4.1.3. EVALUATION

After having generated different production process concepts, these had to be evaluated, screened and compared to find the one(s) with most potential. To avoid superfluous work with concepts very likely to fail, they had to pass through a simple screening step before being passed on to a more elaborate decision matrix.

4.1.3.1 Screening

Since paper pulp moulding is already a very well developed manufacturing method, no incremental innovation appeared possible to achieve, thus it was removed in the screening (see Table 4.1). None of the compression moulding concepts proved to have enough potential to pass, as shown in 4.1.2.2 and 4.1.2.3, and so was the case for Sheet pressing as well. As for the Rotational spray-up concepts, spraying from the inside proved to be much more successful than spraying from the outside*, even though Rotational spray-out with vacuum was approved. Despite practical difficulties Free-form spray-up gained enough confidence to pass. Note that some concepts appear in the table without being presented elsewhere.

*See 4.2.3.2 Spraying.
Table 4.1 P = Passed, F = Failed, P?/F? = Passed/Failed with some uncertainty, * = Test was performed by someone else.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rot. spray-in</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td>Rot. spray-Out</td>
<td>P</td>
<td>F</td>
<td>P</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>Free-form spray-up</td>
<td>P?</td>
<td>P</td>
<td>P</td>
<td>F</td>
<td>P</td>
</tr>
<tr>
<td>Spray with rotating nozzle</td>
<td>P?</td>
<td>?</td>
<td>F</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Dry spray</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>?</td>
<td>F</td>
</tr>
<tr>
<td>Sheet pressing</td>
<td>P</td>
<td>F</td>
<td>P</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>Compression moulding</td>
<td>P?</td>
<td>P?</td>
<td>P</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>Compression moulding with water distillation</td>
<td>P?</td>
<td>F</td>
<td>P</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>Injection Nuking</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>?</td>
<td>F</td>
</tr>
<tr>
<td>Paper pulp moulding</td>
<td>P</td>
<td>P</td>
<td>P*</td>
<td>P</td>
<td>F</td>
</tr>
</tbody>
</table>

4.1.3.2 Decision matrix

Paper pulp moulding was included and rated in the matrix* to work as a benchmarking reference to the other concepts. The only one to underachieve in comparison was Rotational spray-out with vacuum. The top candidate according to the final evaluation was Rotational spray-in followed by the same concept combined with vacuum. Free-form Spray-up rated higher than the reference and so it would be further developed together with the other spray-up concepts.

* See Attachment 6.
4.2. Process refinements

4.2.1. COMMINGLING

When performing basic mixing of PLA, cellulose fibres and water, the cellulose fibres should preferably be added to the water and mixed first as they are easily distributed evenly, while PLA will create undesired aggregated clumps of various sizes when added. Unless broken down, these clumps will stay together throughout the whole production process, causing impurities within the material. Furthermore, a mix of the slurry is less likely to have clumps if the 60/40 mix of PLA and cellulose is mixed in a lower concentration. In some cases, it may be important to keep the slurry free from air bubbles as they cling to fibres and, by pulling them towards the surface, making a non-uniform material distribution in the slurry. This could be done by vacuum exposure, thus forcing the air bubbles towards the surface. If necessary, the slurry could be removed from the vacuum tank occasionally to be stirred carefully to allow bubbles to be drawn out iteratively.

4.2.2. ADDITIVES

No additives of any type (including colouring dyes) were used in the process refinements, as e.g. a darker colour would make the results difficult to analyse.

4.2.3. PREFORMING

While it would be desirable to create a finished product with just one manufacturing step, cellulose fibres need water to commingle, thus making preforming followed by drying essential steps to be performed before the final shape can be accomplished. Preforming can be done in many ways, though the most promising ones follow a principle where the preform shape is created along one or more nets with a mesh size small enough to allow water to pass through quickly, while at the same time catching all the fibres.
4.2.3.1 *Net*

The four nets, seen in Table 4.2*, were tested for their ability to catch and hold the fibres sprayed together with water onto them. This was performed with an approximated measure of the amount of material that passed through the net (which is an inverse measure of the amount of water runs off and the amount of fibres sticking to the net). This test showed that the net made of nylon (number 1), with a mesh size of 78**, did not allow much water to pass through, thus having a larger flow running off the net, taking fibres along with it. Being nearly the opposite, the net (number 4) made of stainless steel and with a mesh size of 17 let nearly all water as well as containing fibres pass through.

*Table 4.2 Different kinds of net and their ability withhold sprayed water and fibres.*

<table>
<thead>
<tr>
<th>Net Nr</th>
<th>Material</th>
<th>Mesh</th>
<th>Amount of material passing through net</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nylon</td>
<td>78</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Few</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>None</td>
</tr>
<tr>
<td>2</td>
<td>Phosphor bronze</td>
<td>70</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Some</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>None</td>
</tr>
<tr>
<td>3</td>
<td>Aluminium</td>
<td>50</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Some</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Very few</td>
</tr>
<tr>
<td>4</td>
<td>Stainless steel</td>
<td>17</td>
<td>All</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Many</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Many</td>
</tr>
</tbody>
</table>

All nets allowed an amount of short fibres, likely broken due to fibre dissolving or worn down during storage and transport, to pass through the net while only one (mesh 17) let a significant amount of longer fibres through.

While all nets were made of different materials, the only property accounting for catching fibres seemed to be the mesh size, which appeared to work best in the range 50 to 80. The differences in weave type, as well as friction between net material and slurry were neglected and material was chosen based on other, more important mechanical aspects, these being rigidity, durability, weldability as well as availability. All the metal nets had the rigidity and durability needed, but only those made of stainless steel were widely available as well as being best suited for

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* The full table can be seen Attachment 7.

** Unit [Inch/Tyler]
welding. A last batch of three nets*, based on the most successful properties among the first four nets, was ordered to find the effects of minor difference in mesh size. They were all made from stainless steel and had mesh sizes in the range of 50 to 80. The net that was chosen to be used for creation of preforming net tools can be seen below in Table 4.3.

Table 4.3 Parameters for the net used for constructing the preforming net tool.

<table>
<thead>
<tr>
<th>Net Nr.</th>
<th>Material</th>
<th>Mesh</th>
<th>Wire diameter [µm]</th>
<th>Opening [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Stainless steel</td>
<td>80</td>
<td>120</td>
<td>200</td>
</tr>
</tbody>
</table>

4.2.3.2 Spraying

The *Free-form spray-up* concept was free from the limit of only creating rotation symmetrical shapes. Spraying together with vacuum creates potential to preform complex shapes. On the other hand, with limited resources such as access to expensive and specialised equipment, the possibility of achieving a professional result can be difficult with the *Free-form spray-up* concept. To be able to apply the material and the draining force of vacuum in coordinated motions for creating a preform, programmable robots are needed for precision and consistency.

