CHALMERS
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Produce the Wood Revolution

Creating a production system and layout design for wind turbine towers

Master's thesis in Production Engineering

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Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

The wind turbine industry is firing on all cylinders and with an expanding market several new companies wants to take part. One such company is Modvion AB (*Modvion*) who is a start-up company with a different approach that makes them stand out from the rest. Modvion specialises in building wind turbine towers using laminated veneer lumber (*LVL*) as the primary material, as opposed to the conventional material choice of steel. Furthermore, Modvion uses a unique modular tower design, further distinguishing them from their competitors as this design makes transportation easier, allowing Modvion to build towers at sites other manufacturers can't reach.

In order to capitalise on the expanding market, Modvion has to create their first production system, meaning that a production facility needs to be designed. This thesis presents possible solutions for how the processes within the production system can be performed, as well as a possible layout of the facility.

Through the results from the project, some conclusions can be drawn. Firstly, the product design has a large impact on the performance and complexity of the production system. Secondly, the future demand that is intended to be met by the new plant needs to be as accurate as possible, so that the risk of designing a either too high or too low production capacity for the facility can be minimised. This is further evident by the demand being the biggest factor when choosing the production layout, thus, affecting the entire dynamics of the production system. Finally, the level of automation within the facility needs to be aligned with the overall manufacturing strategy set by Modvion, in order to maximise the benefits while minimising the drawbacks of automation.

Keywords: Wind Turbine Tower, Production System, Production Layout, Automation, Laminated Veneer Lumber

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Jens Buss, Rasmus Ryrberg, Gothenburg, June 2020

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Introduction

In the following chapter, an introduction to the project will be given. This will entail some background information relevant to the project, the aim and purpose of the project, as well as the delimitations of the project. The chapter will conclude with the presentation of the research questions of the project.

1.1 Background

Alternative, sustainable and renewable energy solutions have never been craved by customers in higher demand than now [11]. One such sustainable solution is wind power. There has been a visible trend of continuously rising demand for wind-towers, both off- and onshore [7]. In fact, the financial investments into the wind power sector has steadily risen throughout the years, with the investments in 2018 increasing by 26% compared to the previous year [7]. This increasing trend can be seen in Figure 1.1.

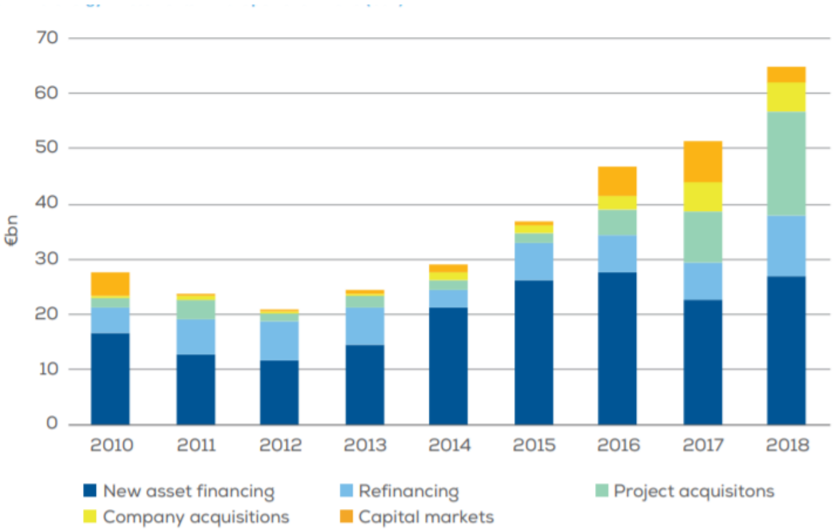


Figure 1.1: Investment trend in European wind power sector 2010 - 2018 [7]

Obviously, this increased demand is a major opportunity for the wind power sector as a whole. One company operating in this sector is Modvion AB (*Modvion*), a small start-up company founded in 2015 out of a venture project at Chalmers University of Technology (*Chalmers*).

Modvion believes that they have managed to identify a truly game-changing niche in the market. Instead of using a traditional wind turbine tower design and steel as the primary material, Modvion will instead use a modular tower design and laminated veneer lumber (*LVL*) as the primary material of choice. While other projects have also developed wind turbine towers using wood as the primary material [32], none have done so using Modvion's modular design.

To prove the validity of their concept, Modvion built a 30 meter prototype of their tower. This prototype was erected in April of 2020 at the coast outside Gothenburg, Sweden. The prototype has been Modvion's biggest step so far, towards their goal of being an industrial manufacturer of tall wooden towers. Their current aim is to be able to regularly produce 150-metres tall wind turbine towers, as well as be able to produce wind turbine towers reaching upwards of 170 meters.

In order to reach their goal, Modvion contacted Semcon AB (*Semcon*), an industrial consultancy firm, asking for help with getting started with their full-scale production. From there, the Production Engineering Masters program at Chalmers was contacted and eventually this masters thesis was formed.

1.2 Project Purpose

The purpose of the project is to design a future production system for 150-metres tall wind turbine towers as Modvion moves towards full-scale production. The capacity of the production system should be large enough for the company to produce 100 towers a year. Due to the modular design of the tower that Modvion has created, the production system should deliver modules which can easily be transported and assembled at the site where the tower will be erected.

1.3 Delimitations

The thesis is expected to be carried out for a period of 20 weeks, starting in late January 2020 and finishing up by June 2020. As a result of the time limitation, the project will be faced with trade-offs for deciding the level of detail of each process of the production. A holistic view of the entire production system will be kept throughout the project. Thus the detail of each individual solution will not be fully-fledged out, plug-and-play, solutions for the production system. Instead, the project will supply Modvion with concept solutions for possible ways of structuring their future production system consisting of improvement suggestions for the innate processes as well as a layout suggestion.

This project will be limited to the production system of the actual tower part of the wind turbine tower. This means that no focus will be placed on generating concepts for production processes for the manufacturing of the wind turbine itself. Instead, the project will solely focus on developing viable production processes needed in order to deliver the modules used in Modvion's wind turbine tower.

Another delimitation of the project is that no effort will be given to the external logistic supply chain, nor the maintenance aspect of the system. Furthermore, the sole area of the internal logistics within the production system that will be addressed is the moving of the products and raw material, while the logistics of secondary flows, such as that of tools and personnel, will be ignored. While these areas can heavily affect the production in reality, Modvion has made it clear that the main focus of the project should be on developing the current production processes so that they are able to produce at the required takt time to meet the demand.

Finally, no breakdowns will be accounted for when determining the performance of the production system. This is due to the fact that most of the processes within the system do not fully exist as of today, meaning that no information concerning the breakdown patterns could be identified with accuracy. Thus, while it is possible to guess estimates of the mean time to failure *(MTTF)* and mean time to repair *(MTTR)* for the different processes, the result of doing this would still most likely be inaccurate. Therefore, to avoid any misconceptions of the accuracy of the performance of the suggested production system, these were not considered within the scope of the thesis.

1.4 Research questions

With the previous sections in mind, the following research questions have been stated:

1. How can Modvion perform its future production of wind turbine towers?
2. What can a plant layout for Modvion's future production look like?

2

Frame of reference

Chapter two presents the relevant theory required to understand the analysis, results and recommendations of this project. The chapter is in turn divided into five sections, each dealing with a specific area. Note that some of these areas are not connected to specific literature, but rather knowledge provided to the project through discussions with experts in their respective fields. The initial sections deal with providing information regarding the wind power industry as a whole, how Modvion differentiates themselves on the market as a manufacturer and finally how the company plans to design its towers. The latter sections will deal with more traditional areas, such as production layout and automation, that are vital to include when designing production systems.

2.1 The Wind Turbine Industry

As an industry sector, the wind turbine industry is a rather unique one. The shear size of the wind turbine towers, with regular hub heights ranging from 70 meters to 140 meters [28], differentiate the industry from other, more conventional mass-producing industry sectors. The height, as well as the weight, of the towers, provides challenges to the industry from both a production and a logistics perspective.

Firstly, the method of transportation, be it by truck, train or boat, limits the possible dimensions of the tower [14]. This is especially a problem for onshore, i.e. land-based, wind turbine towers, as these are often located in places with limited access to, resulting in most transports being made with trucks as the primary alternative. Due to the large dimensions of the tower, special logistics handling is almost always necessary in these cases [14]. This means that extra large trucks are used, often requiring a special certificate that details where and where not the transport is allowed to go and in some cases even a guiding convoy may be required [14], [41]. In order to transport the tower, it is therefore preferable to divide the tower into smaller sections, that are assembled at the site where the tower should be erected [1]. An example of how it can look like when transporting a conventional wind turbine tower can be seen in Figure 2.1. Important to note is that even with the tower divided into smaller parts, the individual sections are still too large for regular trucks and therefore needs to be transported with special trucks [14].

Figure 2.1: Example of a transport of a part of a conventional wind turbine tower

Secondly, from a production standpoint, the dimensions of the tower and its sections places tough requirements on the capabilities of the production systems as well. For example, the production and its processes must be able to handle the size of the products, meaning that both the facility and equipment needs to be adapted to fit large products. However, the perhaps most difficult challenge for the production system is the transportation of the sections and other components of the tower internally. The weight, along with the large dimensions of the tower sections, limits the possible methods of transportation internally.

Furthermore, the towers and the turbines will likely continue to increase in size over time, making all of these challenges even more relevant. This is due to the fact that the bigger the radius of the rotor blades, the more wind the turbine can turn into torque and transform into electricity through an electrical generator [13]. Moreover, wind conditions near the ground are often poor, with low wind speed and/or turbulent winds. However, at higher altitude, the winds are both stronger and more consistent, allowing for more effective energy generation [14]. In other words, the higher the tower and the larger the turbine, the more power can be extracted efficiently from each tower [13]. For the industry as a whole, this conclusion results in the tower and turbines constantly being enlarged. Moreover, for the different wind power farms, which is the specific location where multiple towers are placed and represent the majority of the customers for the wind turbine industry, this also entails that the maximum allowed tower size is always sought after. This means that if the wind power farms have the capacity and space for a 170 meter high tower, they will most likely order a 170 meter tower. If the farm instead have the capacity and space for a 157 meter tower, they will order such a tower instead. For the tower manufacturers, this behaviour amongst their customers leads to them having to maintain a certain level of flexibility when it comes to tower height. If a tower manufacturer wants to offer premium customer service, in the sense of being able to provide the exact order that the customer wants, it is vital that the company can produce towers of altering height and dimensions in their production system in a productive fashion.

As of today, a conventional wind turbine tower is designed to have a service life of 20 years [47]. After that, a decision has to be made on what to do with the tower and the turbine. The options include lifetime extension, re-powering and decommissioning of the site as well as recycling of the components that allow for it [47]. Lifetime extension is a re-manufacturing process that focuses on restoring the used components to its original specifications [4]. Re-powering the towers is a similar method, but instead replaces the older turbines with newer, more modern and larger ones. In this sense, it is the wind power farm that gets re-manufactured, and not the individual towers [4]. If the tower and its turbine cannot be re-used, they must be decommissioned, and preferably the materials should be recycled as much as possible. However, if recycling of the materials is not possible, incarnation or deposition of the materials remains as an alternative [4]. The main material used in the tower is typically steel [6], [3], meaning that much of the tower can be recycled [4]. However, some studies have shown that the reverse supply chain required for the recycling process, i.e. preparing and transporting the material from site to the recycle plant, could prove even more expensive than the initial installation phase of the tower [4], [31].

2.2 The Business Case of Modvion

Through discussions and meetings with staff from Modvion, primarily through contact with Carl-Johan Åkerström, a certification engineer at Modvion, some of the priorities of the company has been given.

As the product design proposed by Modvion uses a modular design, the company argues that one of its competitive advantages is the fact that the logistics of the towers to and from site will be simpler than that of the conventional wind power towers. This is possible due to the modules being stackable, as can be seen in Figure 2.2.

Figure 2.2: Example of three modules placements during transportation

This can be compared with the challenges that conventional wind turbine towers faces from a transportation perspective [14], as mentioned in the previous section.

However, due to the modular design of the tower, a larger assembly process of the tower will have to performed at the site of where the tower should be located compared to the conventional towers. Time spent assembling and preparing the tower on site is assumed to be costly, as equipment, such as cranes, needed for the assembly processes, have to be rented. Hence, the time spent on site should be minimised as much as possible. One easy way to minimise this time is to reduce the number of parts needed to be assembled by using as large dimensions for the modules as possible. This way, the number of modules could be reduced. However, the larger the modules, the more complex the logistics will become, as larger trucks will have to be used in order to be able to handle the larger dimensions and weight. Thus, the company finds itself at a trade-off between the complexity level of transportation and the time spent at site, assembling the tower.

Åkerström, a certification engineer at Modvion, also stresses the difference the material choice makes. As conventional towers are made of steel and concrete, and Modvion's towers use primarily wood as the main material, he argues that the CO2 footprint of each tower will be substantially lower with their design. Åkerström continues with explaining that he believes that the the recyclability of the material used in the tower will be facilitated with Modvion's solution as well. The material may be used as construction material for other wooden structures or, in order to avoid heavy transportation which may be complex and costly [4] [31], most of the material may be shredded and later re-used or incinerated.

Instead of having to transport the used material once the tower is decommissioned, a process that some studies have shown to be complex and costly [4], [31], the overwhelming part of the material could be shredded on site, making it easier to transport.
Due to the characteristics of the wind power sector, Åkerström stressed the importance for the company of being able to be flexible when it comes to which hub heights it is able to deliver. He noted that as the tower had to be adapted to different turbines, as well as different site locations, the ability to adapt the tower dimensions was key. Therefore, the production system needs to be able to deliver towers of varying height and width so that it can match whatever turbine the wind power farm chooses.

2.2.1 Requirements on the production system

As alluded to in the previous chapter, Modvion has requirements and demands on the production system that are aligned with their business case and influenced by the wind power industry in general. Modvion has a requirement that the production system can meet a demand of 100 150-metres tall towers each year and that it should have the capability to produce towers of up to 170 meters. The production system should also be flexible enough to handle a variety of tower heights at a meter level. Furthermore, Modvion has stated that they desire to receive a layout proposal as to give them an idea of what size of factory they would need to use when they create their future production system. Additionally, Modvion has also expressed a desire to have a production system with a high degree of automation.

2.2.2 Tower design

The following section will present the design of Modvion's tower. This information has been obtained through several discussions with Carl-Johan Åkerström, a certification engineer at Modvion.

A drawing of the wind turbine tower was provided by Modvion to visualise the modular design used by the company. The drawing can be seen in Figure 2.3. The tower will be divided into several circular sections. The sections are the parts of the tower that are divided horizontally. These sections will in turn be made up of multiple modules. The modules are the areas divided vertically in each section. Each section will consist of five to thirteen modules while the entire tower will be made up of a maximum of seven sections, depending on the total tower height. The height of the sections, and subsequently the modules, can be up to 25 meters, which is standard for the tower. However, when a shorter tower is desired, sections can either be removed or the modules shortened, depending on how tall the tower is supposed to be.

The tower will be conically shaped, which means that the radii of the different sections and modules will decrease in size the further up in the tower they are placed. Based on a potential tower design, a 150 metre tower will have a bottom diameter of 12.5 metres and a top diameter of 4 meters. This means that a tower has a shape ratio of about 5.67 centimetres decrease in diameter for each metre in height. It is also important to realise that the inner layers of the module will follow the same shape ratio as they too decrease in size.

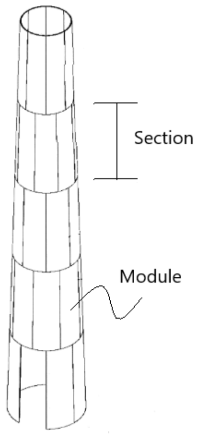


Figure 2.3: Sketch of Modvion's tower design

As the radii will decrease in size the further up in the tower you go, so too will the number of modules in each section. This is due to the fact that Modvion strives to keep the total number of modules as low as possible, in order to facilitate the assembly of the modules to sections on site, i.e. the location where the tower should be raised. Fewer modules equals fewer assemblies required, and thus less time having to be spent on site. Therefore, each module should be made as large as possible, only being limited by the restrictions of size that it faces during the transportation from the production plant to the site. Hence, smaller section radii will be handle by reducing the number of modules present in the section, rather than the size of each module. For full dimensions of the example tower design used in this project, see appendix B.1.

In order to facilitate the decommissioning of the towers, Modvion strives to uses as little metal components within the towers as possible. This means that instead of bolts and screws, Modvion has opted to use glue as their main joining method. However, some metal components will be needed in order to ensure structural integrity. These components will all be located in steel-reinforced glue joints joining the different sections together.

2.2.3 Module design

Each module will have the same type of shape and form. The size and dimensions of the module will vary depending on what section of the tower it belongs to. This is due to the conical shape of the tower as well as the varying number of modules in the different sections. With the tower design used in this project, the modules will be made up of eight layers of LVL-sheets, with each layer being 24 millimetres thick. Hence, the total module thickness will be 192 millimetres. Furthermore, as the shape of the tower is conical, the shape of the modules will also be conical. This means that the radii at the top of the module will be lesser than the radii at the bottom.

Throughout the entire length of the tower, 32 pillars will be evenly spread out across the inner surface of each section. These pillars will further increase the tower's ability to withstand axial forces, as well give the tower more stability and rigidity. For this project, each pillar will be made up of two wooden, glulam beams that are 215 millimetres thick, 405 millimetres wide and 12 metres long, as this was the available dimensions provided by the supplier.

The amount of pillars on each module depends on how many modules there are in each section, as each section will have 32 pillars evenly spread, no matter the size of the section diameter. The section at the top of the tower will consist of five modules and therefore, each module will have between six and seven pillars. For the section at the bottom of the tower, which has twelve modules, there will be between two and three pillars per module.

In order to join modules together into sections, a vertical joint between the modules is required. In this project, a a so called *male-to-male* joint will be used for this purpose, which can be seen in the figure 2.4

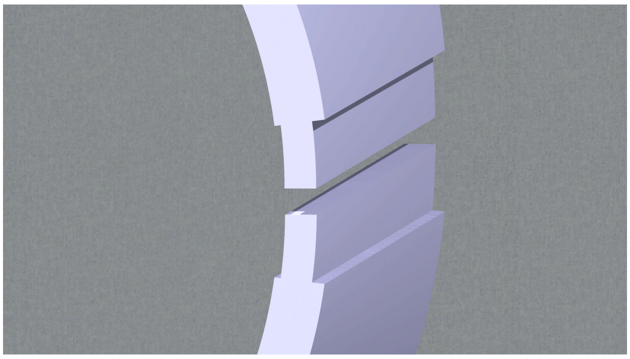


Figure 2.4: The Male-to-Male profiled used to assembled modules to sections

The male will be 5 LVL-layers thick, meaning that the two most outer layers from the centre of the tower as well as the most inner layer will be shorter than the remaining sheets so that the male profile can be achieved. This gives each male the dimensions of 0.240 x 0.120 x 25 metres. At site, the male-to-male profile will be complemented with lids that stretches over one male to the other and thus joins the males together. The lids, which will be reffered to as vertical lids from now on, are in reality two separate lids, that together makes one lid-pair that is required to join one vertical joint. The male-to-male profile, along with the vertical lid used at site can be seen in figure 2.5.

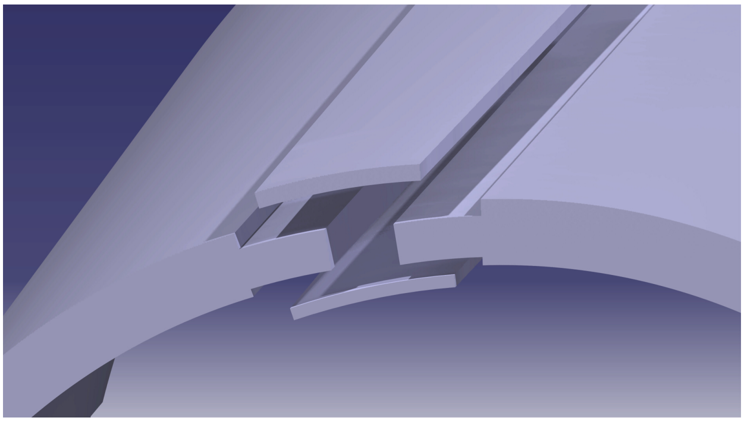


Figure 2.5: Visualisation of how the vertical lids will be attached to join the male-to-male profile

The vertical lid-pair consists of one lid, called the internal vertical lid, that is to be placed on the inside, i.e. on the concave side, of the joint and one lid, called the external vertical lid, that will be placed on the outside, i.e. the convex side, of the joint. The internal vertical lid will have a thickness of solely one LVL layer (24 millimetres) as the male profile only allows for that thickness. Using the same logic, the external vertical lid will be two layers, making the external vertical lid thickness 48 millimetres. Both the internal and external vertical lids can be seen in figure 2.5.

Ultimately, the sections will be stacked together to form a complete tower. Therefore, a horizontal joint is needed to join two sections together. This joining will be done by making slits at the top and bottom of the inside of each module. These slits will be aligned between the sections in question, so that one slit on one of the section lines up with another slit on the other section, forming a slit-pair. In each slit-pair, a perforated steel plate will be placed to join the sections together. For this project, the perforated steel plates will be 700 millimetres long, 220 millimetres wide and 2.5 millimetres thick. Once the steel plate has been inserted at the site, the slits-pair will be filled with glue to make sure that the plate remains still. To make sure that the glue remains inside the slits-pair, a lid, called the horizontal lid, will be mounted ontop of the glue-filled slit-pair. With the tower and module design used in this project, the slits will be positioned with a centre-to-centre measurement (*C-C measurement*) of 40 millimetres. Thus the amount of slits per module will depend on the size of each module and how many slits can fit without being closer than 40 millimetres to each other. For clarity on the design of the slits, see figure 2.6.