The *Free-form* and *Rotational spray-up* methods are based on the same principles with only a matter of substitute means for achieving the same thing in the preforming step. In the case of *Free-form spray-up*, the operation of attaining a controlled movement is realized by coordination of robots for the spray- and the vacuum nozzle. In the case of *Rotational spray-up*, this is done with a motor rotating the preforming net while simply moving the spray nozzle vertically. This creates a controlled application of material while influences from the centrifugal force replace the vacuum by draining and compressing the mass.

* See nets 5-7 in Attachment 7.
Spraying nozzle

There was a selection of eight spraying nozzles with different properties available for use as nozzles were already available because they had been ordered for a previous project. Apart from the capacity sizes and spray angles, the differences these nozzles were minute. When increasing the pressure, it will improve the spraying nozzle’s performance, i.e. capacity and spray angle. However, it does have a negative effect on fibres’ ability to stick to the net. This can be counteracted by increasing the distance between nozzle and net, if an increased spraying capacity is desired. However, an increased spraying distance will also widen the spraying area, thus having to reconsider the choice of nozzle.

In this case, the product to be sprayed had a diameter size limited to approximately 200 mm due to the maximum size of the pressing tool. To allow the nozzle to move around freely inside the net area, the spraying distance had to be lower than approximately 100 mm. For this, the spray angle of 25 ° of the nozzle used in early tests (H1/4U-SS2504) remained suitable for its purpose.

As seen in Table 4.4, the pressure output by the water pump that is most satisfactory lies somewhere between one and two bar with a best distance between nozzle and net at around 60 mm. This allows a capacity of 1.0 to 1.3 litres per minute to be sprayed (See Table 4.5). A lower pressure would not be desired due to slower production times and an irregular fluttering spray angle. Pressures above two bar showed difficulties in handling, but were possible with an increased spraying distance.
Table 4.4 Tests on the effects on two spraying nozzles when the pressure output by the pump varies. The only difference between the nozzles is the capacity size.

<table>
<thead>
<tr>
<th>Pressure [bar]</th>
<th>Nozzle SS2504</th>
<th>Nozzle SS2510</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 1</td>
<td>The spray beam flutters and the distance between net and nozzle should be approximately 3 cm.</td>
<td>Same properties as SS2504, but more than doubled flow/capacity.</td>
</tr>
<tr>
<td>1 – 2</td>
<td>No beam flutter and best distance is about 6 – 7 cm.</td>
<td></td>
</tr>
<tr>
<td>2 +</td>
<td>Pressure is too high and within reasonable distances washes off all other previously applied material. In addition, the effects of different angles become more sensitive.</td>
<td></td>
</tr>
</tbody>
</table>

The nozzle that was primarily used was one labelled H1/4U-SS2504, which had the parameters listed in the table below. Other nozzles were ordered, such as one for an eventual need of spraying round surfaces using its round dispersion matrix when spraying. However, none of them proved to be as useful.

Table 4.5 Two nozzle models and their features parameters.

<table>
<thead>
<tr>
<th>Nozzle Type</th>
<th>Inlet Conn. (In.)</th>
<th>Capacity Size</th>
<th>Equiv. Orifice Dia. (mm)</th>
<th>Capacity (litres/minute)</th>
<th>Spray Angle (º)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-U</td>
<td>1/4</td>
<td>04</td>
<td>1.3</td>
<td>.58 .76 .74 .67</td>
<td>25</td>
</tr>
<tr>
<td>HH</td>
<td>1/4</td>
<td>10</td>
<td>3.2</td>
<td>2.9 3.8 5.4 6.1</td>
<td>67</td>
</tr>
</tbody>
</table>

Concentration

In the case of impure slurry, containing larger fibre clumps or fractions of extraneous materials, there is a possibility these can get stuck and cause an obstruction, completely blocking the tubes. In most cases, these obstructions occur during the spraying start-up when cellulose fibres have aggregated inside the
tubes. These are then pushed into the nozzle where the diameter for the slurry to pass through is reduced to nearly 1 mm. To resolve such an obstruction, the nozzle has to be disconnected and cleared of all blocking material. Some measures can be taken to avoid obstructions from forming inside the tubes. For example, the fibres will only aggregate when in contact with other fibres. Therefore the probability of aggregation can be lowered by reducing the fibre concentration in the water (e.g. 0.25 wt %) as well as disallowing slurry to stay static inside the tubes, e.g. keeping it flowing constantly. It is imperative that all equipment insides are rinsed thoroughly with water after disuse as well as after every use to minimise the risk of clumps, rust or extraneous materials.

Since the dynamic sheet former is commonly used with a concentration of 0.5 wt% cellulose dispersed in water, this was used as a starting point for experimentation. Due to occasional blockages despite the low concentration led to it being adjusted to 0.25 wt%.

*Angles*

If fibres are sprayed with a very small angle ($\alpha$, see Figure 3.2), almost parallel, onto a static planar net it is likely they will be deflected instead of sticking to the net. With no water draining, e.g. vacuum or a centrifugal force, it was shown that most slurry just ran off the net when the net itself was placed in an angle of 45 ° or higher ($\beta$, see Figure 3.2), as shown in Table 4.6. With the use of vacuum, fibres would stick when using any angles as long as the strength of the vacuum was proportional to the amount of sprayed material.

When spraying onto the outside of a rotating net, the centrifugal force is replaced with a centripetal force, causing fibres to release from the net. This is further complicated by the fact water draining will not occur through the net. Instead draining will be done outwards, pulling fibres off the net. Lacking an adequate draining system and applied force holding all fibres in place complicate the process, as it has to be complemented with a strong vacuum source, negating the effects of the centripetal force.
Table 4.6 Experimental results of what amount of fibres sticks/runs off when spraying with varied angles onto a surface with a different angle.

<table>
<thead>
<tr>
<th>Spray angle</th>
<th>Vertical net</th>
<th>Net at 45°</th>
<th>Horizontal net</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sticks</td>
<td>Runs</td>
<td>Sticks</td>
</tr>
<tr>
<td>0-30 °</td>
<td>None</td>
<td>All</td>
<td>Some</td>
</tr>
<tr>
<td>30-60 °</td>
<td>Some</td>
<td>Most</td>
<td>Some</td>
</tr>
<tr>
<td>60-90 °</td>
<td>Some</td>
<td>Some</td>
<td>Most</td>
</tr>
</tbody>
</table>

Movements

When the spraying nozzle is moving relative to the net as pictured in figure 3.3, precautions have to be taken so the fibres are distributed to the material homogenously. In this case, nozzle movement in the same direction as the beam ($v_1$) will scoop fibres in front of the beam, while moving the nozzle away from the beam ($v_2$) does not put as much impact force on the already applied fibres, allowing them to stay on the net.

In the example of a static nozzle inside a rotating drum, a very small angle and a certain spraying pressure can be matched with the rotational movement in a way so there is nearly no impact force when the fibres and water beam hits the net. This is advantageous, as the impact would otherwise force the previously applied material away from the beam.