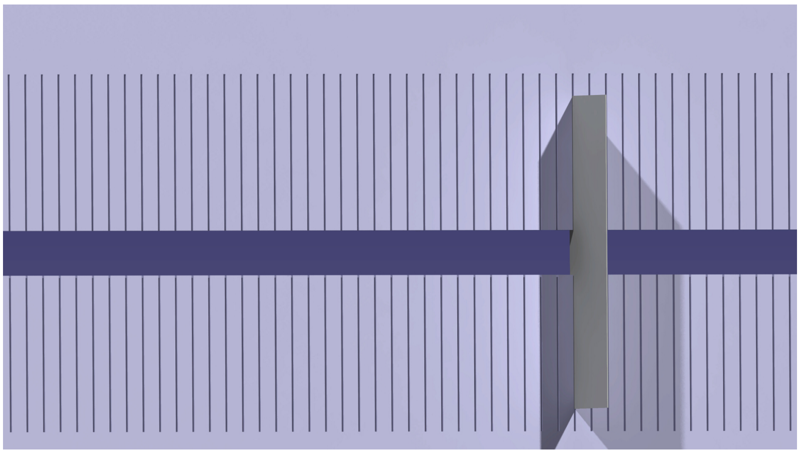


Figure 2.6: How the slits-pair will look with a steel plate inserted

Furthermore, in order to strengthen the horizontal joint, Modvion has decided to increase the wall thickness of the module at the seams between sections. This will be done by adding two layers that wrap around the entire inside of the seam with a width of 0,5 meters above and below the seam. Combined, these two layers will be referred to as braces. Note that these layers have the same thickness as the layers used in the rest of the module, i.e. 24 millimetres. For clarity of the module design with pillars and braces attached, see figure 2.7.

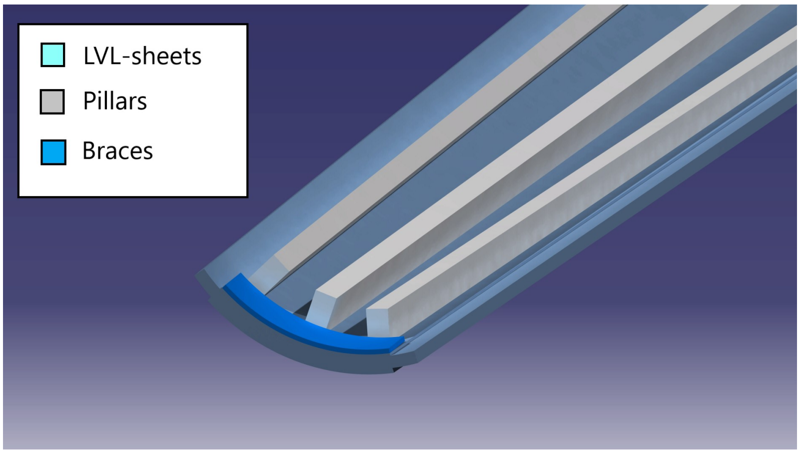


Figure 2.7: A module with pillars and braces attached

Furthermore, the design of the module will affect the characteristics of the production system in several ways. Firstly, the usage of glue rather than conventional joining methods, such as bolts and screws, leads to a larger amount of time being spent on joining components together. This is due to the glue that is used in the production having a hardening time of 5 hours and 45 minutes [2]. During this hardening time, the work piece can not be moved or otherwise processed, without risking damaging the glue bond. Hence, the flow within the production system will have to take this time into consideration during the designing phase.

Secondly, the profile of the slits should be rectangular in shape as the perforated steel plates which are inserted into the slits are square-shaped. This can be hard to achieve as cutting is usually done with some form of circular blade. Thus, a unwanted cavity is cut out which will have to be filled up with glue and/or filler material. This undesired cut profile can be seen in figure 2.8. Clearly, the type of blade used in the process will heavily affect the performance. Additionally, the small spacing between the slits as well as the required precision on the slit placement creates high requirements on the process in the production system that creates the slits. Thus limiting the options of how it can be performed.

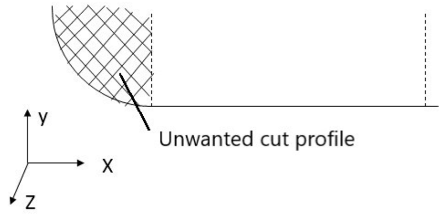


Figure 2.8: Visualisation of area that needs to be filled with glue when a circular blade was used

The processes that were used for the manufacturing of the prototype tower were used as a basis for which processes would need to be included in the future production system. Obviously, the processes will have to be performed at a much greater speed in the future production system as the demand will be much higher, but the main principles of which functions that has to be performed within the system are to large degree the same as those done in the prototype manufacturing. Hence, some knowledge can be drawn from the building of the prototype.

2.3 Manufacturing Strategy

When developing a new production system, it is vital that it is done in accordance with the manufacturing strategy of the specific company. In fact, studies have shown that having a clear manufacturing strategy, and linking it to the marketing and business strategy improves the performance of the company [8], [36], [40].

A manufacturing strategy can be defined as multiple individual decisions that impact the ability of the company to reach their objectives [30]. More specifically, the manufacturing strategy is often thought of to include certain key decision categories, that together make up the overall strategy. These decision categories can be divided into two types - structural and infrastructural decision categories [24]. The structural decision categories are those that define the overall shape of the operations, such as capacity, technology type and facility [24]. The infrastructural decision categories on the other hand are those that deal with the people within the production system, the culture that affects which decisions are taken and the systems in place in order to control the manufacturing [24]. It is important to note that both different types of categories are equally important for the overall success of the company, and neither can be fully neglected in order for the company to be competitive. Diaz-Garrido et al. [12], argues that both the structural and infrastructural decision categories has to be aligned with competitive priorities defined in the operations strategy. The competitive priorities mentioned are *cost, flexibility, quality, delivery* and *service.* Some examples of structural and infrastructural decision categories can be seen in table 2.1.

Table 2.1: Examples of Decision Categories

Decision Categories	
Structural	Infrastructural
Manufacturing Process Technology	Production control system
Vertical Integration Degree	Organisational structure and Design
Facilities	Work Force Management
Capacity	Inventory Planning

As for the structural decision categories, almost all of them have major, long-term, affects on the companies competitive prioritises. However, the decisions are often financially demanding and difficult to reverse once taken [12]. On the other hand, the infrastructural categories require less upfront investment, and as such it can be argued to have an impact on the short-term performance of the company [12].

2.4 Production Layout

The most common layout alternatives for a production plant will be described in the following sections.

2.4.1 Fixed Position Layout

With a *Fixed Position layout*, the product remains "fixed" during the production, often due to its large size and weight [15]. The tools and equipment used during the production is thus moved to and away from the product, while the product remain stationary. Typical industry areas that use a fixed position layout include the naval industry and aircraft manufacturing [15]. The fact that the product remains still throughout the production processes enables larger products to be handled, that would otherwise be too big and/or heavy to produce in an alternative production system. However, the importance of planning and scheduling is increased with a fixed position layout. This is due to the fact that tools and material, as well as paths to and from the product must be kept organised and clear. If this is not done properly, congestion may ensure, with time as well as quality losses as a result [15].

2.4.2 Functional Layout

A *Functional layout* is achieved when machines and functions within the plant with similar purpose are grouped together. That is, for example, all the milling machines in a plant are placed in one group, whereas all the cutting machines are placed in another. The benefits of grouping the equipment in a functional layout are that a higher level of utilisation and efficiency of both machines and work forces can be achieved compared to the Fixed position layout [15]. This is due to the fact that multiple products can be handled at the same time, and with different machines. This reduces the idle time that the equipment otherwise would suffer from if only one or a couple of products could be processed in the entire system at the same time. An example of how the layout would look like with an functional layout can be seen in Figure 2.9. A functional layout excels in production systems of low volume, highly customisable products [22].

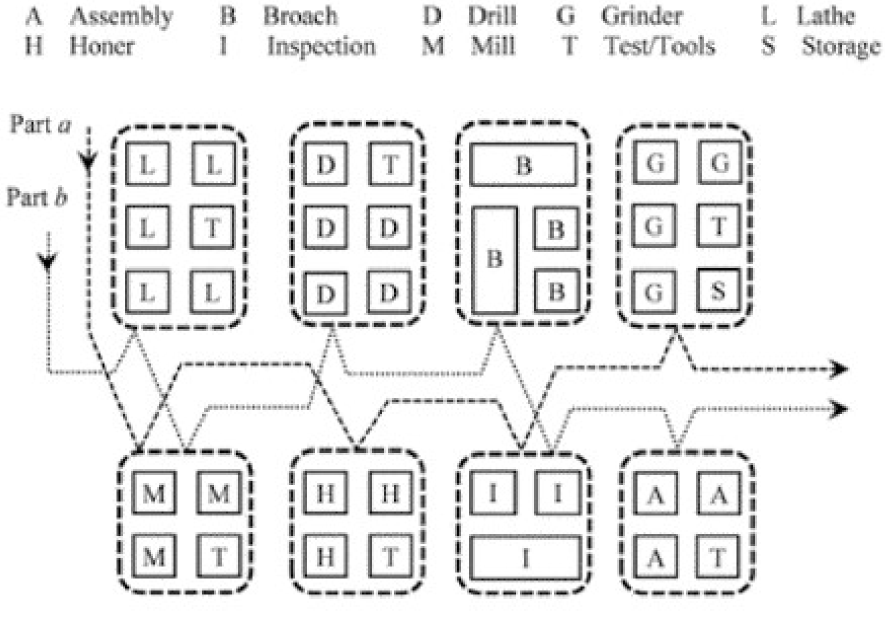


Figure 2.9: Flow of products in a functional layout [15]

2.4.3 Cell or Group Technology Layout

While a *Cell layout* (also known as *Group Technology layout*) can appear similar to that of the functional layout at first glance, there exist key difference between the two concepts. For instance, while the equipment and machines are group according to function within the functional layout, dissimilar machines are instead grouped together according to the manufacturing requirements of a specific product or product family [15]. An example of the flow within a cell layout can be seen in Figure 2.10.

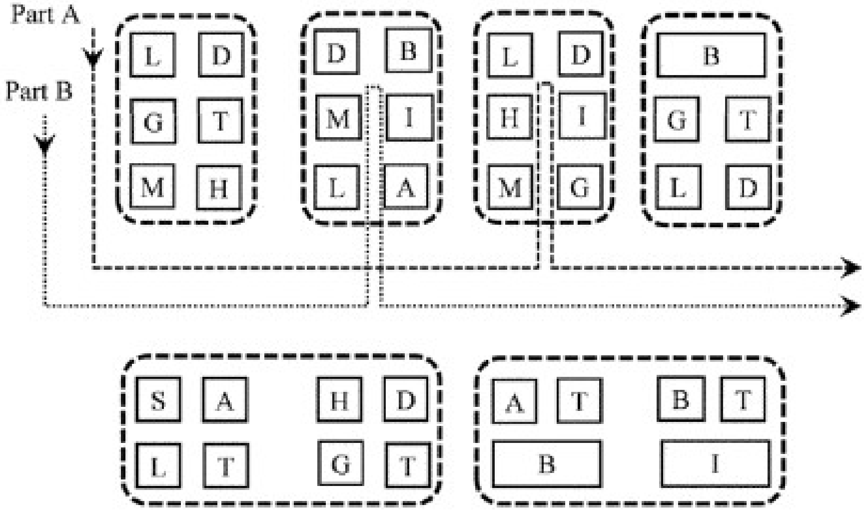


Figure 2.10: Flow of products in a Cell or Group Technology layout [15]

If one compare Figure 2.9 and Figure 2.10, some of the advantages with the latter alternative are obvious. The flow of products are much less complex with a Cell layout as opposed to the Functional layout. This means that less material handling is required throughout the production [15]. Furthermore, the work-in-process (*WIP*) as well as the throughput times are reduced with a cell layout as the flow of products will be smoother compared to that of the functional layout [15]. However, the system with a cell layout is also more vulnerable to machine breakdowns, as an entire cell could be left idle if one single machine included in the cell breaks down [15]. This problem is avoided with a functional layout as one could simply switch to one of the other machines with similar function in the event of a machine breakdown. The ideal scenario for using a cell layout is for production system that are to produce multiple different products in low to medium volume [22].

2.4.4 Line Layout

The opposite of fixed position layout, and final conventional layout alternative is the *Line layout* [15]. With a line layout, the products will be moved from station to station sequentially, or as in the case with parallel lines, in parallel [15]. In other words, the tools and machines are stationary while the products are moved throughout the system, much in opposite to the fixed position layout. Important to note is that the products can only travel in one direction on the different lines, making it crucial that the stations on the lines are sequenced according to the assembly process [15]. It is however possible that certain products skip specific stations or steps in the line. Therefore, some flexibility, albeit significantly lower than that achieved in the previous mentioned layout alternatives, is retained. An illustration of an line layout can be seen in Figure 2.11.

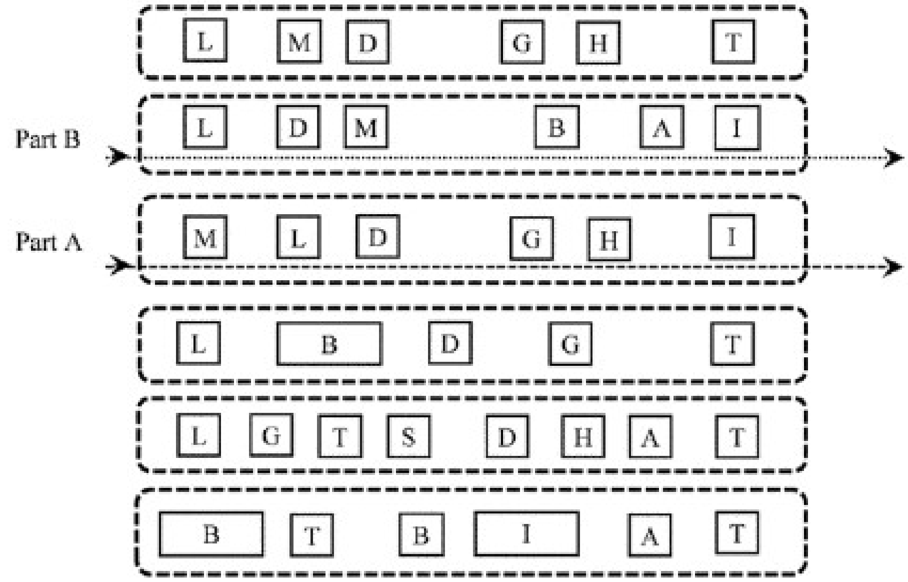


Figure 2.11: Flow of products in a Line layout [15]

If set up correctly, a line layout can lead to a highly productive and effective production system of high volume standard products [22]. Moreover, with a well-balanced line, the idle times of the machines can be reduced further, resulting in an even more resource-effective production system [15]. Many studies exist on methods for optimising the balance of a production line, for instance [34], [35], [23], detailing how to reach an ideal production line layout. However, the line layout struggles with handling large product mixes and have poor flexibility when it comes to processing products that differ from the standard. As such, the line layout yields its best results in environments with high volume of standardised products [22].

2.4.5 Product-Process matrix

In order to align the manufacturing strategy with the production process, it is crucial that the correct production layout is used [20]. Choosing a production layout will also impact both structural and infrastructural decision categories. For instance, the type of production layout chosen will impact the size requirements of the facility, the equipment that is needed and the capacity the production system is capable of producing with. At the same time, the production layout will also affect which control systems are required in order to control the flow of products, what planning approach is needed and how many operators will be included in the production.

One way of selecting a fitting production layout is to use the product-process matrix, as described by Hayes & Wheelwright [20]. This method combines the requirements on the product, such as the demand, with the capabilities of different process layouts. The matrix can be seen in Figure 2.12.

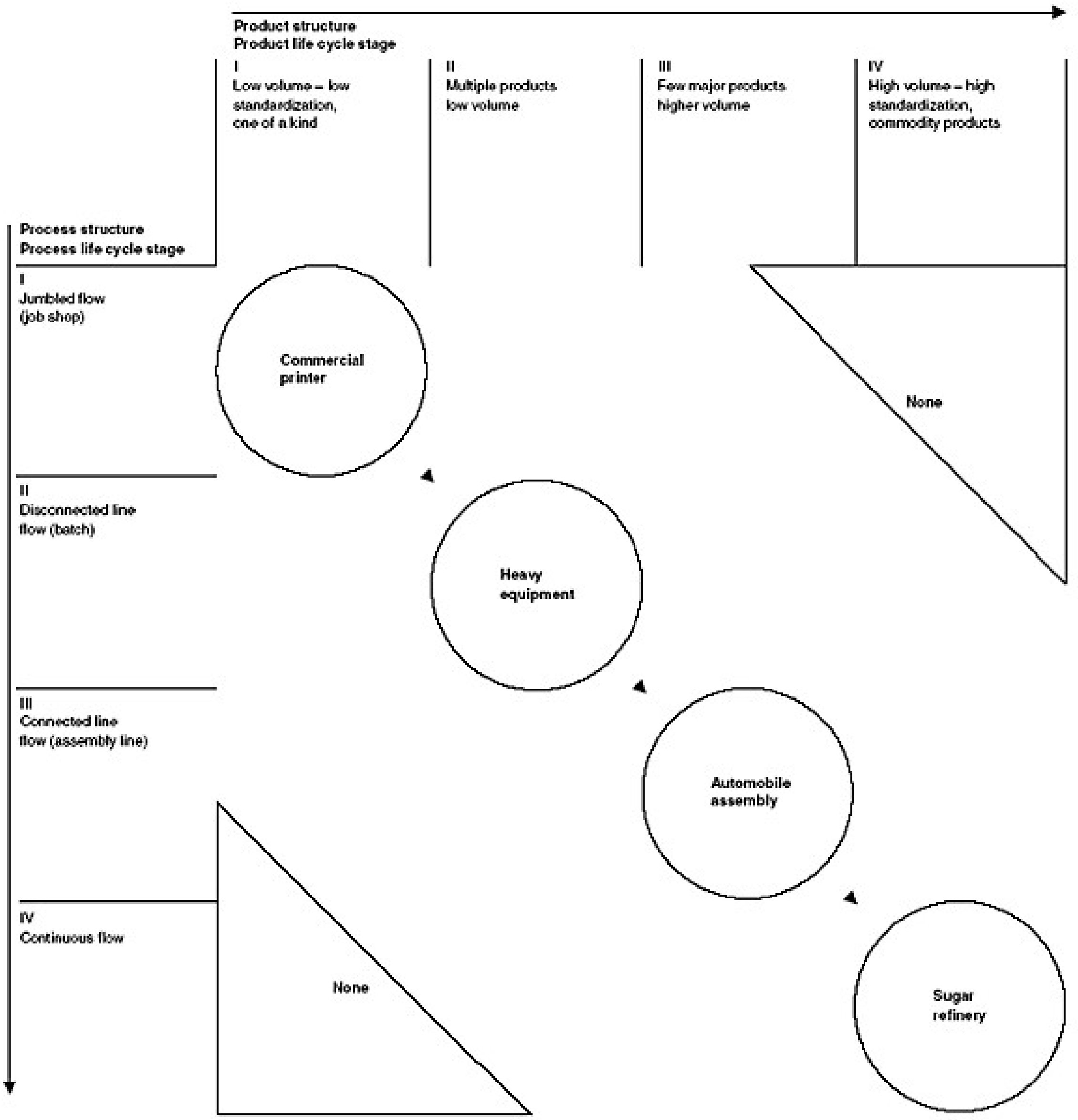


Figure 2.12: The Product-Process matrix [20]

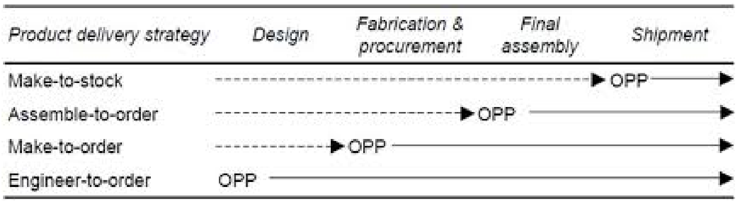
As can be seen in the matrix, the most common and often ideal choice of layout can be achieved by applying the corresponding alternative according to the diagonal in Figure 2.12 [20]. That is, if the production system is to produce single, unique products with a low level of overlap between the different products, a functional layout would be a natural fit. If instead the production is expected to deliver a highly standardised product in large volumes, a continuous flow would be optimal. However, a company is not forced to use the diagonal layout alternative that seems so obvious in the matrix. Hayes & Wheelwright [20] argue that sometimes, it may in fact be beneficial for companies to purposely divert from the diagonal alternative in order to better take advantage of the company's competitive priorities. For instance, a car company that prides itself on their cars customizability and exclusivity might find it advantageous to use functional layout, even though this will reduce their ability to produce at a higher pace and thus drives the price of each product up. However, the authors warn companies to tread with caution when heading off the diagonal path. If a company chooses a layout alternative that is not in line with the diagonal path in the matrix and without understanding the consequences this will have for the company's ability to perform, the outcome could be disastrous [20].

2.4.6 Manufacturing Environments

In general, production system uses three different types of strategies when it comes to determining when to release order to production in relation to order arrival [29]. These are:

1. Make to Stock (*MTS*)
2. Make to Order (*MTO*)
3. A hyrbid of the two (for example Assembly to Order (*ATO*) or Engineer to Order (*ETO*))

The fundamental difference between the alternatives is at which moment in the manufacturing value chain a specific product is linked to a particular customer order. The stage that this linkage happens at is often referred to as the Order Penetration Point *(OPP)* or the Customer Order Decoupling Point *(CODP)* [29]. Depending on the manufacturing environment, the OPP can be placed in different stages of the manufacturing chain [46]. In Figure 2.13, the different OPPs of some of the alternative strategies can be seen.



Product delivery strategy	*Design*	*Fabrication & procurement*	*Final assembly*	*Shipment*
Make-to-stock	- - - - - -	- - - - - -	- - - - - -▶	OPP ——▶
Assemble-to-order	- - - - - -	- - - - - -▶	OPP ——	——▶
Make-to-order	- - - - - -▶	OPP ——	——	——▶
Engineer-to-order	OPP ——	——	——	——▶

Figure 2.13: OPPs in different environments

Obviously, the later the OPP is positioned, that is, the closer to the end customer in the value chain, the requirements on the forecasting and order planning are higher. If the forecasts are lacking in accuracy, the company will be faced with expensive inventory costs or find itself unable to deliver on time.