Velocity difference as well as machinery vibration may be the causes of the ridges seen to the right in Figure 4.14. When spraying in such a way, with very low impact force, it is important to understand that the fibres will be oriented according to the spraying direction and thus the mechanical properties will not be homogenous.

Vacuum

Tests were done spraying on nets using a vacuum mouthpiece on the opposite side. The mouthpiece was made using simple suction cups as base for their outstanding performance in staying tightly against planar as well as free-form surfaces, see Figure 4.10.
Figure 4.10 Vacuum mouthpiece. (A) Flexible material – allowing the mouthpiece to stay tightly against a surface. (B) Tube – connected to a vacuum source.

With the largest vacuum nozzle (maximum diameter 40 mm), it was possible to spray continuously at the same spot without washing off the previously applied material. Instead, it kept building up to form a hill-like structure, as seen in Figure 4.11, thicker than 10 mm at some places. However, it did not create a smooth surface at that height.

Figure 4.11 Left: Thin sample with a smooth surface. Right: Thick sample with a rough surface.

Rotation

As mentioned before, the fibres can be applied either on the outside or on the inside of the net. Both ways were analysed and tested, starting with the outside. The setup for testing this concept was through a cylindrical net, rotating with a vertical axis, where the fibres would be sprayed on its outside. It became obvious that the higher the speed of the rotating cylinder, the harder it was for the fibres to stick to the cylinder.
Vacuum was also applied in a test which involved the rotation of a cylindrical net that was being sprayed from the outside, thus negating the centripetal force. Although vacuum made it easier for the fibres to stick to a rotating net, most of them released as soon as they rotated together with the net outside the area affected by vacuum.

Overall the concept of spraying a symmetrical object rotating on the outside of a net without vacuum was a failure, as seen to the left in Figure 4.12, where only hints of fibres could be spotted. Applying vacuum on the inside was not a failure, though not very successful either. Fibres could be seen without problem and the spraying paths were visible as seen to the right in Figure 4.12. Nevertheless, it might have been shown to improve the contact between net and fibre if the circumstances, such as the vacuum strength and the contact with the net, were better. However, the force of the vacuum, holding the fibres in place, would fail when reaching a critical rotation speed.

Figure 4.12 Tests of Rotational spray-out without vacuum (left) and with vacuum (right).
To examine spraying from the inside, a dynamic sheet former was used, making the circumstances more promising since the rotational force has a desired effect in this set-up. The variables can be seen below in Table 4.7.

Table 4.7 Test for spraying inside a rotating cylindrical net. The 3rd test is a repetition of the most successful settings. (P = Pass, F = Fail)

<table>
<thead>
<tr>
<th>Test Nr.</th>
<th>Pressure [bar]</th>
<th>Rotation speed [rpm]</th>
<th>Fibre concentration [%]</th>
<th>Success with spraying distance [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5</td>
<td>350</td>
<td>0.25</td>
<td>P F F</td>
</tr>
<tr>
<td>2</td>
<td>2.0</td>
<td>1000</td>
<td>0.25</td>
<td>P P F</td>
</tr>
<tr>
<td>3</td>
<td>2.0</td>
<td>1000</td>
<td>0.25</td>
<td>P - -</td>
</tr>
</tbody>
</table>

In the first two tests, three stripes were sprayed at the distance of five, two and one centimetres. The first test resulted in three light and soft stripes (see Figure 4.13), and so did the second test, except the stripes were slightly denser and stiffer (see Figure 4.14). The second stripes that were sprayed from two centimetres were in both cases starting to show symptoms of creating a concave geometry where two thicker edges were created on the sides of the fibre strip.

Figure 4.13 Samples sprayed at 1.5 bar, 350 rpm and distances 50, 20 and 10 mm.

Figure 4.14 Samples sprayed at 2.0 bar, 1000 rpm and distances 50, 20 and 10 mm.
One major difference between tests one and two was that the strip, which had been sprayed from one centimetre in the latter test, had formed distinct ridge-like geometry. The strip immediately formed a strong concave geometry. However, the edges from the concavity were evened out in the second test. Hence, the major difference in topography. This was believed to be due to the higher pressure of two bar, making large amounts of fibres to slide outwards.

When spraying inside a rotating drum, fibres that were normally washed away from a static planar surface will remain on the net because of the centrifugal force draining the fibres of water as well as increasing the exerted normal force between the surfaces, thus leading to higher friction. This makes it possible to either increase the pressure slightly or decrease the spraying distance. Samples made at a low rotation speed of 350 rpm, as seen in Figure 4.13, the distance has to be around 50 mm with a pressure of 1.5 bar, which is a small difference to what is possible with a static, planar net. When increasing the rotational speed to 1000 rpm, which is sampled in Figure 4.14, the pressure can be increased as well. At two bar, the distance can be lowered to approximately 20 mm. However, at this distance, signs of ridges can be seen. A further decrease of distance will make the ridges clearly visible, making the material surface too uneven for being suitable as a product material. High rotational speeds will cause the fibres to commingle more tightly which leads to increased preform density, making further processing more efficient.

The third test was carried out using the most successful parameters*. 24 litres of slurry with 0.25 wt% concentration composite resulted in a 20 mm thick and stiff stripe (see Figure 4.15). (Theoretically, it should weigh 60 grams but due to loss through blending and spraying, it had a weight of 50 grams).

There are several ways of creating well-defined edges and masking may be one way of doing this. Another way is turning the nozzle to spray in a sharp line. This way, the slopes in the edges of the strip can be avoided.

* See third row in Table 4.7 with a spraying distance of 5 cm.
Instructions for manufacturing

With the applied centrifugal force, it is easier to spray variable thicknesses, which cannot be done with e.g. normal paper pulp moulding. Spraying continuously at the same spot when the rotation speed is at 1000 rpm will allow material to build up thicknesses up to 20 mm (and most likely more if attempted). This should be sprayed at a distance of 50 mm with 2 bar pressure. No problem was found in attempting to spray thicknesses up to this level and higher ones should be possible. When attempting to build up a matching material thickness on e.g. a planar net without the use of a force equal to the centrifugal, problems will be encountered in draining the water as gravity is not enough. This leads to a significantly lower dry material density and sharp transitions are difficult, if not impossible to achieve, due to the high water content and preserved liquidity. However, applying vacuum behind the area being sprayed onto is possible and thicknesses higher than 10 mm are possible, as shown in Figure 4.11.

Unfortunately, the behaviour of the slurry when being exposed to vacuum creates a very uneven surface. The difficulty of applying vacuum behind a surface being sprayed is revealed when there is a need for different amounts of vacuum at different spots for making variable thicknesses, i.e. varied heights on a planar surface. For this, different segments of vacuum can be used, as well as a vacuum mouthpiece that moves in synchronisation with the spray beam. This mouthpiece must be able to stay tightly against the surface of the net for it to have the proper effect, which is problematic where there are sharp angles. The choice of spray-up
method is therefore dependent on the shape and properties of the object to be manufactured.