There exist extensive literature on the topic of the factors that affect the position of the OPP [29], [44], [16]. However, most of the literature agrees that the factors can be divided into three separate categories. The categories in question are:

1.Market-related factors
2.Product-related factors
3.Production related factors

Market-related Factors
The market-related factors are very much connected to the demand on the specific product. For instance, if a requirement on delivery lead-time exist, the OPP must be positioned accordingly [29]. Moreover, the volatility of the market, and in turn the demand, must also be taken into consideration. With a low volatility, forecast of future orders are more likely to be accurate and thus such conditions are better suited for a MTS approach, as the high requirements on the accuracy of the forecasts can be met. However, in a market with a high volatility, the forecast will have a difficult time accurately reflecting the future orders, and therefore using MTO might be preferable [29]. Factors such as product range and product customisation requirements are included here. If the market expects a large product mix, with highly customisable options, a MTS approach is practically impossible to use as the inventory cost would go through the roof [29]. Instead, a smaller product mix with few options for customisation enables ATO or MTS.

Product-related Factors
Product-related factors are those that are dictated by product design, rather than market and customer requirements. For instance, in order to take advantage of a modular product design, an ATO is usually preferable, as this gives the customer some customisation options but still allows the producer to experience relatively low lead-times [29].

Production-related Factors
As for the production-related factors, these include factors such as the flexibility in the production, i.e. how long the the setup times are. Short setup times are often seen as a prerequisite in order to be able to handle the large variation in products that comes with an MTO approach [29].

2.5 Automation

Automation is when a process or procedure is carried out by a machine or a piece of technology [19]. The degree to which a process is automated can be expressed in different levels of automation. These levels range from level 1 to 10 where level 1 means that a human operator decides what action to take and carries it out and level 10 means that a machine decides what action to take and carries it out and only informs the operator if it feels that it is necessary [17].

Automation of processes can lead to many benefits such as improved quality, reduction of operating costs and shorter lead times [17], [19]. Since an automated process is, to some degree, made up of a machine, it has higher precision, especially when it comes to repetitive and monotonous tasks where human operator may struggle to keep their precision. The initial cost of implementing automation may be higher than conventional processes. However, the running cost of it is much lower as a machine only needs energy and maintenance compared to human operators who work under a salary [19]. Furthermore, machines can work at greater speeds as well as almost work around the clock leading to an increase in productivity [19].

Additionally, since they are made up off machines, automated processes are capable of working in hazardous environments or with non-ergonomical tasks that would be ill-suited for human operators.

However, the pursuit of automation implementation should not be taken too far or without regards to the manufacturing system or operation it is intended to be used in as it may lead to negative effects [17]. A high level of automation may lead to lower flexibility as it is harder to rebuild and/or reprogram machines to do a task compared to human operators. Therefore, it may not be suitable to aim for a high level of automation when it is uncertain what changes may be carried out to the manufacturing system. Having automated processes requires that they are capable of performing at the highest capacity required of the manufacturing system in order to meat the demand. However, if the demand is not consistent this may lead to overcapacity of the automated processes when the demand is diminished. Furthermore, automated processes are worse at handling variation than human workers [19]. Considering this, automation may not be the best alternative to a process which input varies greatly as it may cause problems for the machine which could lead to break-downs, and thereby revert the positive effects of having an automated process.

Aligning your level of automation with you desired manufacturing strategy is of great importance [25]. Having too low level of automation may lead to having a manufacturing system that is not as capable as it could have been with a higher level of automation. As mentioned above, there are also several negative scenarios that may occur when implementing a too high level of automation.

3

Methodology

This chapter will describe the methodology that was used during the project, what it covered, in what order it was be done and its purpose.

3.1 Structure of the project

The overall structure of the project can be divided into three major phases, the *Research phase*, the *Concept Generation phase* and the *Evaluation phase.* The methodology follows similar principles to that of the plan-do-check-act (*pdca)* methodology used in lean production [33], with each phase seen as a complement to the others. However, instead of using the traditional four phases described in pdca, the check and act phases were combined into one evaluation phase. Furthermore, as can be seen in Figure 3.1, this was an iterative process, meaning that the phases were not solely performed once, but rather multiple times as the project progressed. The objective with using the selected methodology was to establish a structured approach to handling, implementing and validating new knowledge and information as it appeared throughout the project.

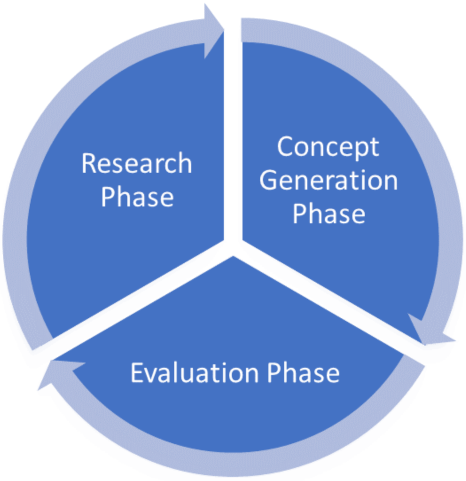


Figure 3.1: Intended structure of the project

3.1.1 Research phase

The initial phase of the project was the research phase. During this phase the main focus was to collect relevant information and knowledge regarding how a possible production systems could be structured. Moreover, this phase also included searching for already existing solutions that could be used in any of the innate processes that exists within Modvion's production system. Hence, this phase of the project dealt mainly with a literature study, benchmarking and discussions with experts. Furthermore, this phase also included stating demands and expectations that Modvion, Semcon and Chalmers may have on this project. Once all required information was gathered, the project moved on to the next phase, using the collected knowledge and information as the foundation of which the future phases were built upon.

3.1.1.1 Literature Study

A literature study, focused on theory regarding creation of production systems, production flows and automation, was conducted in this phase. The aim was to expand the knowledge and information available to the project, so that a better understanding of how to design production systems. This information was used as a basis for decision making during the concept generation phase so that each decision was well-informed, had a purpose and was based on as much knowledge as possible.

In addition, the literature study delved into how the wind power industry works in general. This was so that the conventional challenges in this field could be taken into account when developing the concept solutions.

The literature study was performed through searching in databases such as the library of Chalmers, ScienceDirect and Google Scholar. The search was focused on finding recent and peer-reviewed work from well known sources such as universities and other well-established organisations. This was to ensure that the basis of which a lot of decisions were made on, was strong and verified within the scientific or industrial community. Some of the keywords used during the search were "Production", "Production flows", "Production strategy", "Production layout" and "Automation". The keywords used in the search were combined in various ways, as seen fit, in order to find appropriate literature.

3.1.1.2 Current solutions research

Along with the literature study, research into relevant current solutions was done. This entailed looking at currently up and running production systems that have either similar structure or products, large wooden structures or are active in the wind power industry. More specifically, this research was conducted by speaking with several industry experts and reading different reports from companies and organisations detailing their approach to the production. This was done to get a better insight into what potential challenges the system may face and how these challenges were handled in different scenarios. This would give the possibility to draw as much advantage as possible and create the best potential solution. Moreover, specific process solutions, such as for example cutting of large wooden sheets, and how these were done in different systems were also of interest to the project. These solutions would go on to act as inspiration during the brain-storming activity within the concept generation phase, described in the next section.

3.1.2 Concept Generation phase

The second phase of the project was the Concept Generation phase. As this project did entail several concepts for production processes that Modvion can use as basis for implementation in their future production system, the concept generation phase had the aim to create a potential solution concept for each process.
q This was done by diving the production system into its innate functions. The function describes a single step of what needs to be done in order to create the final product. A function does not describe how a step should be carried out but rather it describes only the input and the output of it. This is to ensure that there are no preconceived biases that may affect the process derived from it. From the functions, processes, which entail a single or several functions, were derived. The processes describe, in detail, how to carry out the steps in the functions. For each process, a sub-solution was generated that met the different requirements and desires that Modvion may have had. The sub-solutions were combined with each other in order to create a complete solution concept for the production system as a whole. In order to generate the sub-solutions, a two-step approach was used, consisting of brainstorming and discussion with experts.

3.1.2.1 Concept Generation - Brainstorming and Discussions with Experts

As mentioned in the previous section, the production system was broken down into functions. Theses functions were used as the basis on which all brainstorming sessions were carried out. The brainstorming sessions entailed analysing the functions and discussing how they could be performed. Furthermore, the sessions were, in part, based on or inspired by principles found in the current solutions investigated in the previous phase. Some parts were modified in order to work with and fit in the production system and the degree of how much they needed to be modified varied from smaller tweaks to almost complete reimaginings of their original form. The solutions that came about from the brainstorming activity were all aimed at performing one or several of the innate functions of the system.

To complement the brainstorming sessions, discussions were held with industry experts as well. The experts in question were either employees at Modvion who have a deep product knowledge or consultants at Semcon who had extensive experience in designing production processes. These discussions provided a more experienced perspective to the brainstorming, as well as providing guidance in what actions within a specific process could prove difficult or complex to perform. Furthermore, during these discussions, the experts also gave relevant data about the functions, both quantitative and qualitative, as well as ideas and improvements for the solutions which were presented. Hence, the brainstorming sessions and the discussions with the experts were performed in an iterative way, as they were closely connected and had a large affect on each other

3.1.3 Evaluation phase

Once concepts of how the production processes could be performed had been generated, it was crucial that these were evaluated to confirm that they met the demands of the production system and Modvion's overall strategy. Moreover, each concept had to be realistic, meaning that it had to be both plausible to perform the process in the intended way, but also that it was possible to do so with a cycle time that met the takt time of the system. Hence, both the takt time of the system, and the cycle time of each concept needed to be calculated.

3.1.3.1 Takt time

As the end product that is to be delivered from the production system is modules, that later will be assembled to sections and towers on site, the takt time per module has to be calculated. This was done through using the formula seen in equation 3.1 and the yearly demand stated by Modvion.

$$T_m = \frac{A}{D_m} \tag{3.1}$$

where T_m = takt time, D_m = annual demand of modules and A = the available work time in a year.

The available work time per year was calculated according to equation 3.2.

$$A = x * d * w * (L - (P * L)) \tag{3.2}$$

where x = number of shifts per day, d = number of days per week that the factory is operating, w = number of weeks per year that the factory is operating, L = length of each shift in hours and P = percentage of each work hour that is scheduled breaks.

The demand of modules was able to be derived from the assigned demand of 100 150-metres towers annually that Modvion had set up as a target for the production system. As it also was known that each 150-metres tower contains six sections, and how many modules each of these sections contains, a total number of modules per 150-metre tower could be calculated with equation 3.3.

$$n = \sum_{i=1}^{s} m_i \tag{3.3}$$

where n = the total number of modules in a 150-metre tower, s = the number of sections in the tower and m_i = the number of modules in a specific section.

The annual demand of modules was then calculated using equation 3.4.

$$D_m = n * 100 \tag{3.4}$$

Important to note is that while the production system ultimately will produces modules, there exists processes within the production system that outputs parts such as braces or LVL-layers, that will be assembled into modules. Even though these processes will not produce finished modules, their takt time can still be derived from the takt time for one finished module, as each process needs to finish one module's worth of material during that time. Hence these processes takt time can be calculated with the help of equation 3.5.

$$T_{process} = \frac{T_m}{p_{process}} \tag{3.5}$$

where $T_{process}$ = the takt time for the specific process, T_m = the takt time calculated in equation 3.1 and $p_{process}$ = number of products handled in the process per module.

The takt time for pillars was calculated slightly differently, due to the fact that the given in this case was how many pillars was to be assembled on each section (32), rather than how many were to be assembled per module. This lead to the takt time for producing all 32 pillars for one section had to be calculated first, which was done with equation 3.6.

$$T_{Ps} = \frac{A}{D_s} \tag{3.6}$$

where T_{Ps} is the takt time for all pillars in a section, A is the available working time and D_s is the annual demand of sections.

Then, the takt time per pillar can be calculated using equation 3.7.

$$T_{pi} = \frac{T_{Ps}}{32} \tag{3.7}$$

3.1.3.2 Cycle time

The cycle time is the aggregated time each action, such as moving the work piece from point A to point B or cutting the work piece in two, within the process takes. Therefore, data is needed to determine how long time it takes to, for instance, move the work piece. This data was found through benchmarking other manufactures solutions. For instance, if a work piece needs to be lifted with a traverse from point A to point B, and the distance between them is known, the possible traverse speed is needed to calculate how long time the lift will take. By benchmarking different traverse manufactures product data, an average traverse speed can be set that is based on real traverses. Thus, a realistic time can be assigned to the action of moving the work piece. An example of one such calculation of moving the work piece with a traverse is shown below.

Example of calculation used to calculate time it takes to move work piece with a traverse

The total time to move the work piece from point A to B is calculated using equation 3.8.

$$t_t = t_{pu} + t_m + t_{pd} + t_{mb} \tag{3.8}$$

where t_t = total traverse time, t_{pu} = the time it takes to pick up the work piece, t_m = the time it takes to move the work piece to location B, t_{pd} = the time it takes to put the work piece down and t_{mb} = the time it takes to move the traverse back to location A.

The equations for each separate time factor can be seen in equations 3.9 and 3.10.

$$t_{pu} = t_{pd} = \frac{d_v}{V_v} * 2 \tag{3.9}$$

where d_v = the distance the traverse needs to move vertically and V_v = the speed of which the traverse moves vertically. The fraction is multiplied with a factor two as the traverse first needs to be lowered the entire distance to reach the work piece, and then moved back up the same distance before it can be moved horizontally. Since the time it takes to pick up the work piece is equal to the time it takes to put it down, $t_{pu} = t_{pd}$.

$$t_m = t_{mb} = \frac{d_h}{V_h} \tag{3.10}$$

where d_h = the distance the traverse needs to move horizontally from point A to point B and V_h = the speed which the traverse can move. Once again, the time it takes to move from point A to point B is equal to the time it takes to move from point B to point A. Thus, $t_m = t_{mb}$

The distances required in the calculations are given from the layout of the plant, whereas the speed of the traverses both vertically and horizontally is given through benchmarking. As the layout of the plant is unknown at the start, the distances between the different stations had to be continuously updated and revised as the different production processes were designed and their cycle times were calculated.

This process of benchmarking is repeated for most actions, no matter if its for moving the work piece, cutting the work piece or milling the work piece. However, in those cases where no realistic speed was found through the benchmarking, the slowest possible speed that allowed the process to keep up with the takt was set. An example of how this was done can be seen below.

Example of calculation while lacking benchmarking data

For the production system to deliver in accordance with the required output, the cycle time of the processes should be equal or lesser than the takt time. If the cycle times are too slow, the system will not be able to meet the demand. However, if the cycle time are too fast, the system will have a lot of overcapacity, which would be unnecessarily expensive. Hence, the following assumption is made.

$$T = C \tag{3.11}$$

where T = the takt time and C = the cycle time which can be calculated through:

$$C = \sum_{i=1}^{n} t_i \tag{3.12}$$

where t = the time it takes to perform each specific action that is to be performed in the process.

Thus, if no data could be found on one of the actions that is to be performed within the process, equation 3.13 could for example be used.

$$t_1 = T - (t_2 + t_3 + t_4) \tag{3.13}$$

where t_1 = the time remaining to perform action 1, T = the takt time, and t_2 through t_4 the time it takes to perform the other actions present in the process.

Through equation 3.13, the available time for the action is provided. As each action takes a certain time to complete, be it to move the part from point A to point B or mill the work piece from top to bottom, the distance is needed to calculate the slowest possible speed of the action through the following relation:

$$V_1 = \frac{d_1}{t_1} \tag{3.14}$$

If the action takes places on the work piece, e.g cut the work piece in half, the distance is known from the dimensions of the part (see Appendix B.1). If the action is to move the work piece, the distance is provided through the final layout.

Once the cycle time of a process concept was calculated, the concept was once again discussed with industry experts to validate that it was possible to be carried out. For full calculations of the cycle times, see appendix D.1 through D.22.

4

Results

The following chapter will present the results of the project. Firstly, the effects of the demand on the production system will be highlighted. Secondly, detailed descriptions of the functions that needs to be included in Modvion's future production system, what processes will carry them out and what capacity requirements each of these have, will be presented. Finally, the chapter will include a suggested layout for a future factory.

4.1 Alternatives for achieving hub height

While this project does not include any product development nor product design, the design of the tower will heavily impact the production nevertheless. For example, as presented in subsection 2.2, Modvion strives to be as flexible as possible when it comes to being able to handle tower height. This flexibility needs to be built into the production system from the start, and will heavily affect how the production processes is performed. Through brainstorming sessions along with both Modvion and experts at Semcon, the following concept alternatives for achieving the desired flexibility are described in the sections below.

4.1.1 Concept 1 for height flexibility

In order to facilitate the production, the first concept alternative enables the tower to be divided into two separate parts. The first part is referred to as the *Base Tower*, and will correspond to that of a 100 meter tower with a base diameter of 9.7 meters and a top diameter of 4 meters. This base tower will be divided into four sections, each with the height of 25 meters. The dimensions of the modules corresponding to each section in the base tower can be seen in Table 4.1, with the first section being the furthest down in the tower.

Table 4.1: Dimensions of each module in the Base Tower

Section [#]	**Module length** [m]	**Bottom Diameter** [m]	**Top Diameter** [m]	**Number of Modules** [#]
1	25	5.42	4.00	5
2	25	6.83	5.42	6
3	25	8.25	6.83	8
4	25	9.67	8.25	9

The second part of the tower is referred to as *Additional Sections*. Just as the name implies, this part includes additional sections that are added to the tower in order to reach the desired tower height. In total, seven possible additional sections can be added to the base tower. These sections will alter between ten and twenty meters in height, allowing towers to be built with a total height of 100 to 170 meters, with an interval of 10 meters. This means that the company fails to deliver towers with the required height flexibility craven by the customers. That is, the company can deliver a 100 meters tower, a 110 metres tower and so on up to a 170 metres tower,but not a 111 metres tower for instance. The additional sections will all be added at the base of the tower, so that the stability of the added height is accounted for. The size of the modules include in all additional sections can be seen in Table 4.2.

Table 4.2: Dimensions of each module in the Additional Sections

Additional Section [#]	**Module length** [m]	**Bottom Diameter** [m]	**Top Diameter** [m]	**Number of Modules** [#]
1	10	10.16	9.67	8
2	20	10.72	9.67	8
3	10	11.28	10.72	8
4	20	11.84	10.72	8
5	10	12.40	11.84	8
6	20	12.96	11.84	8
7	10	13.52	12.96	10

Important to note is that some of the additional sections will never be used at the same time. For instance, additional section one and two will never be used by the same tower. This is due to the fact that the sections both are built to represent the first additional ten meters, i.e. the interval of 100 - 110 meters tower height. The difference between the two sections are that additional section one only covers the first 10 additional meters, whereas additional section two covers the the first 20 meters. In other words, if the intended total tower height is 110 meters, the base tower with additional section one will be used. However, if the intended height is 120 meters or higher, the base tower and additional section two will be used instead in order to reduce parts, reduce the number of trucks needed for transport and to simplify the assembly process.

Provided that both the base tower and the additional sections all have known dimensions, this concept could in theory be built in a ATO or MTS environment. This would allow for shorter lead times, as the modules could be shipped from the production facility as soon as the order is received. Another advantage with this concept is that the customer orders could be directly translated into determining how many and which type of sections that will be needed. This will help facilitate the production planning, as the forecast can be directly linked to the capacity required in the production system.

While this concept might provided advantages from a production stand-point, it also has weaknesses in other areas. For one, the fact that the additional sections' modules will not have the maximum allowed length of 25 meters, but rather ten or 20 meters, the number of sections that needs to be assembled on site will increase. This would lead to more time having to be spent onsite, which would result in increased costs. Moreover, the concept cannot deliver the sought after level of flexibility in tower height. For instance, using this concept, Modvion would not be able to deliver a 137 meters tall tower, but would rather have to settle with either a 140 meters or 130 meters high tower.

4.1.2 Concept 2 for height flexibility

The second concept is similar to the first one covered in section 4.1. Once again, a base tower will be used, with the same dimensions as the one detailed in table 4.1. However, the dimensions of the additional sections used in this concept will not be pre-set, but rather adapted to the individual customer orders. This will be done by taking the additional height, that is any tower height above the base tower, and dividing it equally over the fewest number of sections as possible. For clarity, an example is provided.

Customer order for a 165 meter tower is received.
Base tower height = 100 meters
Additional height = 165 - 100 = 65 meters
Maximum allowed module/section length = 25 meters
Number of sections required =65/25 = 2,6 –> 3 sections
Length of additional sections = 65/3 = 21,67 meters

The base tower could once again be built in an MTO or ATO environment. However, the additional sections will have to be built according to MTO principles.

The advantage with this concept compared to Concept 1 is the fact that the production system will be able to deliver towers with the wanted level of flexibility when it comes to tower height. With this concept, the company can provide towers between 100 and 170 meters high, with no restrictions when it comes to height in that interval. That is, if the customer wants a 137 or a 145,5 meters tall tower, Modvion can deliver it no matter the height. Moreover, as the size of the additional sections are maximised, the number of sections that has to be assembled on site is reduced, resulting in less time spent on site.

As the additional sections for each tower will be unique, it could prove more difficult to handle this concept from a production standpoint. As the dimensions of the modules will differ from tower to tower, the process will have to be able to handle a large variance in dimensions. Moreover, the production planing could also prove more difficult to execute as the link between a customer order and the required capacity in the system is less clear. The setup time in the different production processes could also be prolonged with this concept, as the processes needs to be adjusted to the specific dimensions of the unique modules time after time.

4.1.3 Concept 3 for height flexibility

For the third concept, the idea of a base tower will be scrapped in its entirely. Instead, the focus of the concept will be to reduce the number of sections as much as possible. This way, the highly costly time spent at site assembling the tower will be reduced. By using as large section as possible throughout the tower, the lowest amount of sections used will be achieved. As the restrictions on module size stems from the constraints found during the transport, these constraints will set the dimensions of the modules and in turn sections. All sections will be maximised in size, expect for the final base section which will be adapted so that desired height could be achieved. This way, towers could be delivered at whatever height the customer wants and thus the production system can reach the desired level of flexibility.

As the base section would have to be adapted to the correct size so that the desired overall tower height can be achieved, this concept will have some direct effect on the production system and its processes. Either, the cutting process will have to be updated so that the final section can be cut in the correct dimensions from the start. This would be the optimal solution as this would lead to the least amount of material waste. However, if this is not possible to do, another cutting process would have to be performed at a later stage in the production sequence. This would lead to material waste, but could also simplify the previous processes as all sections and sheets than will be the same height.