### 4.2.4. HEATING

The heating process is divided into two steps, drying the preform and then melting the PLA. Experiments were carried out with recommendations as a starting point and the material’s critical temperatures used as guidelines for not decreasing the mechanical properties through thermal degradation. For drying and melting, the most successful settings of the temperatures and times in the oven are presented as sample 3.7 in Table 4.8* and to the left in Figure 4.16. Subtle differences above critical temperature may have significant impact on the sample as seen on the right side of Figure 4.16.

Table 4.8 Parameters from two samples that had been heated and shaped in a test.

<table>
<thead>
<tr>
<th>Sample Nr</th>
<th>T$_{\text{drying}}$ [°C]</th>
<th>T$_{\text{heating}}$ [°C]</th>
<th>t$_{\text{press}}$ [min]</th>
<th>Pressure [bar]</th>
<th>Sprayed thickness [mm]</th>
<th>Pressed thickness [mm]</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7</td>
<td>40</td>
<td>190</td>
<td>135</td>
<td>15</td>
<td>100</td>
<td>10/20</td>
<td>1.0/2.0 Wheat colour, uniform material, thin parts slightly darker</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>220</td>
<td>140</td>
<td>15</td>
<td>100</td>
<td>3,5/7,5</td>
<td>0.5/1.0 Dark and uniform material, dense</td>
</tr>
</tbody>
</table>

### 4.2.5. SHAPING

It is crucial that the melted preform is transferred to the shaping tool either quickly or at a temperature where the PLA does not degrade at a fast rate or cool down enough to solidify. This must also be done at a temperature low enough to keep the cellulose from degrading further (as its degradation temperature is lower

* See Attachment 8 for the complete table.
than the melting point of PLA [14], [34]). In the case of having to move the melted preform by hand from oven to shaping tool, it is impossible to prevent the preform from cooling down slightly and equally difficult to keep the time that it cools down the same between every sample. The attempt at solving this was moving the preform as quickly as possible, generally around 15 seconds, placing it in a shaping tool heated to a temperature low enough to avoid re-melting but high enough to allow a slow cooling. The settings that appeared most successful* in most cases, was heating the shaping tool to 135 °C and leaving the preform inside it for 15 minutes in a compressed state. This created a smooth and glossy surface, as seen in both samples below.

![Image of two samples](image.png)

*Figure 4.16 The lightly coloured sample (right) has been more successfully processed whereas the darker coloured one (left) became brittle due to thermal degradation when overheating the cellulose.*

When pressing the preform, it is likely its thickness is not completely uniform and therefore the compression ratio will not be uniform either. This leads to samples containing both failed and successful areas, all in the same part. This was first believed to be because of insufficient applied pressure, but this was shown to be untrue as simple samples were pressed sufficiently with a lower pressure. The pressing tool had a maximum hydraulic pressure of 400 bar and used together with the largest object pressed (230 cm²), this lead to a pressure of approximately

*See Table 4.8*
870 N/cm²* which was 5 to 10 times lower than most of the earlier successfully pressed samples.

The factor that would decide the quality was later believed to be the compression ratio. This was iteratively tested and lastly set to approximately 8% of its original thickness. This means an object with a final thickness of 1.0 mm will need to have a preform thickness of approximately 12.5 mm. However, this is difficult to prove when the sprayed preform density is problematic to control.

4.3. Proof of concept - produce a demonstrator
Considering the circumstances of not having access to programmable equipment for precise coordination, the choice of spray method became the Rotational spray-up. If this concept was proven successful, it would also, to some extent, prove the principles of the Free-form spray-up successful but through different means.

4.3.1. Development of demonstrator
With constraints from the requirements and desired features for the manufacturing process, a demonstrator, which would display some of these requirements and features, could be developed.

4.3.1.1 Specification of requirements
One of the main requirements emphasised in the specification of requirements was the ability to produce material in shapes otherwise difficult to reproduce with other paper-based manufacturing processes. Additionally, requirements linked to its thickness, thickness proportions and its surface were of importance in the specification**.

---

* \[ P_{mech} = P_{hyd} [\text{bar}] \cdot \frac{500}{A [\text{cm}^2]} \]

** See Attachment 9.
4.3.1.2 *Concepts*

The material generated on the way from abstract ideas to a demonstrator gradually changed with iterations from quick thumbnail sketches (see figure 4.19) and detailed CAD models with set measurements.

![Figure 4.17 Early concept sketches.](image)

4.3.1.3 *Evaluation*

After generating several demonstrator concepts, they were evaluated to find the one which best fulfilled the criteria. All concepts were rotation symmetrical or nearly rotation symmetrical with isogonal symmetry. Since all contractors that were contacted lacked experience in creating net shapes with advanced curved shapes, many of the concepts had to be screened or changed. Naturally, this had major impacts on the demonstrator concepts as they all had to have curved surfaces simplified, as pictured below in Figure 4.18.
The chosen design (as seen below in Figure 4.19), consists of revolved surfaces and a bottom part.

4.3.2. MANUFACTURING

4.3.2.1 Commingling

The normal size of a slurry batch may vary but to specify the proportions and implement, follow the instructions that follow.

Instructions for manufacturing

20 litres with 0.25 wt% of 60/40 PLA/cellulose:

- Mix 30 grams of PLA with 12 litres of water in the fibre dissolver.
- In the same way, mix 20 grams of cellulose with 8 litres of deionized water.
- Blend the PLA and cellulose in a container with a mixer that stirs continuously.
4.3.2.2 Preforming

The nets for the preforming platform were constructed using CAD software where it was unrolled (feature present in Rhinoceros 3D [35] and explained in figure 4.20). These flat unrolled surfaces were modified to have connector parts simplifying assemblage. These were printed in 1:1 scale and lightly glued to the net to be used and cut out by hand. Preferably, the parts should have been cut out more precisely and welded together, but hot melt adhesive showed to be enough for production of up to 15 preforms.

![Figure 4.20 Illustration showing the original shape, after it has been unrolled and added connector parts.](image)

The other components that the construction consists of are the container, net holder and rotation mechanism. These were dimensioned, bought, sent to be modified and later assembled. The design of the spray-up rig can be seen in Attachment 10. Part of the construction of the prototype can be seen in Figure 4.21. The chosen bearing was water resistant to avoid corrosion and to minimize the risk of exposing the motor to water.

![Figure 4.21 Draining hole and rotation mechanism inside the preforming container.](image)
4.3.2.3 Heating

To keep the preforms from collapsing, they were laid on platforms while heated. The different settings used when first drying the preform and later melting the PLA were the most successful ones that were retained from the process development. See Table 4.9.