As this third concept leads to the smallest amount of time spent at site, while still maintaining a standardised flow within the production, with only one sections worth of material having to be altered, this concept was chosen as the most optimal one for Modvion.

4.2 Yearly Demand Calculation

In order to calculate the takt time for the different components, equations 3.1 through 3.5 were used. Initially, the takt time was calculated using a one-shift approach. However, once the calculations for the individual processes within the production system were performed, it became evident that multiple processes were impossible to perform during the short takt time given. In order to solve this problem, two alternatives solutions seemed obvious. Either the capacity of the processes needed to be increased, or the takt time had to be extended. Increasing the capacity of process would be to increase the number of stations that were included in each process, in other words, introduce parallel flows. For example, if a cutting process had twice the cycle time of the takt time, doubling the number of cutting stations and splitting the work between them would allow each station to maintain its original cycle time, but the process as a whole would still deliver products in the required takt. In order to increase the takt time instead, one could increase the amount of shifts per day. By going from a one-shift approach to using two shifts per day, the available time doubles, leading to a twice as long takt time.

Dividing the alternatives according to the decision categories, as discussed by Lewis [24] and vi sable in table 2.1, the choice of the more optimal solution in this specific case becomes clearer. Increasing the capacity of each process would classify as a structural category, meaning that once this step has been taken, it could prove difficult to reverse it. At the same time, expanding capacity can often be expensive [24]. These two aspects combined make the this alternative less than optimal for Modvion, as it locks the company with a certain capacity, which would require a large upfront investment from the company. On the other hand, increasing the number of shifts would classify as a infrastructural category according to Lewis. Lewis argues that it generally is easier to alter your infrastructural categories, as these changes requires less investments. Therefore, this appears to be the better alternative for Modvion.

Moreover, increasing the number of shifts allows Modvion to be more flexible when it comes to scaling up their production as the demand of their products increase. It is not unlikely to think that the demand on the towers will not be a 100 towers annually from the start, but rather that the demand slowly rises to this level with time. Hence, the company could start operations with solely one shift working, to better adapt to to current demand, and once the demand increases, another shift could be added. Thus, the takt time was increased by expanding the available work time through adding another shift to the system. However, despite this prolonged takt time, one process could not keep up with the takt time by having one station. Thus, two stations were required in this process. This would be the cutting process in the module flow presented further down in section 4.4.1.1.

With two shifts active, the available work time was calculated to be roughly 2933 hours per year using equation 3.2. The calculation was based on the assumptions that each shift was eight hours long, the factory was up and running five days a week, 40 weeks per year and that each hour the workers were allowed a five minute break. Inputting these assumptions into equation 3.2 gives the following:

$$A = 2 * 5 * 40 * (8 - (\frac{5}{60} * 8)) \approx 2933[hours] \tag{4.1}$$

The demand on the production system was calculated with equations 3.3 and 3.4. As can be seen in appendix B.1, a 150-metre tower consist of 6 sections, provided each section is 25 metre high. In appendix B.1, the number of modules in each section can be seen. By inputting these numbers into equations 3.3 and 3.4, the annual demand of modules can be calculate to 5 000 modules.

$$n = \sum_{i=1}^{6} m_i = 500[\frac{modules}{tower}] \tag{4.2}$$

$$D_m = 500 * 100 = 5000[\frac{modules}{year}] \tag{4.3}$$

With the available work time, as well as the annual demand of modules known, the takt time per module can be calculated using equation 3.1 accordingly.

$$T_m = \frac{2933}{5000} = 0.5866[\frac{hours}{module}] = 35.2[\frac{minutes}{module}] \tag{4.4}$$

As eight layers of LVL-sheets are needed to build one module, the takt time for one layer can be calculated through using equation 3.5 as shown below.

$$T_l = \frac{T_m}{p} = \frac{35.2}{8} = 4.4[\frac{minutes}{layer}] \tag{4.5}$$

Given that each layer in turn is made up of two seperate sheets, the takt time for the sheets can be calculated as well.

$$T_{sh} = \frac{T_m}{p} = \frac{35.2}{8 * 2} = 2.2[\frac{minutes}{sheet}] \tag{4.6}$$

The takt time for the vertical lids are equal to the takt time for the modules, as one vertical lid pair will be assembled to each module on site.

$$T_{vl} = T_m = 35.2[\frac{modules}{lid} \tag{4.7}$$

When calculating the takt time for the braces, one needs to realise that for each module, two braces are needed as one brace is placed at the top of the module and one at the bottom. Moreover, the vertical lids will also require one braces at the top and one at the bottom. Thus, four braces in total have to be produced per module takt.

$$T_b = \frac{T_m}{p} = \frac{35.2}{4} = 8.8[\frac{minutes}{brace}] \tag{4.8}$$

Important to note is that each brace is made up of two layers to obtain the required thickness. However, due to the otherwise small dimensions of the braces, these layers will not consist of two sheets, but rather just one. The takt time for a layer used in the braces is therefore half of the takt time for the entire brace (4.4 minutes).

Using equations 3.6 and 3.7, the takt time for pillars was calculated. The total amount of pillars required per year was calculated through equation 3.6.

$$T_{Ptot} = \frac{A}{D_s} = \frac{2933}{6 * 100} = 4.89\frac{hours}{32pillars} = 293.33\frac{minutes}{32pillars} \tag{4.9}$$

From this, equation 3.7 was used to calculate the takt time per pillar.

$$T_{pi} = \frac{T_{Ptot}}{32} = \frac{293.33}{32} = 9.16\frac{minutes}{pillar} \tag{4.10}$$

It should be noted that the production system will not solely produce modules for a 150 meter tower, but towers of altering height, with a maximum tower height of 170 metres. Obviously, towers with a higher total height than 150 meters will require more modules than those towers that are shorter. Thus, the true demand will likely not be based solely on the sales of a 150-metres tower but rather all towers of varying height. However, as no data on these sales are attainable at the moment of writing, the target demand used for this project was simplified to just the 150-metres towers.

4.2.1 Production layout

The relative short takt time of 35.2 minutes per module limits the choices that can be made from a layout perspective. As described in subsection 2.12, the demand plays a role in choosing a suitable layout for the plant. Using the product-process matrix as described by Hayes & Wheelwright, the preferred choice would be to use a continuous line flow as a layout when pairing the demand with suitable layout type along the diagonal line in the matrix. This is because the production system will produce and deliver a large amount of products, with a relatively small product-mix.

Using a line layout also seems like the natural choice when comparing the different alternatives provided in subsection 2.4. While a fixed position layout could seem intriguing at first glance due to the shear size of the modules, a deeper analysis of the situation proves that there are better choices for this production system. For example, the short cycle time would require multiple fixed position stations where a module could be built. Each station in a fixed position layout requires all the tools and material required to build the entire product [15]. Thus, multiple stations will lead to an increased amount of tools being required. This would provide both costly and lead to a low utilisation of each tool.

Both the functional and cell layout described in section 2.4 are useful in production systems that specialises in customasiable products, of low to medium volume [20]. This is not the case in the intended production system that deals with standardised, modular products of high volume. Hence, both these options are not optimal as layout choices. This leave the line layout as the sole viable choice. Thus, the production system was designed with a line layout in mind.

4.3 Production Functions

The production system can be divided into several innate functions, that all need to be completed in order for the product to be considered finished. Moreover, many, but not all, of the functions are restricted in when they can be performed. This is due to the fact that the functions in question are dependent on one or multiple functions having been performed ahead of them in the production. Thus, the sequence the functions are performed in is to a certain degree strict. However, some of the functions are not as restricted when it comes to when they are performed and could even be performed in parallel to other functions. Thus, it is evident that the layout of the production system, along with the sequencing of the functions, will play a large role in how the final production system ultimately performs. The order of the functions and what each function strives to achieve will be further detailed in the following sub-sections.

The production system has been divided into several sub-flows, one for each major component of the module that is to be produced by the system. These flows are the *Module Flow*, the *Vertical Lids Flow*, the *Pillar Flow*, the *Braces Flow* and the *Horizontal Lids Flow*. Some of the flows will merge during the production, while others will run in parallel and only meet each other at the assembly site of the tower. Furthermore, the functions used by Modvion during their construction of the prototype was used as the basis for what functions are needed to be included and also as in what potential order they may be performed in.

Once all functions that are included in the production system are accounted for, the focus will shift to how these functions are to be performed, i.e how they will be executed. The solution for how to perform a certain function will be referred to as a process. Note that one process might included several functions if the functions are possible to be performed in parallel. The processes will be explained in detail in the sub-sections following the sections dealing with the functions themselves.

4.3.1 Module flow

The module flow is the flow where the main parts of the module are created and put together. It is the largest flow in the production system and other flows will connect to it. An example of this is the pillars which have a separate flow but merges with the module flow when the pillars are attached to the module. A possible sequence of the functions can be seen in Figure 4.1.

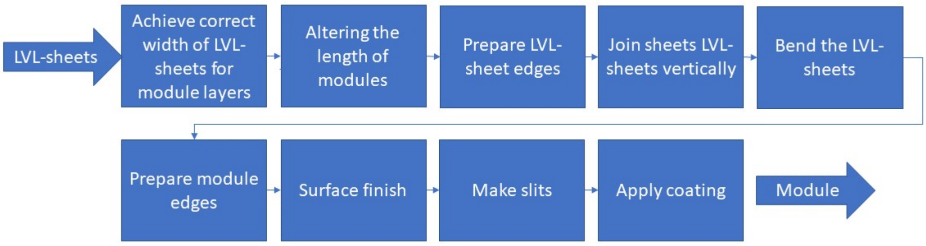


Figure 4.1: Sequence of functions in the module flow

4.3.1.1 Cut width of LVL-sheets for module layers

The sheets that arrive to the plant from the supplier all have the standard dimensions of 25 x 1.8 x 0.024 meters. As described in section 2.2.3, each module will be made up of eight layers of LVL-sheets. Moreover, due to the conical shape of the tower and subsequently each module has, the width of the sheets needs to be altered along the length of the layer as well, as can be seen in figure 4.2. In other words, the width of the individual sheets that are to be joined into layers has to be altered.

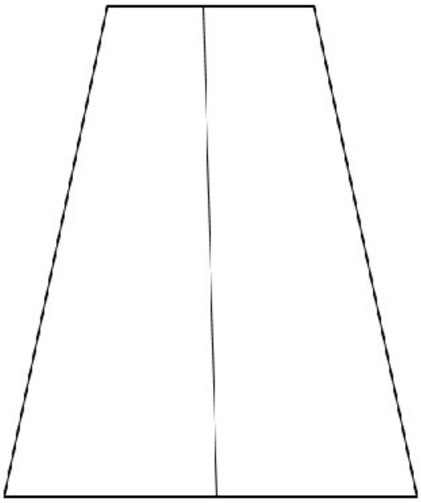


Figure 4.2: Visualisation of a layer that will be used in building a module

This initial function of altering the width of the individual sheets therefore aims to ensure that the width of each sheet is correct so that when they are assembled into a layer, the layer has the correct dimensions. As the layers for all modules will be within the range of 3.09 - 3.58 metres in width, see appendix B.1, all layers will be made up of two sheets.

However, it is important to realise that two main options exists for when this function is performed in the production sequence. Either the function is performed as the very first step in the production system or once two sheets have been assembled to a layer. There exists no requirements that state that the sheet should be cut before they are joined together. Nor does the design of the product force the sequencing of these two actions in any way.

4.3.1.2 Prepare LVL-sheet edges

As presented in the previous section, each layer will consists of two sheets. Hence, these sheets will have to be fitted together. Due to the general disinclination of having too many metal components in the towers, as described in section 2.2.2, the joining of the sheets will use glue as a fastener. One suitable method for gluing sheets together is by using finger joints.

An example of a finger joint with multiple fingers can be seen in Figure 4.3. By using a finger joint, a larger surface area for the glue is created and therefore a stronger bond between the two sheets can be achieved. This also means that the edges of the sheets will have to be prepared for the finger joining, either by cutting the edge into a finger or cutting out a finger shaped cavity at the edge of the sheet.

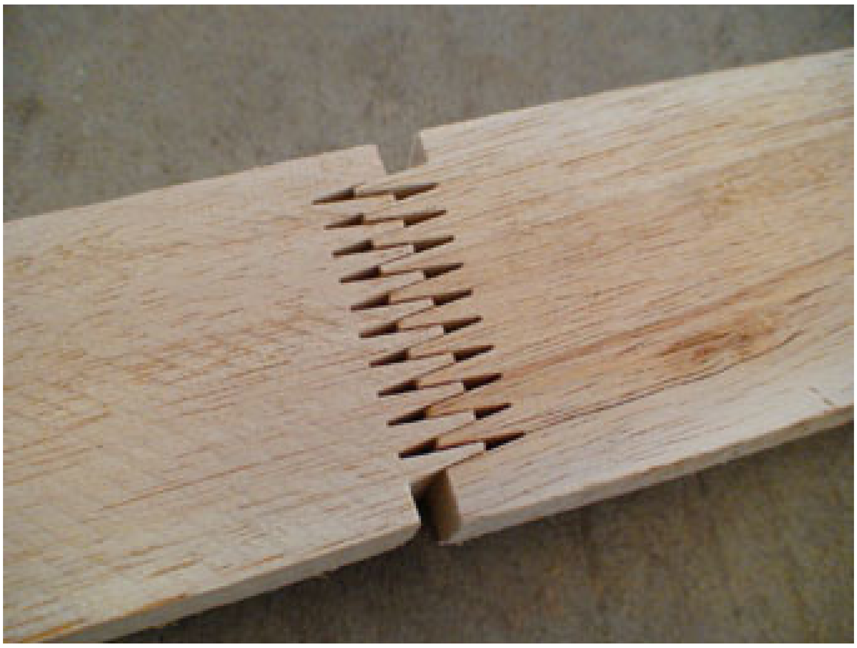


Figure 4.3: Example of Finger joints

Furthermore, as the sheets are only attached in pairs of two, only one side of each sheet should be prepared with a finger joint. Therefore, it is crucial to know if a specific sheet will become the left or the right side of a layer, so that the joint is aligned between the two sheets. Moreover, the sheets will have to have their edges prepared in their entirety, which is 25 meters, since they will have to fit all the way. As previously stated, the preparation of edges function can be placed either ahead or following the function of altering the sheet width.

4.3.1.3 Join LVL-sheets vertically

Once the sheet edges have been prepared for the finger joint, glue have to be applied to join the LVL-sheets, so that two sheets can be joined together in order to form a complete layer.

For clarity, the function of joining sheets together to achieve the correct width is referred to as *Join LVL-sheets Vertically*, as the vertical seam that runs along the full sheet length, i.e the finger joint, on each sheet is joined together.

This function can be done before the sheets are reduced in width. However, it will have to be done after the edges are prepared as they form the finger shapes which are used when joining them together.

4.3.1.4 Bend the LVL-sheets

The structure of the tower is conical and therefore, the flat layers made in the previous function will have to be bent in order to get the appropriate shape. Since the diameter varies throughout the entire height of the tower, the shape of the modules will vary depending on what section they belong to. Therefore, the bending function must be able to handle the variance in diameter present between the different sections.

The shape of the modules is retained by bending and gluing the layers together and allowing them to harden while in the desired bent form. This means that it is the hardened glue between the eight layers of sheets that is what is holding the form of the module. Thus, the bending can not be done without glue between the layers of sheets.

Furthermore, the bending function must be able to produce enough pressure to bend the layers into the correct shape as well ensuring the glue hardens in a correct way. This pressure will need to be kept onto the layers until the glue has sufficiently hardened so that no springback occurs that may deform the shape of the module.

4.3.1.5 Make slits

The slits that will be used to join the different sections in the tower, as described in section 2.2.3, will have to be made in the production. The slits, similarly to the pillars, will need to be in the correct position and aligned in order to match up between the different sections when they are stacked. Therefore, high precision is required in order to keep the variance low enough for successful assembly on site. The top and bottom end of the section will have a different amount of slits since the bottom part of the section has a larger diameter than the top.

No limitations where the process of making slits could be placed exists. The slits could be made as early as before the LVL-sheets have been assembled to layers, or as late as before the module has gone through the surface finish process. This is possible as non of the previous functions are dependent on the slits being there in order to be executable.

4.3.1.6 Prepare module edges

The male profile of the modules must be created so that the modules can be assembled to sections. For the male-to-male profile to be created, material will have to be removed from two sides of both edges of the module.

When in the production sequence, this function is performed is somewhat flexible, depending on the method to achieve the male-to-male profile. Nevertheless, the one certainty of the placement of the function is that it has to be performed ahead of the surface finish process, as this process requires access to the surfaces first reachable once the male-to-male profile has been achieved.

4.3.1.7 Altering the length of modules

Even though the production system is designed for manufacturing 150 meter towers, Modvion has requested that it should be able to manufacture towers of altering height. Thus, sections of the tower will either be added, removed or altered in height. This means that in some occasion, the length of the module will have to be adjusted in order to create sections that are not 25 meters tall. Thus, this function must exist.

This function can be carried out anywhere in the module flow since no other function requires that the length stays 25 meters. Nor does the design of the product affect this in any way.

4.3.1.8 Surface finish

Once the modules have been given the correct shape and size through the previous functions, a surface finish of the module is required. This is because when the modules are assembled, a good fit is needed between each module and the different lids. Thus, the surfaces which has contact with other modules or lids will need to be treated in order to remove any potential excess glue or other unwanted material that may have been left as waste products from the previous functions. If no surface finish is performed, it could prove hard to assemble the modules on site, as the fit between the different modules could be off. Therefore, a surface finish function is vital. As mentioned before, the surface finish function must be performed after the male-to-male profile is achieved, as its primarily these surfaces that needs to be treated.

4.3.1.9 Apply coating

When all the parts of the module has been assembled and its physical appearance has been achieved, the outside of the module will need to be protected from the outside weather and environment the tower will reside in. Since wind towers usually are placed in positions where there is a lot of wind, the environment may be rough on the tower and therefore the protection will have to be strong enough to withstand such conditions. Furthermore, since the tower will be made out of wood and is expected to have a product lifetime as long as a regular steel tower, the protection is crucial. The protection of the tower will be in the form of a protective coating that will be applied as the last part of the production.

The coating function will be the last station in the system, as it could prove damaging to the coating layer if the work piece was machined after the coating has been applied.

4.3.2 Vertical lids flow

Starting with the raw material and ending with vertical lids sent to the assembly site, this flow covers the functions needed to make vertical lids of the correct size and shape. A possible sequence of the functions can be seen in Figure 4.4.

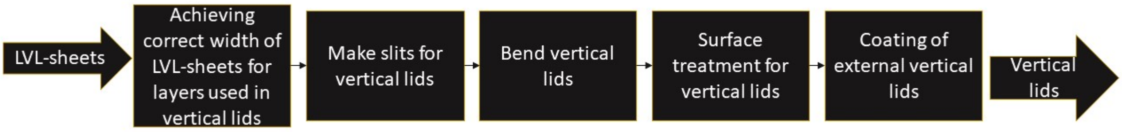


Figure 4.4: Sequence of functions in the vertical lids flow

4.3.2.1 Cut width of LVL-sheets for layers used in vertical lids

The vertical lids, as described in section 2.2.3, are made up of similar layer structure as the one used in the modules. However, the vertical lids are not as wide as the modules, as they only have to cover two male-to-male profiles lengths of 0.48 metres, which can be compared with the 3-plus metre width of the modules. As the sheets that are delivered from the supplier are 1.8 metres wide, the layers in the vertical lids will not have to be made up of two sheets. Instead, the single sheet used for the layer will have to be decreased in width to accommodate for the small width of the lids.

This function of altering the width of the layers used for the vertical lids is flexible when it comes to placing it in the production sequence, just as the similar function of altering the width of the sheets for the modules is.

4.3.2.2 Make slits for vertical lids

For the slits to be effective in joining sections together, they need to be displaced along the full diameter of the section. As part of the top and bottom diameter will be the gap between two modules, slits has to be incorporated in the vertical lids as well. This function will be similar to that of the function of making slits in the modules, as the same principles apply here.

4.3.2.3 Bend vertical lids

As the lids are to follow the shape of the modules they are assembled with, they too need to be bent in similar fashion to that of the modules. However, as discussed in section 4.3.1.4, the bent shape of the modules are achieved through the glue hardening between the different layers in the bent position under pressure. Bending the layers without any glue in between the layers could lead to a "spring-back" effect once the pressure is released, leading to a deformed module. For the external vertical lids, this does not cause any problems, as each of these lids consist of two layers. However, the internal vertical lids are only one layer thick, meaning that there does not exists anything to glue together that could help hold the shape once the pressure is released. Therefore, the internal vertical lids will have to be assembled on site, where they will have to be fastened to the module with the help of screws or nails so that the bent shape is achieved. This also means that no pillars nor braces can be attached to the internal vertical lids in the production, but rather needs to be attached on site once the lids have been bent. The external vertical lids on the other hand will be able to be bent in the production, in a similar fashion to that of the modules.

4.3.2.4 Surface treatment for vertical lids

As the surface treatment is meant to remove any excessive amount of glue after the bending of the lids, this function will only be needed for the external vertical lids. The function shares similarities with the surface treatment function for the modules.

4.3.2.5 Coating of external vertical lids

Since the external vertical lids will be a part of the most outer layer of the tower, they too need to be coated so that they can survive in the harsh outside climate. The same coating material and principles will be applied for the external vertical lids as for the coating of the module.

4.3.3 Pillar flow

The pillar flow is the flow that handles the pillars from the arrival of the raw material, to the function in which they are attached to the module or are sent to the assembly site to be attached to the vertical lids. A possible sequence of the functions can be seen in Figure 4.5.

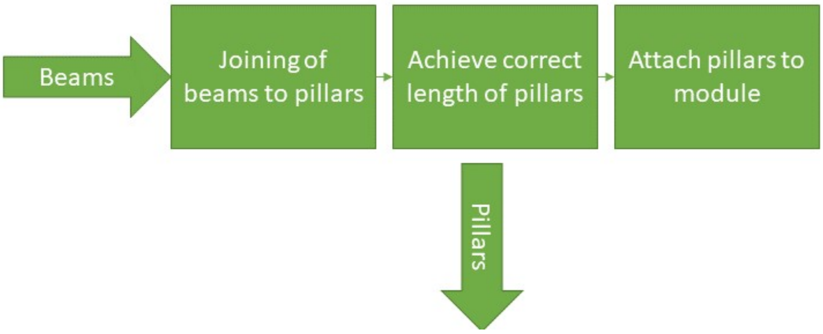


Figure 4.5: Sequence of functions in the pillar flow

4.3.3.1 Joining of beams to pillars

Pillars will be mounted on the inside of each section to strengthen the tower. Moreover, these pillars will each be 24 metres long, meaning that they will stretch from the end of the bottom brace to the start of the top brace at each module. However, the input material to the production system will be beams with a length of 12 metres. Thus, two beams are required to be joined in order to achieve the desired length of 24 meters. This will be done with the help of finger joints, similar to that of the finger joint in the joining of LVL-sheets to layers in the module flow.