Instructions for manufacturing

- A transfer tool should most preferably be used to remove the preform from the preforming rig.
- It should be put in an oven together with a support structure, keeping it from collapsing.
- The preform should be dried at 40 °C for about 24 hours (thicker materials may need longer time).
- This is followed by melting the PLA by increasing the temperature.
- Extract the preform when it reaches 187 °C. The temperature is measured in the core to ensure that all the preform material reaches the melting point and not much higher.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Drying</td>
<td>40</td>
<td>24</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Melting</td>
<td>195</td>
<td>188</td>
<td>135</td>
<td>15</td>
<td>8.5</td>
<td></td>
</tr>
</tbody>
</table>
4.3.2.4 Shaping

The pressing tool was drawn and outsourced to be manufactured and built. As for heating the form halves, optimized settings were used when pressing the preforms. See Table 4.9.

Instructions for manufacturing

- By spraying the form halves with Teflon spray, an easier ejection of the pressed product is possible.
- Heat the pressing tool to 135 °C.
The following is done in as short time as possible:

- Remove the preform from the oven after the PLA has melted.
- Mount it in the press between the form halves that have been sprayed with Teflon.
- Apply a pressure of 8.5 MPa.
- Maintain under pressure for 15 minutes.
- Remove it from the tool carefully.

![Figure 4.24 A finished demonstrator after pressing.](image)

### 4.4. Summary of results

The two major aims in the thesis were to develop a manufacturing process concept that could produce three-dimensional objects in a 60/40 PLA/cellulose fibre mixture, as well as proving the concept successful through the development of a proof of concept demonstrator. A full manufacturing process was identified and divided into four steps: commingling, preforming, drying and shaping.

The first milestone was reached after a number of manufacturing concepts had been evaluated. Based on this assessment, further development was focused on spray-up and the methods needed for the spraying-up principle. After some development and reasoning, it became evident that in the choice between Free-form
spray-up and Rotational spray-up, the latter was the most suitable to develop further. Important factors in the concept, such as rotation speed, spraying pressure and spraying angles, were thoroughly tested to find the settings to be used in the finished concept. When the concept was fully developed, it was possible to design and produce a demonstrator. Equipment for the manufacturing rig was constructed and several demonstrator objects could be produced. Figure 4.25 illustrates all steps taken and equipment used when producing a demonstrator.

Figure 4.25 Illustration of the steps used in the final Spray-up concept. (A) Fibre dissolver, (B) Mixer to keep the slurry at a uniform distribution, (C) Pump able to work with fibres, (D) Spraying rig with nozzle, net, rotating drum, draining system and motor, (E) Oven for drying and melting, (F) Pressing rig with shaping tool, (G) Stacked finished products.
5. Conclusions

The tests performed and the concepts developed lead to a vast amount of results, ranging from material behaviour to tool design for specific applications. The important conclusions of what has been achieved and the methods with less success, have been listed below.

**Concepts**

- With just one tested concept based on additives changing the viscosity of the composite material, it cannot be said with certainty that it can or cannot achieve an adequate result. However, the composition tested (using a large percentage pre-gelatinised cornstarch) did not work. This was mainly due to the evaporation of the high content of water.

- While sheets of fibre-based materials are easy to produce, these cannot be used without complications for making non-flat products since the material is being sheared and torn during pressing. It can however be layered with multiple sheets to create variable thicknesses.

- Paper pulp moulding is an existing and established concept that can create products with the composite material in question, but with a few limitations such as no thickness variation.

- Spraying fibres directly onto a surface is a successful production method with a few existing areas of application. In some of these methods, the spraying creates a preform that has to be further processed.

**Commingling**

- To avoid causing impurities within the material and clumps clogging the system, blend the cellulose fibres with water before mixing them with PLA.

- A batch of slurry is less likely to have clumps if it is mixed in a lower concentration. It is implicit that it is stirred continuously.

**Additives**

- With further research, another type of thickening agent could possibly solve the concept of moulding a PLA-cellulose composite material.
The starch indicated success in binding the PLA and cellulose fibres while it was in a gelatinised state.

**Spraying**

- When spraying, moving the nozzle in the opposite direction from where the beam is aimed, works much better than the inverse. The beam will otherwise wash away the previously applied fibres.
- Strong vacuum can eliminate the problem of the spray beam washing away previously applied fibres.
- Even at low material concentrations (e.g. 0.25%) in the slurry, there is risk of clogging in the nozzle. At higher concentrations (about 1.0%), clogging may occur in other parts of the spraying system.
- Spraying at too small angles will cause the water beam and the fibres in it to deflect, whereas spraying perpendicular or close to perpendicular to the net will cause more fibres to stick as well as pass through. This assumes neither net, nor nozzle is moving.
- When the pressure output of the pump is too low (less than 1 bar with the selected nozzle), the water beam may flutter and cause uneven distribution, whereas a higher pressure (typically over 2 bar at a close distance to the net) will wash away already applied fibres.
- Spraying perpendicular and too closely to the net may cause unwanted crater-like shapes.
- When the sprayed thicknesses increase, the time which it takes for water to be removed increases, therefore it becomes more difficult to create details such as sharp corners when a high material thickness (>10 mm on a wet preform) is required.

**Spraying with vacuum**

- Vacuum works very well when applied as a force keeping the sprayed fibres in place but only if the vacuum source (e.g. a vacuum nozzle) is positioned tightly against the net.
Moving a vacuum nozzle and at the same time keeping it tightly enough against a net is problematic, but possible.

Much higher material thicknesses are possible when using vacuum, compared to a static net with no other force than gravity pulling fibres towards it.

**Rotation**

Spraying on a rotating net from the outside is not successful due to the centrifugal force.

Using the centripetal force from the net to counteract the centrifugal force when spraying on the inside is successful for applying the fibres.

The centrifugal force drains the water from the preform and increases with the rotation speed and radius.

The centrifugal force is more effective in draining a preform than only using vacuum as draining force. The vacuum affects all particles in the system. The strength of the vacuum is dependent on several factors and therefore tends to vary.

To further reinforce the draining, vacuum is desired when applied uniformly in the preforming container. However, superfluous vacuum can have unwanted results such as patchy patterns on the preform, which will affect the result.

Increasing the rotation speed or vacuum will increase the density of the preform.

**Nets**

Nets are required to have a certain mesh size to be able to let water through for drainage and reduction in water splashing elsewhere. It is also important to keep long fibres from passing through.

Nets made from stainless steel with mesh sizes 50 to 80 had the desired results for the type of fibres used.

Short cellulose fibres do not contribute much to the material’s mechanical properties, so allowing them to pass through the net is positive.
Apart from rigidity and wearing resistance, it does not matter if the net is made from e.g. stainless steel, aluminium, copper or nylon. However, the production of the net shape must be taken into consideration as well. Stainless steel was the most widely available with the best potential for shaping and tooling.

**Nozzles**

- There are many types of nozzles with different properties, though their differences are only relevant during detailing stages. For spraying onto a rotating net, nozzles with a flat beam fulfilled the amount of spraying details required.

**Drying**

- Preforms that have been sprayed under low rotation speed will have lower density (assuming no vacuum has been used). Nevertheless, they will contain more water and prolong the drying cycle as a result.

- Depending on the thickness and density of the preform, the drying time varies. 15 mm and 25 mm thick preforms can take from 24 hours up to 48 hours to dry.

- Due to PLA being hygroscopic as well as being subject to hydrolysis at certain temperatures, the dried preforms must be kept in an environment with no humidity before being melted.

**Melting**

- While PLA melts at about 160 to 180 °C, extract the preform when the core has reached 187 °C with the oven set to a slightly higher temperature. This temperature is high enough to move the process along and low enough not to burn the preform while the core is reaching its temperature. For a preform with a maximum thickness of 20 mm, this time was typically around 10 minutes.

- Because cellulose degrades at a temperature lower than the melting point of PLA, rapid melting is essential to avoid an unnecessary loss in mechanical properties.
When measuring the time needed to melt the preforms, a digital thermometer’s sensor should be placed in the middle of the preform’s thickest part.

Pressing

- When pressing a non-flat melted or non-melted preform, the material will be sheared, possibly breaking and disorienting fibres, due to the high compression ratio.

- Folds and ruptures can possibly be avoided by pressing the sheets in additional steps, distributing the stress throughout the whole preform.

- During the time the melted preform leaves the oven and enters the shaping tool, it should not be allowed to cool down below its melting temperature. If it does, the material surface will become rougher, similar to that of paper.

- The pressed preform must be given time to cool down inside the shaping tool. However, it cannot be allowed to cool down below its melting point during the initial moment of compression in the tool. Therefore, it is beneficial to have a heated shaping tool with a temperature slightly below the preform’s melting point. A combination that works is to keep the shaping tool at 135 °C and leave it compressed for 15 minutes before removing the final product.

- A pressure of 8.5 MPa is enough to create a fully compressed material.

5.1. Specification of achievements

See Attachment 3 for the specification of requirements on which the specification of achievements is based on.

Geometry achievements

- Fully processed material has been compressed down to 7-8 % of its preform thickness, creating a product with a final thickness of 2 mm.

- A product has been created with constant density and variations in material thicknesses ranging from 0.3 to 2.0 mm, setting the variation within the
same product at over 500%. However, samples have not been dissected of proving this true.

- Sharp, 0.0 mm transition lengths between material thicknesses has been achieved in a created product.
- Spraying free-form, non-flat shapes have been tested with success, but have not been proven.
- Creating rotation symmetrical products have been done with success.
- Neither products containing isogonal shapes or with overhanging part features have been tested. However, this was left out since it had a lower priority than other requirements.
- Draft angles up to 10-20° have been achieved with a high level of success.

**Material achievements**

- The level of uniformity in the fibre dispersion has not been measured, but is considered sufficient, as it exceeds the requirements.
- Fibre alignment in the rotation symmetrical products has not been analysed, but is believed to be oriented towards the shaping step because of the way the fibres are applied.
- Both smooth and glossy product surfaces have been achieved.

**Processing achievements**

- The developed concept does contain a few production steps, but none of these are considered unnecessary.
- Many areas within the chosen production concept have been too quickly explored to find their full potential. See suggestions for further work below for some of the concept’s improvement potential.
- The cost for tools and materials as well as lead-time calculations for a large-scale production has not been made.
- No ecological measurements, such as energy cost or amounts of waste material for the production have been made.
6. Discussion/Recommendation

6.1. Discussion

The developed manufacturing process proved to be successful as it was able to produce several demonstrators. However, a perfect demonstrator where all the surfaces had been processed enough was not achieved. Since the same process was able to create simpler samples without visible defects, the imperfections are believed to be caused by the complex shape and the difficulties in creating a perfect preform.

While the chosen manufacturing concept is limited to rotation symmetrical objects, it is still able to prove the underlying manufacturing principle. Spraying fibres dispersed in water onto a preforming net while having a perpendicular force draining the preform. The rotational spray-up concept was the most practical way of proving this. It was not intended to be able to create all geometries. However, the free-form spray-up concept which is based on the same principle is not as constrained to types of geometry but it requires much more work and equipment to function and. It is likely that concept would not have been able to achieve as much as the chosen concept within the time frame of this thesis. However, this can be the next advancement after all the information from the rotational spray-up concept is gained.

6.2. Recommendations for further work

■ Advanced spraying – Research in fibre distribution, spraying pressure, angles and speeds as well as the possibility of using multiple nozzles.

■ Improved shaping – Research in melting the PLA in the composite material, times and temperatures to create the fastest production with best mechanical properties as well as compression and cooling times.

■ Semi-automated production line – Construction of heavy duty, automated machinery with included transfer tools.

■ Detailed spraying – Exploring the possibility of vacuum and other forces keeping the fibres in place after they have been applied to a net (e.g. being
able to create sharp corners). Optimising the rotation speed in relation to the radius. This also includes the problem of draining water from the preforming net fast enough.

- Material properties – After the conceptual production method has been performed, it is essential to confirm that the produced product’s general (e.g. density), mechanical (e.g. Young’s modulus, elasticity, etc.), and thermal properties (e.g. minimum and maximum service temperatures, etc.) is what they should be through analysis.

- Advanced shapes – Explore possibilities of creating objects containing either isogonal shapes or with overhanging part features.
7. Acknowledgements

Primarily we would like to thank Pr. Mikael Lindström for the confidence of letting us take on this thesis at Innventia AB and for the enthusiasm we have been shown. We are very much in debt to Dr. Fredrik Berthold, the initiator and supervisor of this project, for his patience, knowledge and constructive talks. We appreciated the personal nature of his guidance and we are grateful for making us a part of his working environment.

At the Royal Institute of Technology, we want to acknowledge the guidance we have received from our supervisor Pr. Priidu Pukk. We are thankful for all our constructive and interesting discussions.

We would also like to express our gratitude towards Eva-Lisa Lindfors for guidance in the laboratory and for letting us work by her desk. We are very much grateful to all our colleagues at the chemistry house for making us feel welcome and lastly for having patience with us when overbooking the oven. We really enjoyed the daily coffee breaks with many laughs, great coffee bread and Thursday volleyball games, making Innventia a stimulating and sociable environment to work in.

We appreciated the cooperation from Anette Lindé and Per-Åke Turesson at EuroFex. Without access to the wet-lab, dynamic sheet former and pump this project would not have gone as smoothly and we would not have been as successful.

We were also fortunate to get to work with professionals when choosing our contractor CNC-Process for machining the pressing tool. They perfected the result of our drawings. We also want to acknowledge the support we have gotten from Ulf Andorff with colleagues who gave us access to the KTH metalworking shop at times when we needed to make corrections to the work of Transema AB.