4.3.3.2 Achieve correct length of pillars

Since the modules will need to have the flexibility to be altered in length, so too must the pillars. Therefore, the pillars will need to be altered length-wise before they are attached to the modules.

The function of altering the length of the pillars can be performed either before or after the joining of the beams to pillars. However, it will have to be performed ahead of the function that is to attach the pillars to the module, as the pillars needs to be of the correct dimensions once attached to the module in order to fit.

4.3.3.3 Attach pillar to modules

The pillars need to be attached to the inside of the module in order to give the tower more strength. In the production system, the pillars will also be attach with glue as a fastening element. There will be 32 pillars for each section, evenly distributed between the modules.

This function can not be carried out before the layers are bent into modules. This is because the bond between the pillars and the unbent inner layer of the module would risk being compromised and the structural integrity can not be guaranteed. The attachment of pillars will either be done during or after the modules have been bent into shape.

4.3.4 Braces flow

The braces flow handles the braces that are used to give extra thickness at the top and bottom of the module for the slits. The flow starts at the raw material and ends either when the braces are attached to the modules or are shipped to the assembly site of the tower where they will be attached to the vertical lids. A possible sequence of the functions can be seen in Figure 4.6.

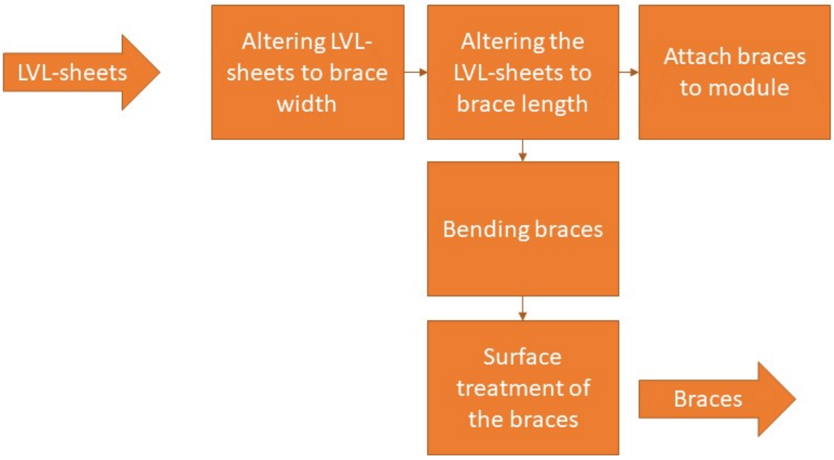


Figure 4.6: Sequence of functions in the braces flow

4.3.4.1 Cut LVL-sheets to brace width

The braces that are at the top and bottom of each module will have to have the correct dimensions, meaning that they will have to be adapted to the specific module they to be attached to. Thus, the width of the sheets used for braces will have to be altered. The braces will be the same width as the top of the module or the bottom of it, depending on if the brace should be attached at the top or bottom. Furthermore, the braces will have the same conical shape as the modules, meaning that they will be narrower at the top than at the bottom. The braces will be made from the same material as the module, 25 x 1.8 x 0.024 meter LVL-sheets. Thus, it can be said that the function is to alter the length of the sheet so that the width of the braces matches the width of the module that they will be attached to.

4.3.4.2 Cut the LVL-sheets to brace length

The LVL-sheets which are to be made into braces will have to be altered in length in order to achieve the correct dimensions, as the braces will only be 0.5 metres long. Therefore, the sheets will have to be altered so that they are 50 centimeters long. However, depending on if the length or the width of the braces are altered first, the input may vary. Since there are no requirements of which of the two should be done first, they can both be the input to one another.

4.3.4.3 Bending braces

The braces, just like the modules, must be bent into the correct circular and conical shape, as they are to be mounted on bent surfaces. This bending function follows the same principles as the function of bending the module. This means that it is the glue between the layers of braces that holds them into shape, the hardening time is the same and a pressure of the same magnitude will need to be applied during the hardening process.

This function will need to be carried out after the altering of width and length of the braces. This is because otherwise the entire sheet would need to be bent. It is possible to bend the entire sheet if desired. However from a pragmatic standpoint it would be very unpractical due to its size. Thus, the input to the function will be braces that have been altered in length and width.

4.3.4.4 Attaching braces to modules

Once the layers used for the braces have received their required dimensions, they can be attached to the modules. Glue will be used as a fastening element when performing this function. Important to note is that not all braces will be attached to the module, but rather half of them will be attached to vertical lids.

Attaching the braces to the modules can first be done once the braces are of the correct sizes, as it will prove hard to alter their dimensions once assembled with the module.

4.3.4.5 Surface treatment of the braces

The braces will need to be surface treated just like the modules. This is done for the same reason, to ensure a good fit during the tower assembly at the site of the tower. There may exist residual glue and other material from the previous functions that will need to be removed.

This function will be the last function carried out on the braces as the residual glue and excess material comes from the other functions. Thus, by having it last it guarantees that no impurities to the surfaces exist.

4.3.5 Horizontal lids flow

The horizontal lids will have a flow that includes the functions that are needed to create a horizontal lid. The flow will, as the other flows, start with raw material and end with horizontal lids that are ready to be sent out to be assembly on the tower once it has been erected. A possible sequence of the functions can be seen in Figure 4.7.

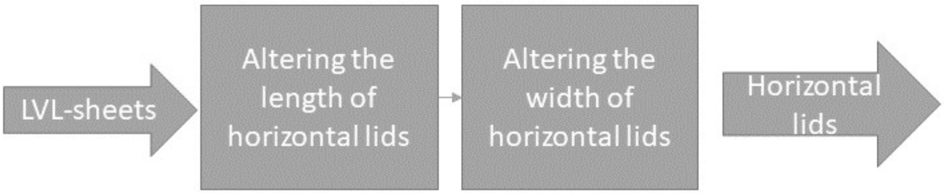


Figure 4.7: Sequence of functions in the horizontal lids flow

4.3.5.1 Altering the length of horizontal lids

The horizontal lids that will cover the slits once the section have been assembled will have to be manufactured within the production system as well. These lids will only consists of a single layer of LVL, meaning that it will not be possible to bend the lids in the production due to the same reasons as why the internal vertical lids can not be bent. Furthermore, as the lids will only have to be as long as the length of a slits-pair (roughly 0.7 metres), the layer will only have to be made up of one sheet. Thus the sheets need to be altered in length in order to cover the slits.

4.3.5.2 Altering the width of horizontal lids

The horizontal lids will cover the entire width of the module which they are assembled to. Therefore their width will have to be altered in order to fit with the module when they are assembled at the site of the tower.

This and the previous function of the horizontal flow can be done in any order since there are no requirements on them based on the module or tower design or for any other reason.

4.4 Production Processes

In the following sections, an explanation of how the functions described in section 4.3 are performed. The processes will be presented in the same order as they are executed in the production system.

In a similar way to how the functions were organised and presented, the processes also has sub-flows of how the different parts of the modules will move within the production system. The flows are the same once as the flows for the functions as this is a natural segregation of the parts of the module. The merging of flows and what flows will run in parallel is also the same for the same reason.

4.4.1 Module flow

The module flow includes the processes needed in order to perform the functions for the module. However, the processes are not necessarily structured in the same way. This means that functions may have been combined and carried out at the same time or that the sequencing of the functions has been altered in order to improve the production system.

4.4.1.1 Cutting and Milling process

The first process in the module flow is the cutting and milling process. This process is placed at the start of the line to facilitate the handling of the material at later processes. The included functions in the process are *Achieve correct width of LVL-sheets for module layers*, *Prepare LVL-sheets edges*, *Altering the length of modules* and *Prepare module egdes.* Important to note is that the male profile at the edge of the module is prepared at this step by altering the width of the sheets.
The station can be seen in Figure 4.8

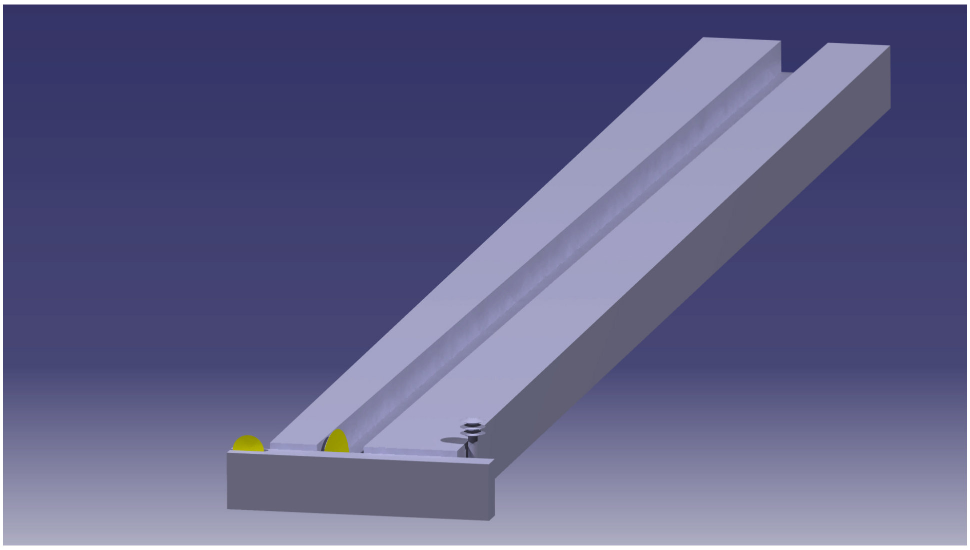


Figure 4.8: Visualisation of the cutting and milling station

The input material, which is the LVL-sheets delivered to the plant from the supplier, will be moved to the station one sheet at a time to enable a one-piece flow. The material will be moved to and from the process by using a traverse equipped with a suction cup tool. This way, the traverse can lift one sheet at a time from the stack that is delivered to the plant and put down the sheet at the process. An example of a traverse with a suction cup can be seen in Figure 4.9.

Figure 4.9: An example of a traverse equipped with a suction cup [43]

Once placed at the station, the saw blade which is placed in the groove as seen in figure 4.8, will cut along the full 25 metres of the sheet. Note that the groove is not strictly straight, but rather angled slightly. This is to achieve the shape of the sheets as shown in figure 4.2. However, as the different modules will have different width, the cut must be able to be placed at different positions on the sheet. Therefore, the possibility to place each cut at a slightly different position must exist. This is done by moving the blade in a horizontal direction as this allows sheets to be cut at varying width. This horizontal movement ensures that each cut is placed at the correct position regardless of what layer in the module the sheet will ultimately become.

At the same time as the cut is made, the finger joint profile will be milled out at the other side of the sheet. The milling head can also be seen in Figure 4.8. The milling tool will move along the full length of the sheet. Note that the finger joint always will be placed on the side of the sheet that is uncut, as this is the side that will be joined with another sheet , as can be seen in Figure 4.2. Hence, the milling process will have no variance in where the finger joint should be placed. However, as a finger joint requires one "male" profile and one "female" profile to function, a decision has to be taken which profile each sheet should have. The male and female profiles can be seen in figure 4.10 and 4.11 respectively.

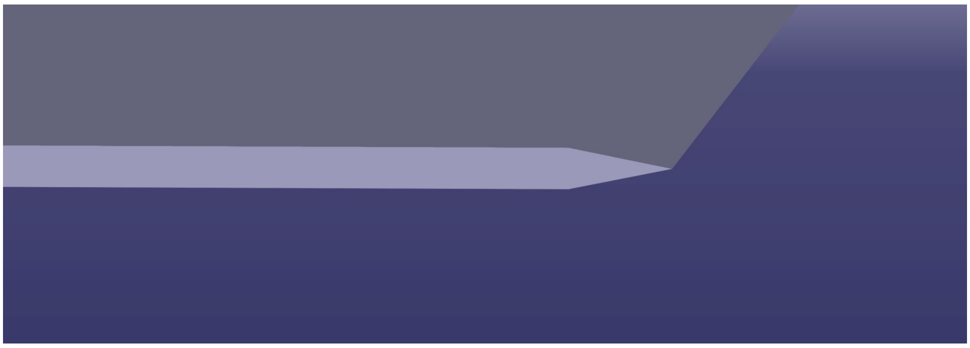


Figure 4.10: A sheet with a male finger joint profile

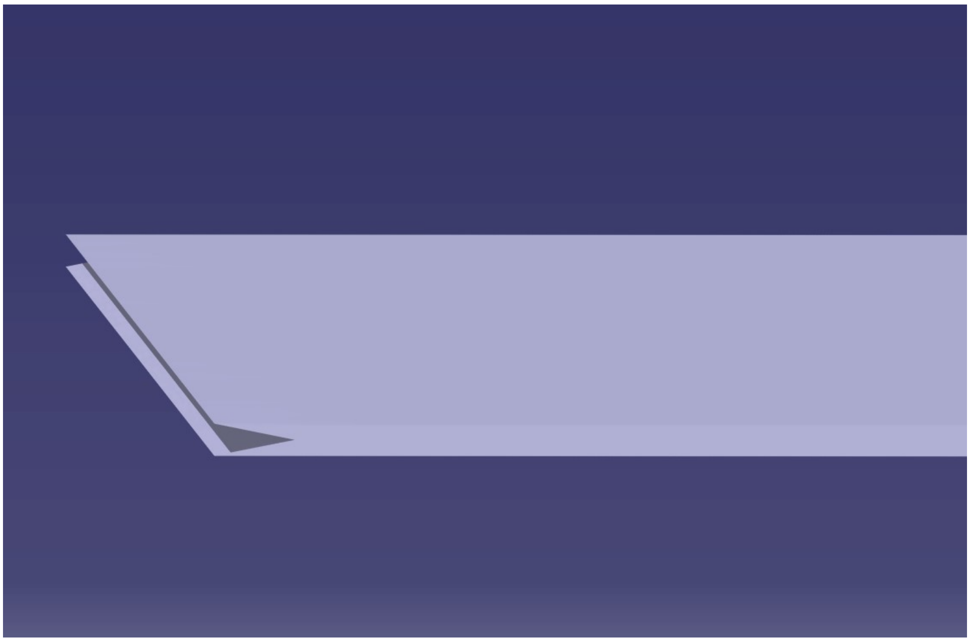


Figure 4.11: A sheet with a female finger joint profile

Optimally, the process will sequence the sheets so that the female sheet of one layer is immediately followed by the male sheet of the same layer. This way, the time each sheet spends waiting for their counterpart before being joined together is reduced as much as possible. If the sheet that is to be cut will be used in the bottom section of a tower that has a customised height, an initial cut along the width of the sheet will be performed to guarantee that the sheet is as long as required. In the rare cases where this is needed, this will be the very first step of the process.

Through discussions with Adam Hestergård, a sales agent at Sågspecialisten AB (*Sågspecialisten*), a range of expected cutting speed for the process was given.

Sågspecialisten is a swedish company specialising in industrial solutions for processing of wooden products, with customers all over Europe [37]. According to Hestergård, a modern automatic cutting solution for the suggested process could be expected to have a feed rate of 60 - 100 metres per minute, and potentially an even higher feed rate than that. In order to make sure that the cutting speed was attainable and sustainable, a feed rate of 60 metres per second, or one metre per second, was thus set for the process.

In similar fashion, a realistic milling speed for the process was attained through benchmarking the capacities of different companies milling solutions [45], [18]. From the benchmarking process, it was established that there already exists solutions today that have a capacity of milling 120 metre per minute, when specifically preparing finger joint profiles in wooden products [45]. Once again, a conservative approach was used in order to ensure that the selected milling speed was both attainable and sustainable. Thus, the milling speed was also set to one metre per second.

The process will require three separate lifts with the traverse. First, the raw material needs to be moved from the input storage to the working station. Then, once the cut has been made, the scrap material left from the process will have to be moved away from the work station so that the next sheet can be handled. Finally, the desired work piece will be moved onward in the production flow to the next station. The time that each of the three lifts take are all calculated in accordance to the example presented in subsection 3.1.3.1.

As the time for each action in the process is known, the cycle time of the process can be calculated by adding all of these together. The cycle time is calculated to be 2.54 minutes. For full calculations regrading the cycle time, see appendix D.1. As the takt time dictates that a sheet needs to be finished every 2.2 minute (as shown in section 3.1), two cutting station are required in order to keep up with the high demand even with two shifts. As two stations are required, it could prove beneficial to always handle the female sheets at one station and the male sheets at the other. This way, only one milling tool is required at both station, as opposed to two if both stations should be able to handle both types of sheets.

4.4.1.2 Vertical Joining Of Sheets

With the sheets cut and equipped with the finger joint profile, the following step will be to assemble the two sheets into one layer, as described in subsection 4.3.1.3. A traverse with a suction cup, as the example seen in figure 4.9 will be used within this process as well as when moving the sheets to the process. A visualisation of the station can be seen in figure 4.12.

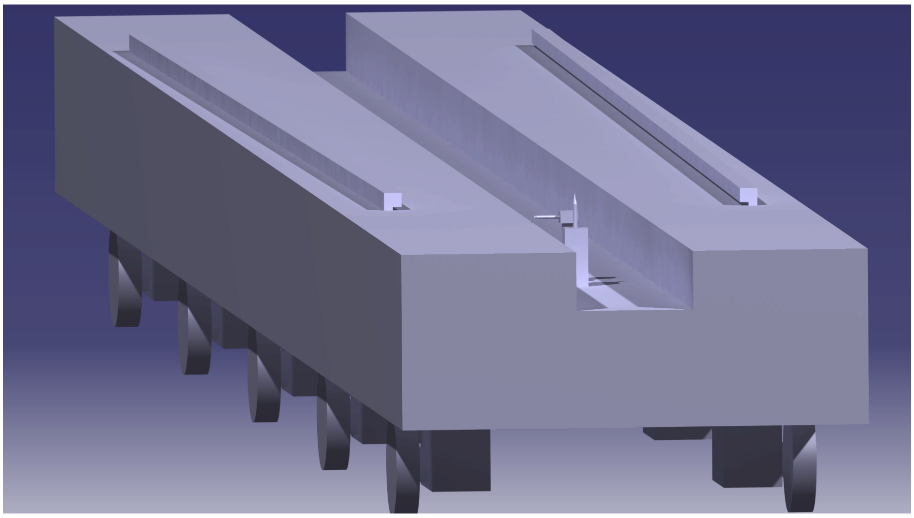


Figure 4.12: Visualisation of Vertically Joining Station

In order to join the different sheets into the desired layers that will be used to assembly the module, glue will be applied in the finger joint of the sheets and then the sheets will be pressed together. In order to standardise the process, the glue will always be applied to the sheet with the male profile. Furthermore, the glue will be applied at both sides of the milled male profile, so that it is certain that the glue is evenly spread across the joint. This also means that the glue will be applied to the full length of the sheet as well. As the sheet edge that is to be glued will always be located at the same place, an automatic solution can be used, as little to none variance will exists in the gluing of the different sheets. The gluing will be done by having two nozzles, placed so that they together cover both sides of the male profile, applying the glue as they are move up or down the sheet length on a rail.

The glue that will be used throughout this function is similar to AkzoNobel's 1247/2526 adhesive system. See appendix E for the full technical data of the glue. From the technical data of the glue, it can be read that the required pressing time, that is the time the bonded piece should be kept under pressure before further handling, is 5 hours and 45 minutes. This pressing time of the glue is also referenced as the hardening time of the glue. However, there are several factors that can affect the pressing time. These include the temperature of the work piece, the mixing ration as well as the clue bond line, i.e how much glue is applied [2]. It should also be noted that the glue has an assembly time of 30 minutes. The assembly time represents the time that is allowed to transpire from the moment that the glue is applied to the work piece and pressure is applied. If pressure is not applied to the work piece within the assembly time, the quality of the bond might suffer.

At the same time as the glue is being applied to the sheet with the male profile, two guiding holes that will be used during the bending process of the layers, will be drilled. The holes are meant for guiding pins used during the bending process of the module. These pins will help stabilise the layers once the pressure during the bending has been applied. The goal of the pins is to keep the layers in place during this process so that they do not slide or twist during the bending, leading to unwanted deformations in the shape of the module. As the pins needs to penetrated all the layers to function, it is vital that these holes are located at the correct spot for all different layers. If, for some reason, the holes do not line up, the pins will not go through each guiding hole in every layer. By performing the drilling operation at the same time as the gluing, no additional time is needed to be added to the cycle time of the station. The drills that are used at the station can also be seen in figure 4.12 in the groove.

Once the glue has been applied and the guiding holes drilled, the two sheets will be pressed together by using the barriers seen on each side of the grove in figure 4.12. These will press the sheets together through hydraulic pumps. The sheets need to remain under pressure and in position during the full hardening time of the glue. Hence, the platform that is used will be lifted to the next process in its entirety. This will be made possible by using a traverse.

The time it takes to lift the platform from the station and onwards is calculated according to the example provided in section 3.1.3.1, and the distance provided by the final layout plan of the plant, see appendix C.1. No suitable data was found for the gluing speed. Hence, the speed that was required for the gluing action was calculated according to the second example provided 3.1.3.1. The required gluing speed in order to keep up with the takt was found to be 0.125 metre per second. Full calculations of the process can be see in appendix D.2. As the lowest possible speed to keep up with the cycle time was used in the calculations, the cycle time of the station is 4.4 minutes, i.e. exactly as long as the takt time.

4.4.1.3 Glue sheets into layer

The hardening time for the specific glue used in this process is 5 hours and 45 minutes, as presented in section 4.3.1.3. From a production stand-point, this would mean that the layer would have to be placed in a storage, while under constant pressure, for the full hardening time. With a takt time of 4.4 minutes, this would lead to, in total, 79 takts of material having to be stored at the same time in order to harden the glue. Obviously, this is not ideal as this would increase the Work-in-Progress (*WIP:s*) in the system greatly. However, it is possible to decrease the hardening time by increasing the temperature of the work piece [2].

One example of where a gluing process has been optimised by altering the work piece temperature for a quicker hardening time is at a company called Moelven Byggmodul AB *(Moelven)*. Moelven is a large provider and manufacturer of raw material and wooden products [27]. The product portfolio of Moelven also includes glulam beams, which also uses the 1247/2526 adhesive system from AzkoNobel. Through personal contact with Thomas Johansson, a production manager at Moelven's factory in Töreboda, information concerning their handling of the long hardening times of the glue was shared. Johansson explained that Moelven utilises something they refer to as a "furnace"-solution. In short, the glued beams are passed through a machine, similar to a furnace in function, that increases the temperature of the glue bond from room temperature, 20 degrees Celsius, to around 80 degrees Celsius. This increased temperature drastically reduces the hardening time. In fact with this solution in places, the company is able to process beams with a thickness of 165 millimetres with a speed of 4.5 meters per minute. That is, the glue of a beam with the length of 4.5 meters and a thickness of 165 millimetres, is hardened in one minute. The constraining factor on how fast the glue can be harden with this process is the beam thickness, according to Johansson. He provides another example of a beam with a thickness of 90 millimetres, and in that case the machine is able to harden the glue six meters per minute. Provided a similar machine could be found and implemented in Modvion's future production system, it is not unreasonable to expect a substantially faster hardening time than five hours and 45 minutes.

Utilising a similar furnace solution as the one at Moelven seems like the obvious choice. As the thickness of the layers is only 24 millimetres, it is reasonable to expect an even quicker hardening time than the hardening times in the presented case. However, in order to keep up the with the demand, provided that the distance to and from the stations is as given in appendix D.3, the speed of the furnace line only needs to be 3.75 meters per minute. As this speed is lower than the speed Moelven uses for their 90 millimetre beams, it seems reasonable to expect the furnace line to be able to move with this speed and still harden a thinner object.

With such a speed, the one-pieces flow could continue, and no large buffer would be required to hold all the drying layers. Once the glue has hardened, the pressure from the platform will be released, and the layer will be picked up using a suction cup traverse and moved to the next process, while the platform is returned to the previous station.

4.4.1.4 Make Slits

As stated in 2.2.3, the circular cut profile of the slits lead to a large amount of glue and/or filler material being used. Therefore, it was deemed important that the future solution avoided this problem altogether. In order to cut the slits, there exist several solutions besides the usage of a circular saw blade. One solution would be to mill the the slit. This would once again leave a circular cut profile in the slits, as can be seen in the figure 4.13.

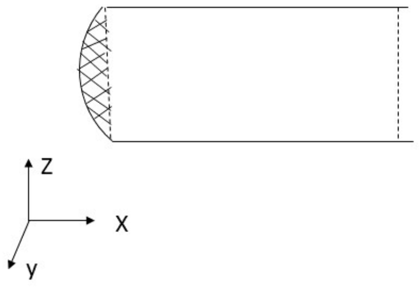


Figure 4.13: Visualisation of cut profile while milled from an above perspective

However, due to the smaller radius of the milling tool, as opposed to the radius of the circular saw blade, the additional space that needs to be filled with glue is smaller in volume. At the same time, it could prove difficult to find a milling tool that is strong enough to mill at the required speeds to keep up with the demand, but at the same time is small enough to fit within the slits dimensions.

A second option is to saw the slits with the help of a straight saw blade. This would lead to a completely straight cut profile. The cut profile can be seen in the figure 4.14.

Figure 4.14: Visualisation of cut profile with a straight blade from a side perspective

This solution would be optimal, as no glue is required to fill up the slits. Possible saw types include, but are not limited to, reciprocating saws, jig saws and band saws. However, through consultation with Jan Bragee, a research engineer at Chalmers, it was conclude that there would exist a significant risk of failing to keep a straight line throughout the cut with reciprocating saws and jigsaws. This is due to the fact that the blade would move back-and-forth over the work piece. This is a risk as it could lead to vibrations in the material that could move it while the cut is being made. This would lead to a cut that is warped or crooked. However, with a band saw, the cut would always be made in one direction over the work piece, preferably so that it is pushed down. This would reduce the risk of moving the work piece during the time the cut is made, as the vibrations that the work piece is experiencing during the cut is lowered. Therefore, a band saw seemed as the best blade type as this would generate the best cut profile, with the lowest chance of a crooked cut.

The typical problem with band saws is the size of them, making them difficult to move around. Therefore, its is usually the work piece that is moved or altered in angle to the blade when using a band saw, as opposed to the saw itself. However, in this case, the work piece itself is a 25 meters long and close to 3.6 meter wide layer that could be likened to a giant wooden plank. In other words, moving the work piece with the required precision in this scenario could prove very hard. However, with the use of a tool similar to that of a small chain saw, these problems could be avoided. As the cutting tool has a revolving blade rather than a blade that moves back and forth, it is similar to a band saw. Thus, the same benefits of reduced vibrations can be obtained. Furthermore, as the size of the tool is smaller than a regular band saw, the saw could be moved while the work piece remains stationary. These types of tools already exists, albeit for manual tools. One example is *Bosch multi-tool Advancedcut*, which can be seen in Figure 4.15 [5].

Figure 4.15: Example of manual cutting tool with straight blade

By cutting the slits before the layers are assembled into a module, the size of the blades can be reduced, as they only need to cut through a maximum thickness of 24 millimetres as opposed to the full thickness of the module along with the braces of 240 millimetres. Moreover, if the slits cutting is performed when the module has been bent, the blade would need to be angled differently for each slit as the module has a circular shape. However, by performing the process for each individual layer instead, this problem would be resolved as the layers are straight. It was therefore decided that the best choice of the alternative methods to perform the cut was to do it with a straight blade.

As the slits will be placed with a C-C measurement of 40 millimetres, as discussed in section 2.2.3, the number of slits per module varies depending on its size. However, as the module dimensions are known, see in appendix B.1, the range of number of slits per side of the module can be calculated according to the equations below.

$$S_{max} = \frac{M_{max}}{C_c} = \frac{3.58}{0.04} = 89.5 \tag{4.11}$$

$$S_{min} = \frac{M_{min}}{C_c} = \frac{3.24}{0.04} = 81 \tag{4.12}$$

Important to note is that the overwhelming majority of the modules will have slits at both the top and bottom of them, meaning that the number of slits per module is roughly around 160-180 slits. For layers that are not 25 meters long, i.e that belong to a shorter module, the station will not be able to cut slits at both ends of the layer as the station is 25 meters long. However, the layers, and modules, that are shorter than 25 meters will always belong to the bottom section. The bottom and top section will never have slits at both ends since the bottom and top of the tower will be mounted to the ground or have a turbine mounted on top. These will be mounted with other solutions that are not within the scope of this thesis.

As the takt time for one layer is 4.4 minutes, it is hard to see how any manual cutting process of the slits will be able to keep up with the demand. Moreover, the process of cutting the slits is quite repetitive and standardised, with only the slight changes in the number of slits and their horizontal position between the different layers. Additionally, there are strict requirements on the precision of the processes, as the slits needs to line up between the different sections. Thus, it seems like an autonomous solution is the best fit for this station.

Autonomous cutting stations is nothing new, nor revolutionary. Large companies like Homag [21] or Sågspecilastien [37] both work exclusively with providing large, industrial cutting machines for wooden products. One concept for how the cutting machine could look is provided in figure 4.16

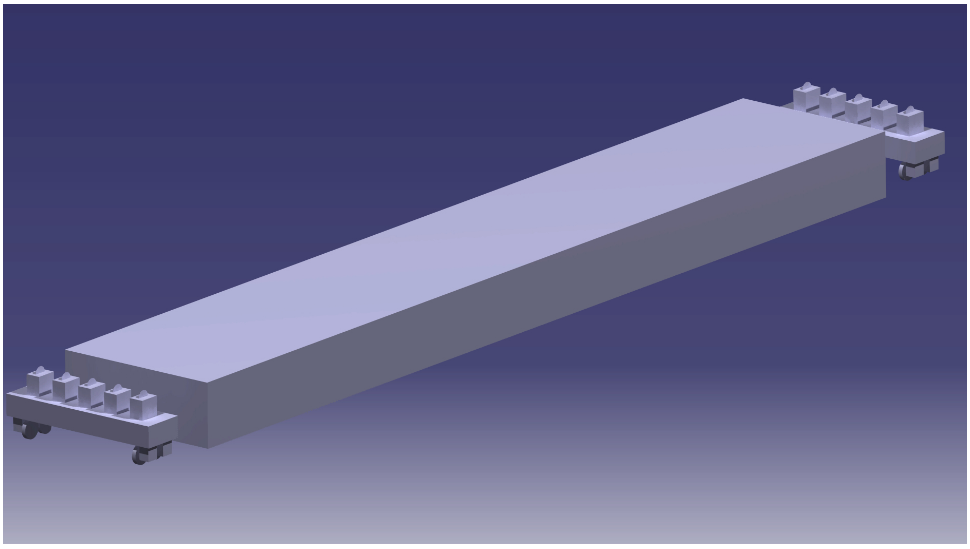


Figure 4.16: Visualisation of slits cutting station

The layer is moved and placed on the table with the help of a suction cup traverse and then the blades at both sides of the table cut the slits at the correct dimensions. Note that in order to be able to handle different layers, the blades will have to be able to move horizontally.

The process includes one lift, which is the lift from the slits station to the following station in the flow. The time it takes to perform this lift is calculated according to the second example in section 3.1.3.1. The distances that needs to be travelled during this lift is provided from the final layout plan of the plant, see appendix C.1.

A conservative approach was used when setting the cutting speed that the slits were made with. From the previously mentioned discussions with Hestergård, a cutting speed of one meter per second for modern, automate cutting tools was not at all an unreasonable high speed. However, when cutting the slits, the emphasise of the cut is on precision, as the cut will neither be applied to the full length of the layer nor be cut one at a time in the specific moment of time. Hence, the cutting speed will have to be lowered for this process. By dividing the cutting speed with a factor ten, meaning that the cutting speed in the slits cutting process was set to 10 centimetres per second, it was deemed reasonable that the feed rate was maintainable. During the cutting action, time was also added for redacting the blades once the cut had been made, move the blades to the next position and other necessary set-up times. For full calculations of the actions performed in the process, see appendix D.4. With all the times for each action preformed at the station known, the cycle time can be calculated to 3.56 minutes.

4.4.1.5 Gluing and Bending Process

The functions of gluing and joining the layers of sheets, attaching the braces and the pillars to the module, and finally bending the entire module into the desired shape have all been combined into one process. This is due to the fact that all of these different parts will be joined through the usage of glue, which all needs to be given time to harden under pressure once applied. As the glue hardens, no additional work can be performed on the work piece. Therefore, dividing this process into several, where each product is added and glued as well as hardened sequentially, would lead to an excessive amount of time spent waiting for the glue of the different joints to harden. If furnaces were used to decrease the hardening time, additional furnaces would have to be introduced to the system, which could prove costly. Instead, by applying all the glue at the same time, the fully assembled module need only harden once, leading to a more resource effective production.

This makes the gluing and bending process perhaps the most important process for the entire system, as the station will have to deal with the input from three separate part flows, each with their own takt time. Hence, buffers will have to be located at this station in order to balance the different takts. Moreover, as the station will include a lot of lifting with traverses, it is vital that these buffers are located as close as possible to the actual work area of the station. If the buffers are too far away from the station, each individual traverse lift will take too long time to keep up with the takt time of the station. The buffers are also needed to make sure that all the required material needed to build the module is available. For instance, the module requires eight LVL-layers to be assembled. However, up until this point, the layers have been treated in a one-piece flow, meaning that they will arrive at the bending process one by one each layer takt. The buffer is therefore needed to collect the batch of eight layers that are needed to build one module. Once all the required material is placed in respective buffer, the process will begin. Note that the takt time for the station will be 35.2 minutes, as the output is a fully assembled module.

The process will be carried out on a fixture that matches the inside of the module. The fixture will have a cylindrical appearance that has the same diameter as the inside of a finished module and the same conical shape. Furthermore, there will need to be grooves in the fixture where the pillars can be placed in order to get them in the right position once attached to the module. The position and number of these grooves will vary from each individual module due to that there are 32 pillars that run from the bottom to the top of the section. As the amount of modules per sections varies, and no section is able to evenly divided the 32 pillars across its innate modules this is problematic. Thus, Modvion are left with the case where some modules in the same section will have for example five pillars, whereas other modules in the same section have six. As the distance between the pillars is the constraining factor, the placement of the “first” pillar on each module will differ, as this needs to be adapted to the “last” pillar on the previous module. Thus, it is required that each module in the entire tower will have its own separate fixture. This means that there will need to be 50 individual fixtures for a 150 meter tower and 63 fixtures for a 170 meter tower at this station. The braces that belong to the module will also have to be accounted for in the fixture, this is done by giving extra room for the layers that become the braces at the top and bottom of the fixture. Furthermore, the fixture will need to have two guiding pins for the guiding holes mentioned in the section 4.4.1.2. This is so that when the layers are placed on the fixture, they will always be in the same place, even when pressure is applied. A visualisation of one of the fixtures used at the station can be seen in figure 4.17.

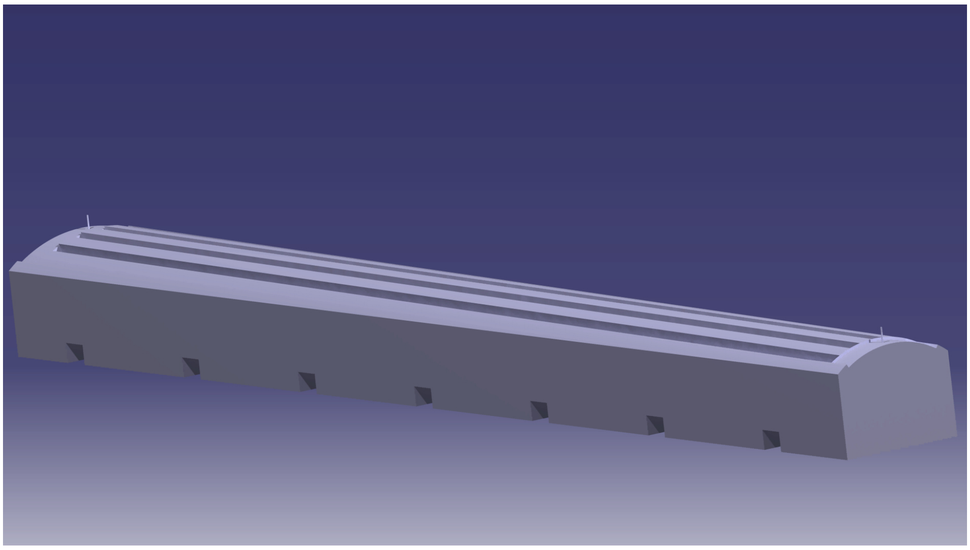


Figure 4.17: Visualisation of one of the fixtures used at the bending station

The process will be performed in the following steps. First, the initial layer of the braces as well as the pillars will be taken from their respective buffers and placed at the fixture. Secondly, glue is sprayed on the upwards facing side of the braces. This will done at both the top and bottom of the fixtures as there are braces at both locations. At each location an arm fitted with nozzles will move over the brace and spray a layer of glue as it passes over. The first application of glue is postponed as much as possible within the process as the glue has an assembly time of 30 minutes, which can be seen in appendix E. This means that as soon as the first glue is applied, there are only 30 minutes until everything has to be assembled and put under pressure or the hardened structure of the glue can not be guaranteed. The third step is that the final layer of the braces are placed at both the top end and the bottom end of the tower. The fourth step is that the two glue arms move forward and cover both the braces and the pillars with glue.

For the glue arms, during the crossing over from braces to pillars a setup is required. This is because the braces lie over the entire width of the fixture whereas the pillars have spacing between them. In these gaps between the pillars, no glue should be applied as this risk gluing the module to the fixture. Once the required glue has been applied, the arms will retract from the fixture. The next step is to apply the first layer of the actual module. Once a layer has been placed at the station the glue arms will apply glue over it once again and then retract, with each arm covering half the length of the module. This will be repeated eight times until all the layers of the module has been put in place. However, the gluing arms will not glue on the eight layer since it is the most outer layer in the module.

Once the pillars, the braces and layers for the module itself all have been placed on the fixture and glued, the final step is to bend the module into the desired shape. This is done by wrapping the fixture and the module with straps at evenly spaced intervals along the length of it. The straps will be tightened and thus apply a force that bends all the layers into the both circular and conical shape as they form after the shape of the fixture. The length of the module is 25 meters and a strap will be placed every 3 meters. This means that there should be 8.3333 straps on the module which is rounded up to 9 in order to ensure that there is enough pressure to bend the module and that there is not too much spacing between the straps where deformation or shapes bent in a non-desired way are created. The straps will be applied by two teams starting at each end of the tower as this ensures that the pressure is applied more evenly in comparison to starting at only on end. This will decrease the risk of warping the module or creating any other shape issues. As the module needs to be under pressure under the full hardening time of the glue, the full fixture will be lifted to the next station, with the module strapped in. To summarise, all the required steps performed in the process, along with their sequence can be seen below:

1. Pillars and the first layer of braces are placed in the fixture.

2. The glue arms, which each are located at one end of the fixture, applies glue to only the braces by moving across them and spraying glue. Hence, the clock for the assembly time of 30 minutes is started.

3. The second layer of braces are placed upon the glued braces.

4. The glue arms each move across one half of the fixture and applies glue to both the pillars and braces.

5. The first module layer is placed upon the fixture.

6. The glue arms apply glue to the module layer by moving across on half of it each

while spraying glue. At the same time, the next layer is lifted to the station.

7. Steps 5 and 6 are repeated for until all eight layers have been assembled.

8. Pressure is applied over the entire module at evenly spread out points through usage of straps. This step must be performed within the assembly time of 30 minutes.

9. The fixture, with the module still under pressure, is lifted to the next process.

For full calculations of the cycle time of the process, see appendix D.5.

4.4.1.6 Harden Glue

Due to the same reasons as given in section 4.4.1.3, a furnace will be used to speed up the hardening time of the glue. However, this time, the takt time is 35.2 minutes, instead of the 4.4 minutes that are used at the hardening furnace for the gluing vertically process. Additionally, the thickness of the modules are in total 240 millimetres, meaning that the speed of the furnace needs to be reduced, as the relation of material thickness and hardening time as pointed out by Johansson in section 4.4.1.3 still applies here.

The process will entail one lift each takt, as the module will have to be picked up once it has passed through the furnace and moved to the next station. The distance this lift entails is gained from the final plant layout and the time the lift takes is calculated.

With the lift time and the distance that the module needs to travel on the furnace conveyor belt known, the slowest possible speed this movement can be done in can be calculated using the second example in section 3.1.3.1. Doing so leads to a slowest possible conveyor speed of 1.75 metres per minutes in order to keep up with the demand. This can be compared with Moelven's speeds of 6 and 4.5 metres per minute for a 90 respectively a 165 millimetres thickness, while the module has a thickness of 240 millimetres. As the speed of the line is substantially lower than both of these examples, its is considered to be an realistic speed.

Obviously, one can allow the glue to harden without using a furnace. As the hardening time of the glue is 3 hours and 45 minutes [2] and the takt time is 35.2 minutes, 9.8 takts would transpire before the first takt's glue has dried. Thus, a buffer of in total 10 takts material would have to be used to allow each module to fully dry before being sent to the next station in the flow. This option was not chosen due to the negative effects on throughput time, layout size and number of WIPs this would have.

4.4.1.7 Surface treatment

Once the glue has dried and the module has achieved its desired curved shape, the following step will be to surface treat the module. This will be done at a station that could look like the concept visualised in Figure 4.18.

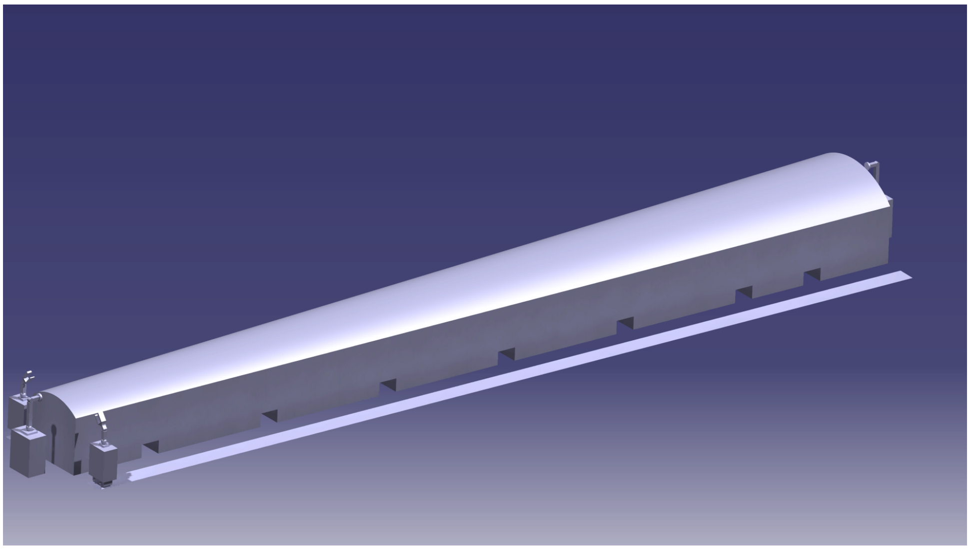


Figure 4.18: Visualisation of concept for surface finish station

The fixture will exit the furnace with the module still on it. From there, the module will be lifted off and placed at a station where all the edges of the module are exposed. As the surface treatment aims to remove any excessive glue material that has been pushed out during the bending process, there exists multiple surfaces that needs to be handled. The surfaces in question are marked out in Figure in red 4.19

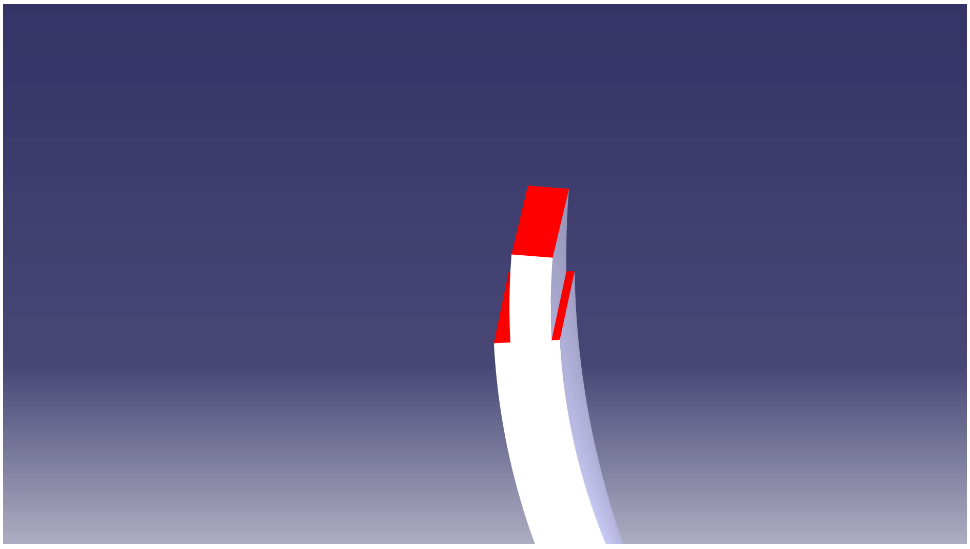


Figure 4.19: Highlighting of areas that are in needed of surface treatment

As multiple surfaces needs to be handle on the male profile of the module, one is left with two options. Either each surface is processed in succession, meaning that one surface will be treated at a time, or all surfaces are processed at the same time using a specialised tool. In order to be time effective, a choice was made to process all surfaces at the same time. However, this forced the station to have a specialised grinding machine, uniquely designed for the shape of the male profile that is to be surface treated. A concept for how that tool could look can be seen in figure 4.20. As the grinding has to be done along the full length of the module, the tool will have to be movable as well. This was solved through putting the tool on rails that ran alongside the module length, as can be seen in Figure 4.18.