Finally, we would like to thank our families and friends for their valuable help and support.
8. Bibliography


26. ”Fibre Dissolver”, Stockholm: AB Lorentzen&Wettre, Type 6-2, No. 589

27. “Pump”, Örebro: Johnson Pump AB, Type WUDA800G-C, No. 1079


9. Attachments

9.1. Attachment 1: Stiffness – Strength chart

Figure 9.1 The chart is showing the properties positioning of cellulose, 60/40 PLA and cellulose reinforced polylactic acid.
## 9.2. Attachment 2: The suppliers nozzles

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 H 1/4 U - SS 15 10</td>
<td>Standard flat spray, 15 ° angle, capacity size 10</td>
</tr>
<tr>
<td>2 H 1/4 U - SS 25 04</td>
<td>Standard flat spray, 25 ° angle, capacity size 04</td>
</tr>
<tr>
<td>3 H 1/4 U - SS 25 09</td>
<td>Standard flat spray, 25 ° angle, capacity size 09</td>
</tr>
<tr>
<td>4 H 1/4 VV - SS 25 04</td>
<td>Higher capacity flat spray, 25 ° angle, capacity size 04</td>
</tr>
<tr>
<td>5 H 1/4 MEG - SS 25 05 TC</td>
<td>High pressure flay spray with tungsten carbide inset, 25 ° angle, capacity size 04</td>
</tr>
<tr>
<td>6 H 1/4 MEG - SS 25 10 TC</td>
<td>High pressure flay spray with tungsten carbide inset, 25 ° angle, capacity size 10</td>
</tr>
<tr>
<td>7 H 1/4 MEG - SS 25 20 TC</td>
<td>High pressure flay spray with tungsten carbide inset, 25 ° angle, capacity size 20</td>
</tr>
<tr>
<td>8 B 1/4 HH - SS 10 Fulljet</td>
<td>Full cone spray, angle depending on capacity size and pressure, capacity size 10</td>
</tr>
</tbody>
</table>
9.3. Attachment 3: Specification of requirements for manufacture

Geometry requirements
- Fully processed high-density material must be able to achieve a thickness of minimum 1 mm.
- A 50% variation in material thickness, based on its average thickness, must be achieved while maintaining a constant density.
- Transition lengths between material thicknesses must be able to be lower than the difference in thickness.
- The manufacturing process must be able to produce planar objects with hills and cavities OR the manufacturing process must be able to produce rotation symmetrical objects.
- The manufacturing process should be able to create isogonal shapes.
- Achieving overhanging part features is optional.
- Draft angles must not be limited to any higher than 30 degrees.
- Draft angles should not be limited to any higher than 10 degrees.

Material requirements
- The fibre dispersion must be uniform.
- Aligning the fibres in a certain direction should be possible to achieve.
- A smooth and glossy surface must be possible to achieve if desired.

Processing requirements
- The amount of steps in the manufacturing process should not be more than that of paper pulp moulding.
- There should be potential for further process development and optimisation.
- The production method should have possible business potential.
- The tool costs should not be higher than that of paper pulp moulding.
- The lead-time of products manufactured with the said process should not be higher than one with equal complexity made using paper pulp moulding.
- The amount of waste material (excluding water) should be lower than products made using paper pulp moulding.
9.4. Attachment 4: F/M-Tree

Figure 9.2 The F/M-Tree showing different possibilities to fulfil stipulated requirements.
9.5. Attachment 5: Additives

Several additives have been mixed with the material in attempts to accomplish certain types of effects or material properties, starting with colouring dies and then thickening agents.

Before exposure to heat, the PLA is colourless and the cellulose fibres used are bleached white. After drying, the colour changes to that of natural paper. The tests showed that the food colouring was completely unsuccessful, as it would apply itself to neither PLA nor cellulose. After drawing vacuum from the material sample, about 90% of the colour was gone. The highly concentrated black colouring proved to be more successful as it would colour both PLA and cellulose and as shown in Figure 9.2 below, would remain after drying, heating and pressing.

![Figure 9.2 Material samples showing the effect of colouring. From left to right: Uncoloured (somewhat burned) and non-pressed sample, sample with 0.025 % colouring, sample with 0.075 % colouring.](image)

Thickening agents are substances that are mainly added to water-based foods to increase their viscosity, without affecting the taste. One of the reasons why a thickening agent would be desired to be used is for the production where a viscous material is needed to transport and distribute fibres evenly throughout a form. An example of thickening agent is gelatinised starch, which can be made from regular corn- or potato starch used for cooking purposes. These can be heated to 60-80 °C for gelatinisation, and can afterwards be dried for later use. Once gelatinised and dried, it becomes a pre-gelatinised starch, which can be added to gelatinise a water-based mixture without the need for heat. See the result of an experiment in 4.1.2.3(Gelatinised) Compression moulding.
## 9.6. Attachment 6: Decision matrix/ Process concept evaluation matrix

Table 9.1 Evaluating the performance of the different concepts through rating them against criterions of different importance (rating 0-3).

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Importance</td>
</tr>
<tr>
<td>Geometry</td>
<td></td>
</tr>
<tr>
<td>1 Material thicknesses over 1 mm</td>
<td>high</td>
</tr>
<tr>
<td>2 Variable thicknesses with 50% variation from the base thickness</td>
<td>very high</td>
</tr>
<tr>
<td>3 Variable thicknesses not based on an average thickness</td>
<td>low</td>
</tr>
<tr>
<td>4 Low thickness variation transitions</td>
<td>high</td>
</tr>
<tr>
<td>5 Can create planar objects with hills and cavities</td>
<td>high</td>
</tr>
<tr>
<td>6 Can create rotation symmetrical shapes</td>
<td>very high</td>
</tr>
<tr>
<td>7 Can create isogonal shapes (without extreme details)</td>
<td>med/high</td>
</tr>
<tr>
<td>8 Can create overhanging part features</td>
<td>low/med</td>
</tr>
<tr>
<td>9 Low draft angles</td>
<td>med/high</td>
</tr>
<tr>
<td>Material</td>
<td></td>
</tr>
<tr>
<td>10 Uniform fibre dispersion</td>
<td>very high</td>
</tr>
<tr>
<td>11 Uniform product surfaces</td>
<td>very high</td>
</tr>
<tr>
<td>12 Few defects</td>
<td>very high</td>
</tr>
<tr>
<td>13 Make the best of the mechanical properties</td>
<td>med/high</td>
</tr>
<tr>
<td>14 All products should have the same material properties</td>
<td>high</td>
</tr>
<tr>
<td>Processing</td>
<td></td>
</tr>
<tr>
<td>15 Few production steps</td>
<td>med</td>
</tr>
<tr>
<td>16 Potential for optimisation</td>
<td>high</td>
</tr>
<tr>
<td>17 Business potential</td>
<td>high</td>
</tr>
<tr>
<td>18 Tool cost</td>
<td>low/med</td>
</tr>
<tr>
<td>19 Potential lead time</td>
<td>high</td>
</tr>
<tr>
<td>20 Low amount of waste material</td>
<td>low/med</td>
</tr>
<tr>
<td>Satisfaction</td>
<td>317</td>
</tr>
</tbody>
</table>
Table 9.2 Different nets and their design.