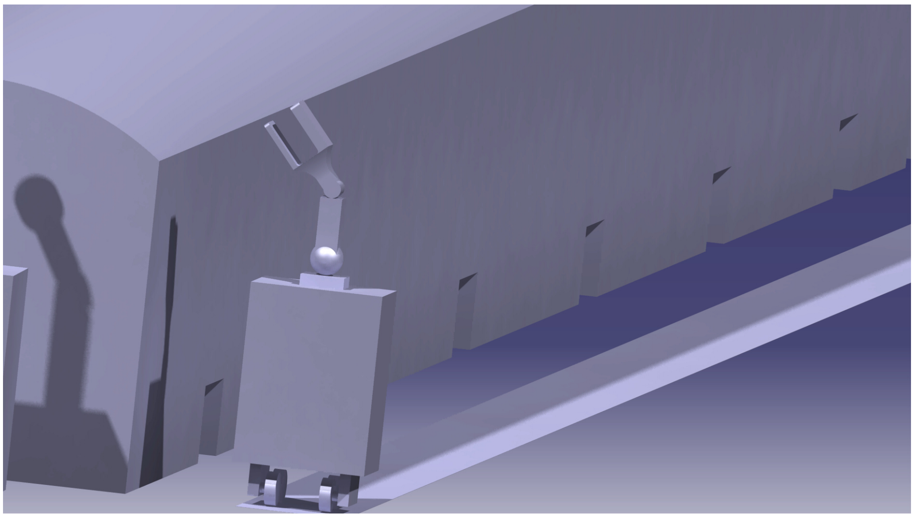


Figure 4.20: Visualisation of Surface Treatment tool for male profile

The edges on the short ends will be treated by an automated robot that will be equipped with a disc grinder that has a diameter that is slightly more than half the thickness of the edge, meaning that two passes is needed in order to cover the entire area. Thus, the robot will grind from one end to the other and then back again. The robot can also be seen in figure 4.18. For full calculations of the cycle time of the process, see appendix D.7.

4.4.1.8 Coating of Module

The final process of the system is to apply coating to the module so that the tower is able to withstand the wear and tear of nature for 20-plus years, as this is the product life time of a wind turbine tower [47]. The coating will be applied in three layers:

1. A primer,that has similar properties to a coating material known as TEKNOFLOOR 110F
2. A base layer, which will be similar to TEKNOPUR 300 - 800
3. A top layer, which also will resemble TEKNOPUR 300 - 800 in properties

Obviously, the coating material will have to harden before a new coating layer can be applied or the module can be handled. The hardening times for the different coating material are all known as they are similar to the material presented in each respective product sheet [38], [39]. From these product sheets, the hardening time of the primer material and material used for the other layers are given as four hours and less than two minutes respectively, provided that the work piece temperature is

23 degrees Celsius. Furthermore, it can also be read that the hardening time of the coating material is heavily affected by the temperature of the work piece, just as the glue in the previous processes. Moreover, due to safety reasons, it is important that the coating process will be kept in a well-ventilated and separate area, as the coating material is toxic if inhaled excessively.

Most importantly, the hardening times for the two different coating materials is radically different, with the primer material having a hardening time of four hours whereas the other layers harden in less than just two minutes. From a production stand-point, this difference is important, as the module cannot be handled during the time that the coating material dries. With a hardening time of less than two minutes, this will not be that big of a problem, as that represents a relatively small part of the overall takt time. However, if the module needs to be stored during the hardening time of four hours, a buffer with capacity to store as many takts as required will be have to implemented. By dividing the hardening time of four hours with the takt time for modules (35.2 minutes), it is found that seven takts will transpire during the hardening time of the primer. Hence, a buffer with a capacity of at least storing seven modules during their hardening time is required after the primer coating material has been applied. However, as discussed in section previously and seen in the product data sheet [**?**], the surface temperature of the work piece heavily affects the hardening time, with a higher surface temperature drastically reducing the hardening time of the coating material. Thus, using a furnace to heat up the module as the coating material has been applied could remove the need for the previously mentioned buffer altogether. This would be beneficial from multiple points of view. Firstly, the number of WIPs in the total system will decrease. Secondly, no additional space for the buffer is needed to be allocated in the factory, making it possible to have a smaller plant. Thirdly, the throughput time of the factory would decrease, as less time is spent in a buffer. Due to these benefits, the suggested solution chosen uses a furnace. The suggested solution for the process can be seen in Figure 4.21.

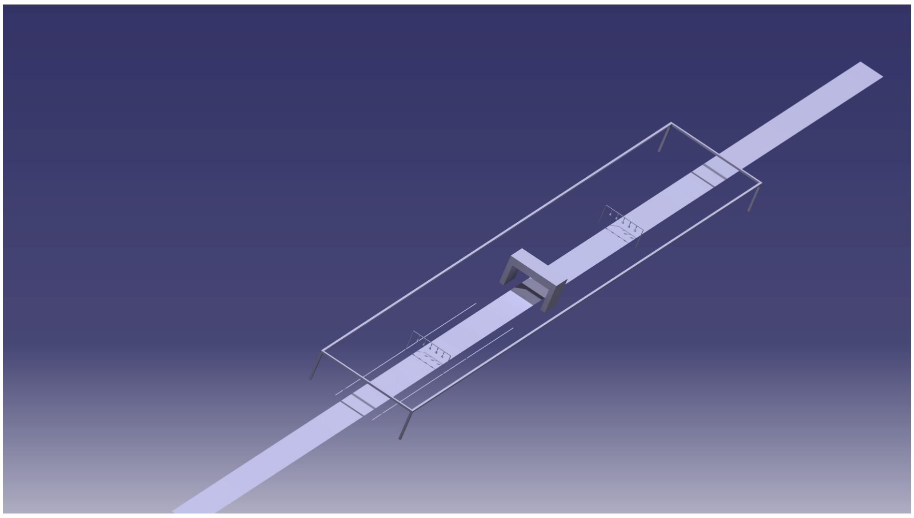


Figure 4.21: Visualisation of the Coating Station

The station will work as following. The takt will start with the module arriving from the surface treatment station and placed on a conveyor belt that will carry it into the sealed off coating area, through the furnace and finally allow the module to exit the sealed off area and being carried on wards to the final storage. Before the conveyor belt starts to move, the guiding holes that were used during the bending of the module will be plugged. This will by done manually. Once the holes have been plugged, the conveyor belt will move the module into the coating area. The first step will be to apply the primer coating layer to the module. To apply the primer, an arm equipped with an air nozzle that sprays the coating material onto the module is used. The conveyor belt will move the module under this arm, allowing the arm to remain stationary throughout the process. In order to make sure that the coating material is applied to the entire outer surface of the module, it is crucial that the nozzles are able to move vertically, horizontally and even alter their spraying angle. The arm along with the nozzles can be seen in Figure 4.22.

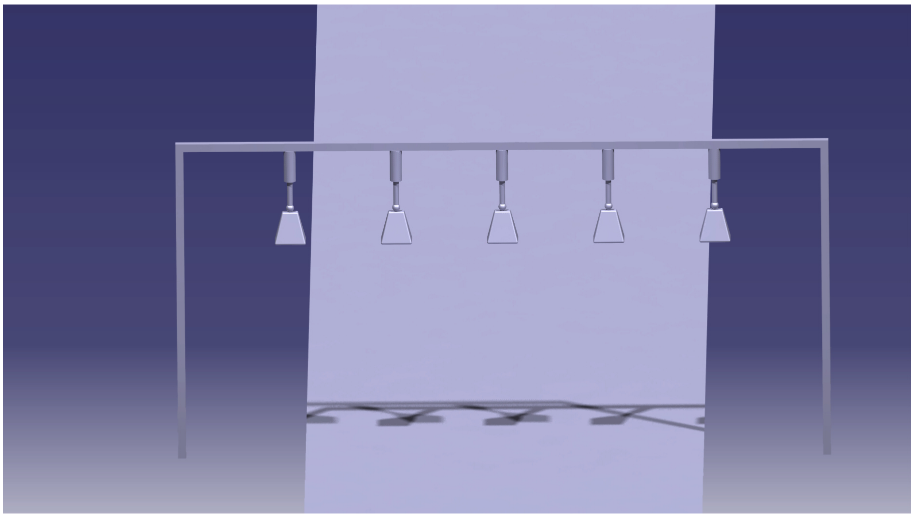


Figure 4.22: Visualisation of the arm equipped with nozzles to apply the primer coating layer

When the primer coating layer has been applied, the module will continue straight through the furnace. Here, the temperature of the work piece will be increased and thus a substantially quicker hardening time will be achieved. It is assumed that the hardening time when the work piece is heated for the coating material follows a similar trend as the glue used previously in the system. In the glue's case, a furnace temperature of 80 degrees Celsius allowed for speeds of up to 6 metre per minute when the thickness of the work piece was 90 millimetres [27]. However, in the case with the coating material, the coating layer will always be applied at the surface of the work piece, meaning that the heat from the furnace will not have to penetrate the whole thickness of the work piece, but rather just the thickness of the coating layer. This allows for a even quicker speed through the furnace in the coating station compared to the hardening of the glue.

Once the primer layer has hardened, the module will continue to the part of the conveyor belt where the second and third layers of coating are applied. This area can be seen in figure 4.21 as the area directly after the furnace. Once again, the final layers of coating will use TEKNOPUR 300-800 as material, which have a substantially shorter hardening time compared to the primer material. Thus, no furnace is needed to speed up the hardening time of this coating material. The final layers will be applied to the module using a similar arm equipped with nozzles as used to apply the primer layer. This arm will remain stationary while the module passes under it on the conveyor belt while applying the first of the final layers. However, when the applying the final layer of coating, the arm will move along the length of the module while the module itself remains still. Thus, the arm will be placed on rails that run in parallel with the conveyor line. By applying both layers using the same nozzles and arm, less investment cost in equipment is needed as the same tools are used for both. Moreover, the total length of the conveyor belt and coating area is reduced. Once the final layer has been applied, the module finally exists the coating area and is lifted with the help of a traverse to the output storage before being shipped off to the tower construction site.

As both the modules and the external vertical lids will have to be coated as a final step in both flows, an effort was placed on doing both of these coating process within the same coating area. As the demand of modules and vertical lids are equal, the takt time for the coating stations needs to be halved, compared to the takt time of the previous module flow processes as it now has to fit in twice the amount of products. As a result, the takt time of the coating station is 17.6 minutes, instead of 35.2 minutes. Through dividing the entire length of the distance that the module will have to move on the conveyor belt with the time left of the takt time once the time for plugging and the final lift to the output storage have been subtracted, the speed of the conveyor belt was gained. Through this calculation, it was found that the conveyor belt had to move at the slowest with a speed of 7.95 metres per minute through the furnace. For full calculations of the cycle time, see appendix D.8.

4.4.2 Vertical lids flow

The processes needed to perform the functions presented in section 4.3.2 will be presented below. Note that the order of the processes will not necessarily line up with the order of the functions, as functions may have been combined into one process or changes in sequence may have been made to improve the flow of products.

4.4.2.1 Cut vertical lids

In this process, the function covered in subsection 4.3.2.1, is performed. The function is performed as the first step in the flow to facilitate the future handling of the lids at later processes. The process begins with lifting a sheet from the input storage to the work station with traverse. As the intended width of the lids is 0.480 metres, and the raw material sheets are 1.8 meters wide, three full lid layers can be extracted from one sheet. Hence, once the sheet has been placed at the station, three blades will run in parallel along the full length of the sheet. This will result in three desired lid layers, and one scrapp piece. At the same time as the blades are preparing the cuts, a guiding hole, identical to those used in the module bending process, will be drilled at both the top and bottom of two of the lid layers. These guiding holes will be used during the bending phase of the lids. Some of the drills used for drilling the holes can be seen in Figure 4.24. Note that the vertical lid consists of one external vertical lid that requires two layers and an internal vertical lid that only requires one layer and hence can not be bent. As the third lid layer will be used for the internal lid, no guiding hole is required there. Once the cuts and holes have been made, the layers are lifted off, one by one using a traverse, to the following process in the flow, as space is made available at the following station. The scrap piece is also lifted using the same traverse to a recycling buffer. The cutting station for the vertical lids can be seen in Figure 4.23. If the lid should be included in the special case order where the bottom section's height will be smaller than the standard 25 metres, the lid must also be shorter as well. Thus, a cut along the width of the sheet that guarantees that the correct layer height is achieved will be performed in these special cases before any of the previously mentioned process steps are taken.

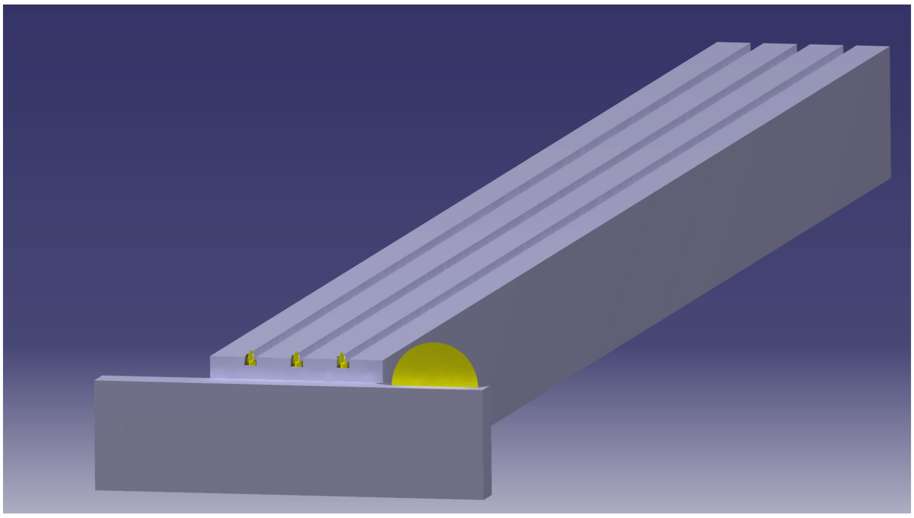


Figure 4.23: The cutting station used for vertical lids

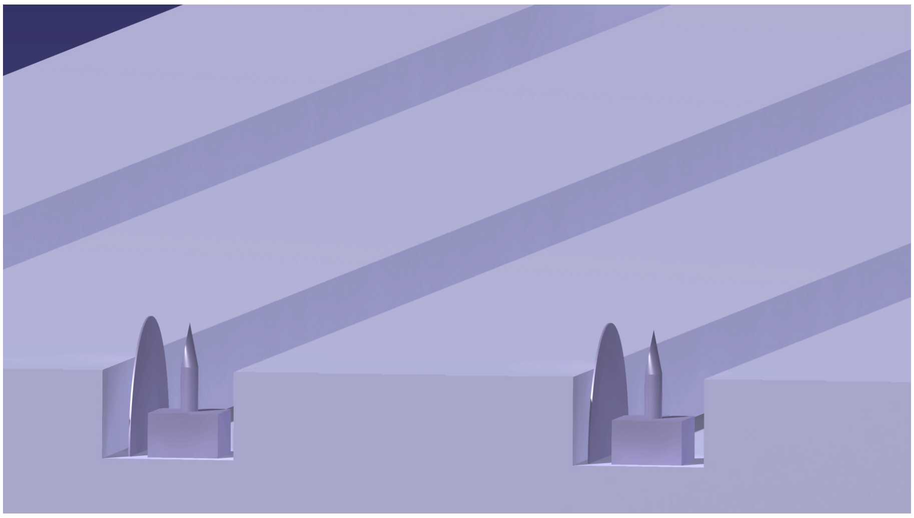


Figure 4.24: A close-up on the blades and drills

The cutting speed used to calculate the cycle time in the process is set to the same speed as provided by Hestergård, one metre per second. The time each lift takes is calculated. The distance that needs to be covered in each lift is provided from the final layout plan, see appendix C.1. For full calculations of the cycle time, see appendix D.9. The cycle time of the station is found to be 6.28 minutes, meaning that a large overcapacity exists at the station as the cycle time for a vertical lid is 35.2 minutes, as provided in section 4.2. However, the overcapacity may be reduced by allowing slower cutting speeds or by only performing the process periodically. Moreover, the excess time could be used to perform maintenance activities, administrative work or other work activities that lies outside of this projects scope. However, as the productions system strives for a one-piece flow, the overcapacity is left as is.

4.4.2.2 Make slits for vertical lids

The slits process for the vertical lids is nearly identical to the slits process used in module flow. The slits process is placed ahead of the bending process to simplify the process, as only straight work piece needs to be handled. Identical blades will be used as those used in the module flow process due to that the circular cut profile should be avoided here as well. The same cutting speed of 0.1 metres per second will be used and even the station itself is nearly identical to its twin process in the module flow. The station can be seen in Figure 4.25.

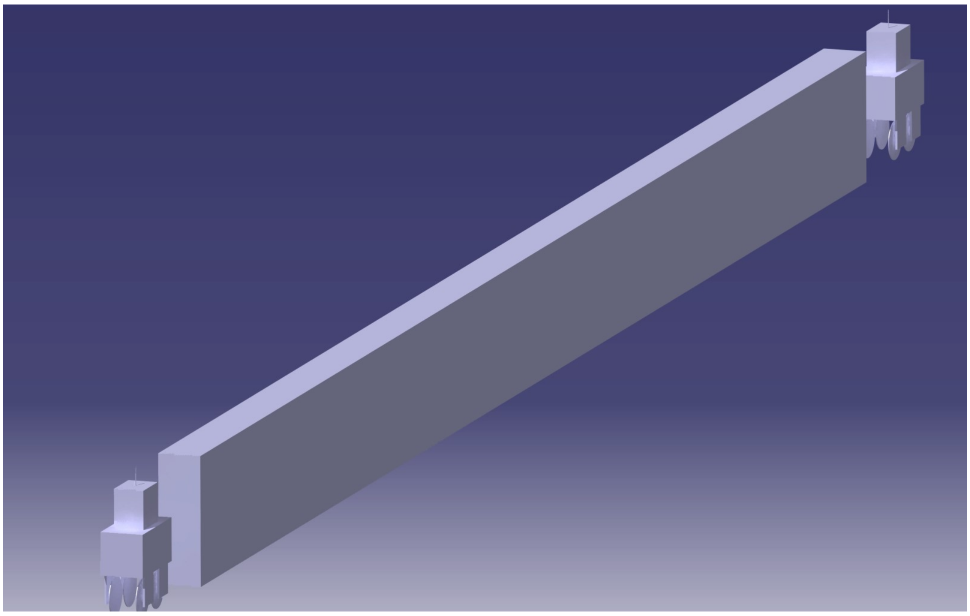


Figure 4.25: The slits station used for vertical lids

However, due to the much smaller width of the vertical lids, compared to the modules, each side of the lid will have a maximum of twelve slits, which can be compared with the 89 slits needed for the modules. Hence, the process of cutting the slits will be much shorter in this version of the process. Once all slits have been cut at the top and bottom of the lid layer, it is moved ahead to either the next process in the flow if it is a layer that will be used in the external vertical lids, or onwards to the final output storage if it is a layer is to be used as a internal vertical lid. The cycle time of the station is calculated as 15.54 minutes. Once again, this represents an overcapacity as this is roughly half the takt time. However, as state before, this time can be spent on other additional activities such as maintenance or administrative work. The process could also be performed periodically. For full calculations of the cycle time of the process, see appendix D.10.

4.4.2.3 Bending external vertical lids

The process of bending the external vertical lids is somewhat similar to the bending process for the module flow. However, as only the external lids are to be bent, no pillars nor braces needs to be attached. Hence, the problem with each module needing a individual fixture is eliminated. Instead, each lid within a section of the tower can be bent using the same fixture, as they will have the same bent shape. Hence, the require amount of fixtures drops from 50 to 6 for a 150-metre tower. An example of a fixture used at this process can be seen in figure 4.26.