<table>
<thead>
<tr>
<th>Material</th>
<th>Mesh (cm)</th>
<th>Mesh (Inch/Tyler)</th>
<th>Wire diameter [µm]</th>
<th>Opening [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Nylon</td>
<td>31</td>
<td>78</td>
<td>175</td>
<td>145</td>
</tr>
<tr>
<td>2. Phosphor bronze</td>
<td>28</td>
<td>70</td>
<td>150</td>
<td>210</td>
</tr>
<tr>
<td>3. Aluminium</td>
<td>20</td>
<td>50</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>4. Stainless steel</td>
<td>7</td>
<td>17</td>
<td>200</td>
<td>1300</td>
</tr>
<tr>
<td>5. Stainless steel</td>
<td>20</td>
<td>50</td>
<td>200</td>
<td>310</td>
</tr>
<tr>
<td>6. Stainless steel</td>
<td>24</td>
<td>60</td>
<td>150</td>
<td>270</td>
</tr>
<tr>
<td>7. Stainless steel</td>
<td>32</td>
<td>80</td>
<td>120</td>
<td>200</td>
</tr>
</tbody>
</table>

Figure 9.3 Top row: Nylon, Phosphor bronze. Bottom row: Aluminium, Stainless steel.
9.8. Attachment 8: Heating and shaping test-2 and -3

Table 9.1 Tests of the heating and pressing steps. The parameters are; Temperature in oven, time of sample in oven, temperature of pressing tools, pressure, time in press, thickness of sprayed preform and thickness of pressed preform.

<table>
<thead>
<tr>
<th>Sample Nr</th>
<th>$T_{heating}$ [°C]</th>
<th>$T_{heating}$ [min]</th>
<th>$T_{press}$ [°C]</th>
<th>Pressure</th>
<th>$T_{press}$ [min]</th>
<th>Sprayed thickness</th>
<th>Pressed thickness</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>220</td>
<td>125</td>
<td>140</td>
<td>100</td>
<td>1.5</td>
<td>3.5/7.5</td>
<td>0.5/1.0</td>
<td>Large streaked area.</td>
</tr>
<tr>
<td>2.2</td>
<td>220</td>
<td>130</td>
<td>140</td>
<td>100</td>
<td>1.5</td>
<td>3.5/7.5</td>
<td>0.5/1.0</td>
<td>Small streaked area.</td>
</tr>
<tr>
<td>2.3</td>
<td>220</td>
<td>140</td>
<td>140</td>
<td>100</td>
<td>1.0</td>
<td>3.5/7.5</td>
<td>0.5/1.0</td>
<td>Large streaked area. Rough surface.</td>
</tr>
<tr>
<td>2.4</td>
<td>220</td>
<td>150</td>
<td>140</td>
<td>100</td>
<td>14</td>
<td>3.5/7.5</td>
<td>0.5/1.0</td>
<td>Uniform material. Slightly transparent.</td>
</tr>
<tr>
<td>2.5</td>
<td>220</td>
<td>175</td>
<td>140</td>
<td>100</td>
<td>15</td>
<td>3.5/7.5</td>
<td>0.5/1.0</td>
<td>Uniform material. Denser.</td>
</tr>
<tr>
<td>2.6</td>
<td>220</td>
<td>180</td>
<td>140</td>
<td>100</td>
<td>1.0</td>
<td>3.5/7.5</td>
<td>0.5/1.0</td>
<td>Large streaked area.</td>
</tr>
<tr>
<td>3.1</td>
<td>220</td>
<td>80</td>
<td>175</td>
<td>100</td>
<td>15</td>
<td>7.5/15</td>
<td>1.0/2.0</td>
<td>Formed fibre channel in bottom. Pure PLA on sides.</td>
</tr>
<tr>
<td>3.2</td>
<td>220</td>
<td>105</td>
<td>145</td>
<td>100</td>
<td>7.5</td>
<td>7.5/15</td>
<td>1.0/2.0</td>
<td>Large streaked area. Part</td>
</tr>
<tr>
<td>3.3</td>
<td>220</td>
<td>120</td>
<td>145</td>
<td>100</td>
<td>15</td>
<td>7.5/15</td>
<td>1.0/2.0</td>
<td>Small streaked areas.</td>
</tr>
<tr>
<td>3.4</td>
<td>183</td>
<td>135</td>
<td>225</td>
<td>15</td>
<td>10/20</td>
<td>1.0/2.0</td>
<td>Natural beige colour. Uniform surface</td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>180</td>
<td>135</td>
<td>100</td>
<td>10</td>
<td>10/20</td>
<td>1.0</td>
<td>Lack of PLA in bottom exposing the fibres.</td>
<td></td>
</tr>
<tr>
<td>3.6</td>
<td>200</td>
<td>135</td>
<td>100</td>
<td>15</td>
<td>10/20</td>
<td>1.0/2.0</td>
<td>Dark wheat colour</td>
<td></td>
</tr>
<tr>
<td>3.7</td>
<td>190</td>
<td>135</td>
<td>100</td>
<td>15</td>
<td>10/20</td>
<td>1.0/2.0</td>
<td>Wheat colour. Uniform material. Thin part slightly darker</td>
<td></td>
</tr>
</tbody>
</table>
9.9. Attachment 9: Specification of requirements for demonstrator

**Geometry requirements**

☐ The object **must** demonstrate shapes otherwise hard to reproduce with other manufacturing processes in the same material.

☐ The design **should** allow combining the demonstrators, giving them a sense of a new purpose.

☐ The object appearance **should** have different intuitive function depending on the observer.

☐ The objects appearance **should** have different intuitive purpose when combining them.

☐ When evaluating the geometries of the concept, the tool costs must be kept in mind.

☐ The material **must** be fully processed high-density material.

☐ The thickness **should** vary from 0.5mm to 2.0mm

☐ The material gods **must** have a sharp transitions achieved while maintaining a constant density.

☐ Transition lengths between material thicknesses **must** be able to be lower than the difference in thickness.

☐ Draft angles **must** not be higher than 30 degrees.

**Material requirements**

☐ Must be made using a cellulose- PLA composite

☐ The fibre dispersion **must** be uniform.

☐ A smooth surface **must** be achieved.

☐ A glossy surface **should** be possible to achieve.

**Processing requirements**

☐ Must be made using the chosen process.

☐ The tool costs **should** be kept as low as possible.

☐ The tool costs should be kept in mind when evaluating the concepts
Figure 9.4 Assembly showing the design of preforming apparatus and its components.