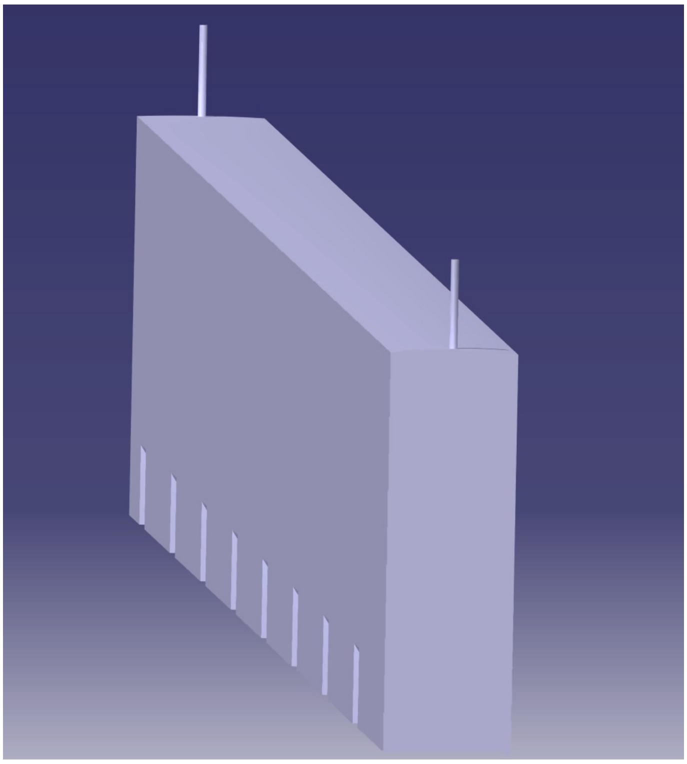


Figure 4.26: An example of a fixture used in the bending process for vertical lids

The process itself follows the same steps as the ones performed in the bending process of the module and the same principles apply. However, due to the fact that no pillars nor braces, in combination with the fact that only two layers are to be bent as opposed to eight as in the module, the number of lifts required are drastically reduced. This leads to the cycle time being reduced as well, which is calculated to be 10.4 minutes. All calculations of actions preformed at the station can be seen in appendix D.11. Once again, this represents an overcapacity in the process, as the takt time is 35.2 minutes.

4.4.2.4 Harden glue and surface finish

The following process includes both the function of hardening the glue applied in the bending process of the external vertical lids and the surface finish of the same lids. The functions were combined into one process as the cycle time of the each function by themselves were low enough that combining them into one was possible. By doing this, the WIPs and the throughput time of system is decreased, making for a more effective system.

The process begins with the fixture from the previous process, with the vertical lid strapped onto it, sent through a furnace to decrease the hardening time of the glue. Important to note is that the external vertical lids are only two layers thick, meaning that a they have a total thickness of 48 millimetres. This is about half of the thickness of the example given by Johansson. In the example, a 90 millimetre thick work piece could be harden with a speed of 6 metres per minute. With a conservative approach used, the same speed was set for the lids, despite that they are only half as thick.

Once the lids have hardened, they are lifted to the surface treatment area with the help of a traverse. Here, the remaining time of the takt is spent on grinding the sides of the lid, as well as move it to the final step in the flow. As no benchmarked speed of the grinding process has been found, the grinding speed is calculate using the principles in the second example in section 3.1.3.1. This provides that in order to keep up with the demand, 1.5 centimetres needs to be grinded per second. However, it is believed that this speed could be increased drastically if needed. The surface treatment station is similar in looks and function to its twin process in the module flow. For full calculations of the cycle time of the process, see appendix D.12. The station can be seen in figure 4.27.

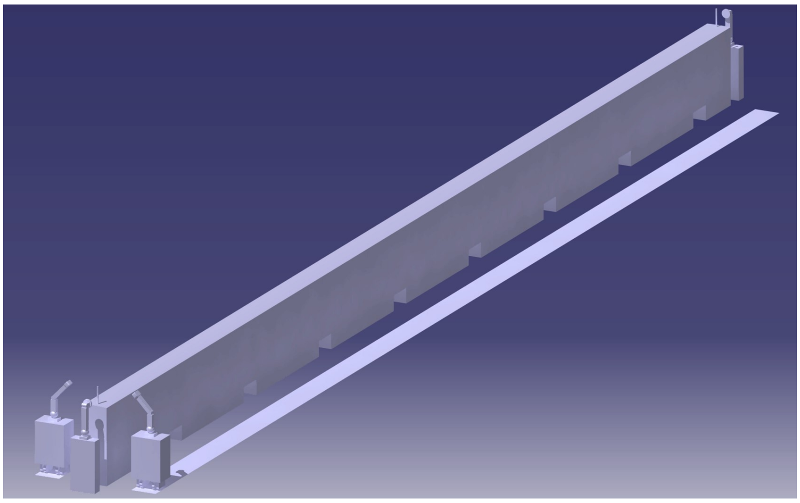


Figure 4.27: The surface finish station for vertical lids

4.4.2.5 Coating of external vertical lids

The final process in the flow is the coating of the external vertical lids. This will be done at the same coating station that is used in the coating of the modules. Hence, all steps of the process can be seen in section 4.4.1.8.

4.4.3 Pillar flow

The pillar flow will contain the processes needed to carry out the functions presented in section 4.3.3. Once again, the processes may not follow the same structure or sequencing as the functions did due to alterations done with the aim to improve the flows and the production system as a whole.

4.4.3.1 Prepare edges of beams

The beams are lifted from a buffer at the start of the line by traverse onto a milling machine where they are placed in a fixed position and at one end of the beam, fingers for a finger joint are milled out. Once the fingers have been milled out, the pillar is lifted from the current process onto the next process which is the gluing and joining of beams. Hence the takt includes in total two lifts. The milling station used in this process can be seen in Figure 4.28.

Figure 4.28: The milling station used in the pillar flow

The milling works on the same principles as the milling station in the module flow. This means that the same feed rate of 1 meter per second will be used for the milling. However, as the distance to be milled in this process is only 0.215 metres, compared to the 25 metres that is to be milled in the module process, the cycle time is far shorter. In fact, this process has a large overcapacity in cycle time, as the cycle time is only about half of the takt time. This overcapacity may be reduced by milling at a slower speed or by only using this process periodically and building up a buffer. This could be combined with doing other tasks that are beyond the scope of this project such as maintenance, administrative work or similar. However, for this project, in order to have the desired one-piece-flow, the overcapacity is left as it is. For full calculations of the cycle time of the process, see appendix D.13.

4.4.3.2 Gluing and joining of beams

When the beams are lifted from the previous process into this one, they are placed in a fixture that also works as a buffer. The fixture used can be seen in Figure 4.29. As can be seen in the figure, the fixture consists of two main parts, each with grooves that are large enough to fit a beam. Each groove in the two parts have a corresponding groove in the other part, where another beam can be placed. Hence, the grooves should be viewed as groove-pairs, rather than individual grooves.

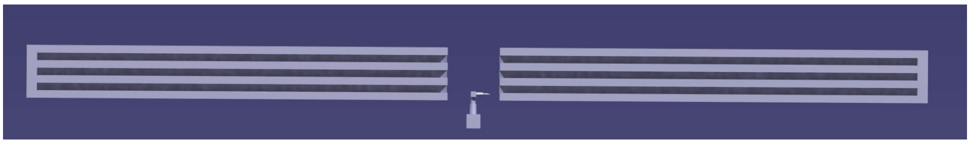


Figure 4.29: The fixture used at the gluing and joining of beams station

The beams are placed in the grooves so that the finger joints are facing the corresponding groove in the groove-pair. Once all groove-pairs have been fitted with beams, glue is applied to the joints. The glue is applied through the usage of the glue gun, as seen in Figure 4.30. When all three pairs of beams have their glue applied, the two parts of the fixture are pressed together with the required pressure for the glue hardening process. The entire fixture is lifted of to the next process and a new fixture is moved to the station, ready to handle the next three pairs of beams. For full calculations of the cycle of the process, see appendix D.14.

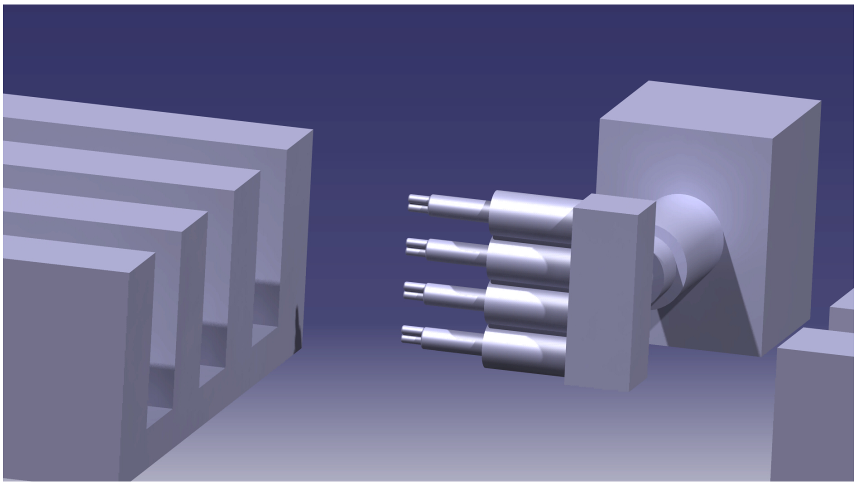


Figure 4.30: The tool used to glue during the Glueing and joining of beams process

The usage of the fixture contradicts the one-piece flow approach used throughout the production system. However, this is done because the takt time of the following process, the hardening of the pillars, is too short compared to the cycle time to have a one-piece flow. This due to the fact that if a single pillar is sent through the furnace at a time, the speed required to keep up with the takt time would be far greater than what the benchmarked example by Moelven suggests is feasible. However, by using a fixture such as presented above, a sort of batching is done by processing three pairs of beams at the same time. This leads to a takt time which is three times longer and therefore the feed rate of the furnace can be reduced by almost three times. Thus, the speed of which the pillars pass through the furnace can be reduced to speeds more in line with the benchmarked values, making sure that the glue is given sufficient time to harden.

4.4.3.3 Hardening of pillars

As mentioned previously on multiple occasions through out this report, the long hardening time of the glue is an issue with the short takt time that is needed in order to reach the high demand. This issue is resolved by using a furnace which heats up the temperature of the glue allowing it to harden faster. Furthermore, the furnace for this process is the same as the one used in section 4.4.1.3 as the two process are accomplishing the same goal.

The fixture from the previous process is lifted directly onto the furnace line which proceeds to transport the fixture through the furnace at a feed rate of just below 1.4 meters per second. This feed rate is far less than the benchmark provided by Moelven and has been calculated according to the logic used in the second example in section 3.1.3.1. Since the pillars have a thickness of 215 millimetres, it is crucial that the feed rate is lower than those provided by Moelven, since those dealt with thinner work pieces, while still being able to keep up with the demand. For full calculations of the cycle of the process, see appendix D.15.

Once the the entire fixture has gone through the furnace, the full-length pillars are either lifted to the pillar cutting process if a pillar length shorter than 24 meters is required or to the buffer ahead of the gluing and bending process for the modules. In some cases, where the pillars should be mounted on the internal vertical lids, the pillars are sent directly to the final storage area after this process for reasons covered in section 4.3.2.3.

4.4.3.4 Pillars Cutting

In cases where the tower will be a different length than the standard 150 meters, the last section of modules may be shorter. Thus, the pillars that are on the inside of such a module will also need to be shorter. This is accomplished by laying the pillar in a fixed position that can be adjusted to the desired length of the pillar. A saw blade, positioned perpendicular to the pillar, will cut across the width of the pillar, removing the excess material and thereby cutting the pillar into the correct dimension.

However, since the demand is based on a production of 150 meter towers, no demand for cutting pillars exists and therefore, no takt time can be calculated.

4.4.4 Braces flow

The braces will have its own flow that starts with raw material in the form of LVL-sheets and will end by either joining the module flow at the gluing and bending process or by being shipped out to the assembly site. This is because some of the braces shall be placed upon the inside of the internal vertical lid which can not be assembled until they are at the assembly site due to reasons covered in section 4.3.2.3.

4.4.4.1 Braces vertical cut

The input to the process is LVL-sheets which are 25 x 1.8 x 0.024 meters. The sheets will be lifted up from a buffer and placed in a fixed position, thereby ensuring that the cut is made at the correct position at all times. The station at which the sheet is placed has three saw blades. These three saw blades are placed with a 0.5 meter distance between them so that when they cut the sheet, the pieces will have the correct dimension. The process station can be seen in figure 4.31. The three saw blades will cut along the entire 25 meter length of the sheet so that three pieces that are 0.5 x 25 meter and one scrap piece are created. Furthermore, each saw blade has a drill paired with it. The drill will drill out on or two guiding holes, depending on if the brace is going to the module flow or continue in the braces flow. The holes will be drilled at the same time as the cuts are made. These two actions are done in parallel in order to save as much time as possible. The scrap piece will be lifted away and the three pieces of correct dimensions will be lifted to the next process which is the horizontal cut. For full calculations of the cycle time of the process, see appendix D.16

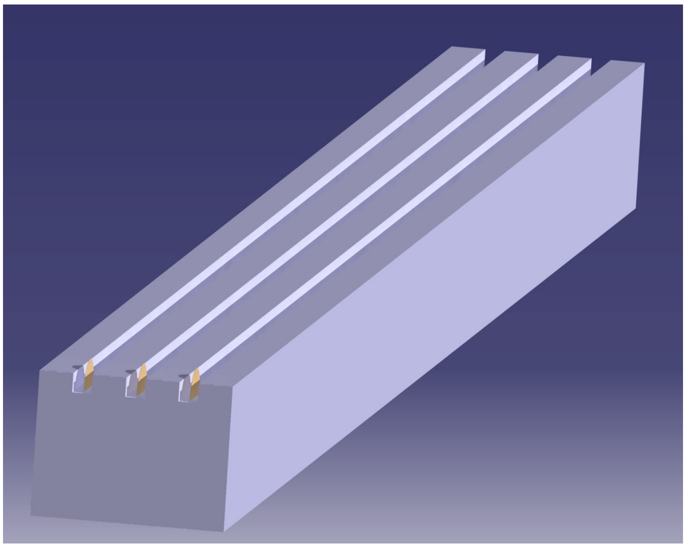


Figure 4.31: The cutting station used for the vertical cuts of the braces

4.4.4.2 Braces horizontal cut

Once the pieces arrive at the horizontal cutting process. They are placed on a table that has a saw blade at one end. The saw blade is positioned perpendicular to the table and will therefore cut across the braces. Furthermore, the table will be able to feed the piece forward, towards the blade, in a controlled manner. This means that the piece will be fed forward until one brace width has passed the blade and can be cut into the correct dimension. The station can be seen in figure 4.32.

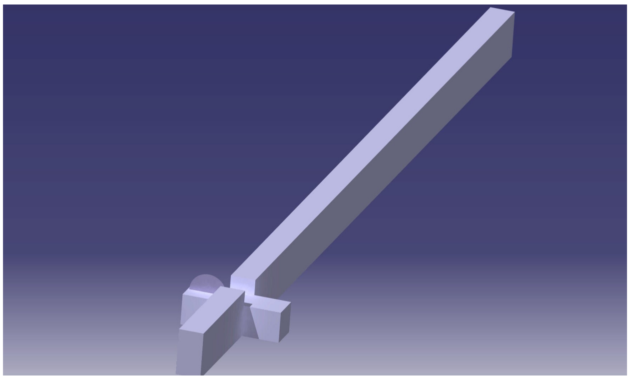


Figure 4.32: The cutting station used for the horizontal cuts of the braces

Once the braces have been cut they are lifted away to the next process which is the slits process. For full calculations of the cycle time of the process, see appendix D.17.

4.4.4.3 Braces slits

Since the entire purpose of the braces is to give extra material for the metal plates that are to be inserted into slit, the braces will also need to have slits cut out of them. This is true for both the braces that are going to be applied to the module and the braces that will be assembled on the internal vertical lid.

The principles of cutting the slits on the braces and how the actual station will look like is very similar to that of the slits process used in the module flow, with the exception that it is not carried out at both ends of a 25 meter long sheet. Instead, it will be done at one end of a 0.5 meter long sheet. Therefore, the station will only have the saw blades on one side of the fixture compared to the twin process in the module flow, which has saw blades on both sides. The station can be seen in 4.33.

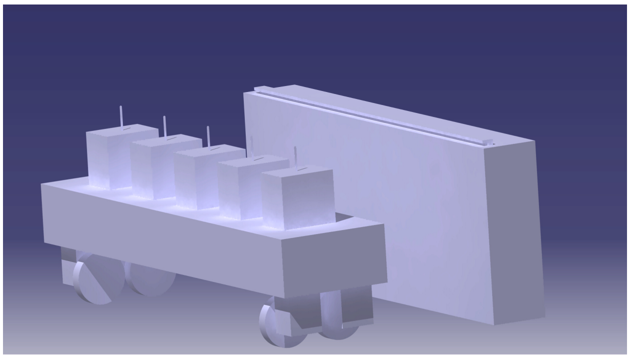


Figure 4.33: The station for cutting slits into the braces

Once the braces have their slits cut out, they will either be lifted to a buffer at the glueing and bending station in the module flow or to the next process of the braces flow, depending on if they are to be attached to a module or a vertical lid. For calculations of the cycle time of the process, see appendix D.18.

4.4.4.4 Gluing and bending of braces

The braces that are to be assembled onto the internal vertical lids will be two layers thick and will therefor be glued and bent into the correct shape. The station that does this is a smaller replica of the bending station in the module flow.

The braces are placed on a fixture which has the desired circular and conical shape that the braces will have to have in order to fit on the inside of the internal vertical lids. Furthermore, the fixture will have guiding pins that will match with the guiding holes of the brace sheets so that when they are pressed together they will stay in place and not move around. Once the first layer has been placed, a glue arm will spray glue over it and the next layer is placed. After the second layer has been placed, straps will be wrapped around the layers and the entire fixture and tightened and pressure between the layers is created. The entire fixture is then lifted off to a furnace that works by the same principles as the other furnaces in the production system only that it is considerably shorter at 0.5 meters, which is the length of the braces. Thus, saving space in the facility and reducing the cycle time as the fixture travels a shorter distance.

Once the fixture has gone through the furnace, the braces are lifted off to the next station and the fixture is lifted away in order to give room for the next one coming through the furnace. For full calculations of the cycle time of the process, see appendix D.19.

4.4.4.5 Braces surface treatment

Note that only the braces that are to be attached to the internal vertical lids reach this process. This means that the braces at this station will only have the dimensions of 480*500*0.48 millimetres. Hence, the part is much easier to handle than the other products in the production system and can even be lifted by hand instead of relying on traverses. Moreover, due to the small dimensions of the braces that are to be surface finished, it was concluded that the grinding could be done manually as the required speed that the grinding has to be performed at can be drastically reduced. The process starts with the braces being lifted from the furnace line onto a table where they are grinded manually. Once the braces have been surface treated, they are placed on an internal material supply train that takes them to the final storage area. For full calculations of the cycle time of the process, see appendix D.20.

4.4.5 Horizontal lids flow

The last flow is the horizontal lids flow. This flow entails the functions presented in section 4.3.5. The horizontal lids flow is completely separated from the other flows.

Meaning that it starts and ends without interacting or merging with any of the other flows. Furthermore, it also worth pointing out that this flow is the shortest one as it is made up of only two process.

4.4.5.1 Horizontal lids vertical cutting

The horizontal lids will be made out from LVL-sheets like most other parts handled by this production system. The sheets will be stored at a buffer close to the first station of the flow. From the buffer the sheets will be lifted onto a cutting fixture that is very similar to the vertical cutting done for the braces, which can be seen in Figure 4.34. In this case however, there will only be two blades as the horizontal lids are 0.7 meters tall instead of 0.5 and a 1.8 meter sheet can only provide two 0.7 meter pieces.

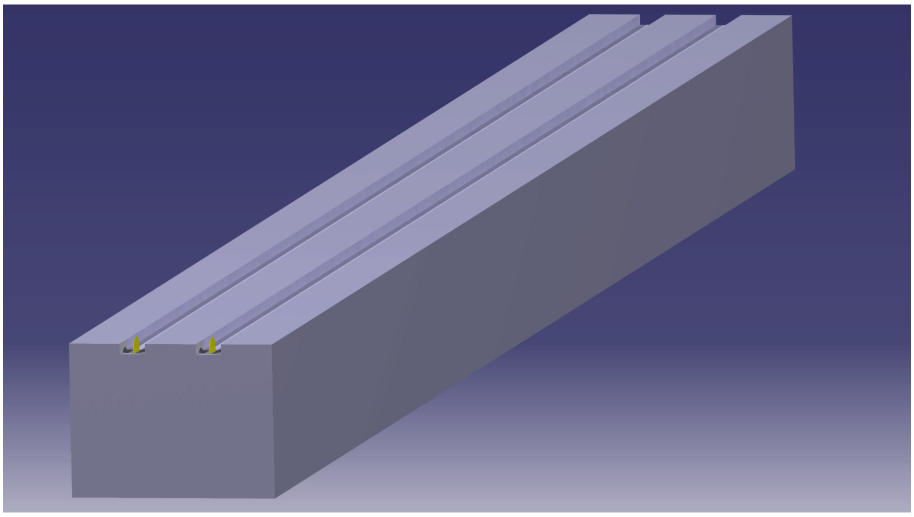


Figure 4.34: The station for horizontal lids vertical cut

From this, two correctly sized pieces and one scrap piece are created. The scrap piece is lifted away and the correct pieces are lifted onto the next station. For full calculations of the cycle time of the process, see appendix D.21.

4.4.5.2 Horizontal lids horizontal cutting

The correct pieces from the previous process are lifted onto a fixture that has the same design as the one used in the horizontal cutting of braces. The pieces are fed forward to a blade that cuts perpendicular to the piece at the desired interval, thereby giving the lids their correct width. Once the cut has been made, the lids are lifted off to the final storage. For full calculations, see appendix D.22.

4.5 Plant layout

In order to gain a sense of the size of the required plant to house this production system, a plant layout was made. The layout was designed through usage of the software Catia V5. A simplified model of each process was created in Catia V5 and all the processes were placed in accordance with the chosen line layout and sequence. The layout includes all the processes described above. The distances between the different processes used during the calculation of the cycle time of each process can be derived from the layout and can be seen in appendix C.1. The distances were intentionally kept as short as possible, as this meant that the lifts required less time in each cycle time as well as the overall size of the plant could be kept down. This would allow Modvion to use a smaller facility than otherwise possible, leading to a lower cost needed in facilities. Note that the layout does not include the size of the input or the output storage. This is due to the external supply chain, that determines how often material will be brought to the plant as well as how often products will be shipped away, falling outside of the scope of this thesis. The layout can be seen in Figure 4.35. The module flow is visualised as the green flow, the pillar flow as the red one, the vertical lids flow as the yellow flow, the horizontal lid flow as the purple flow and the braces flow with the colour blue.

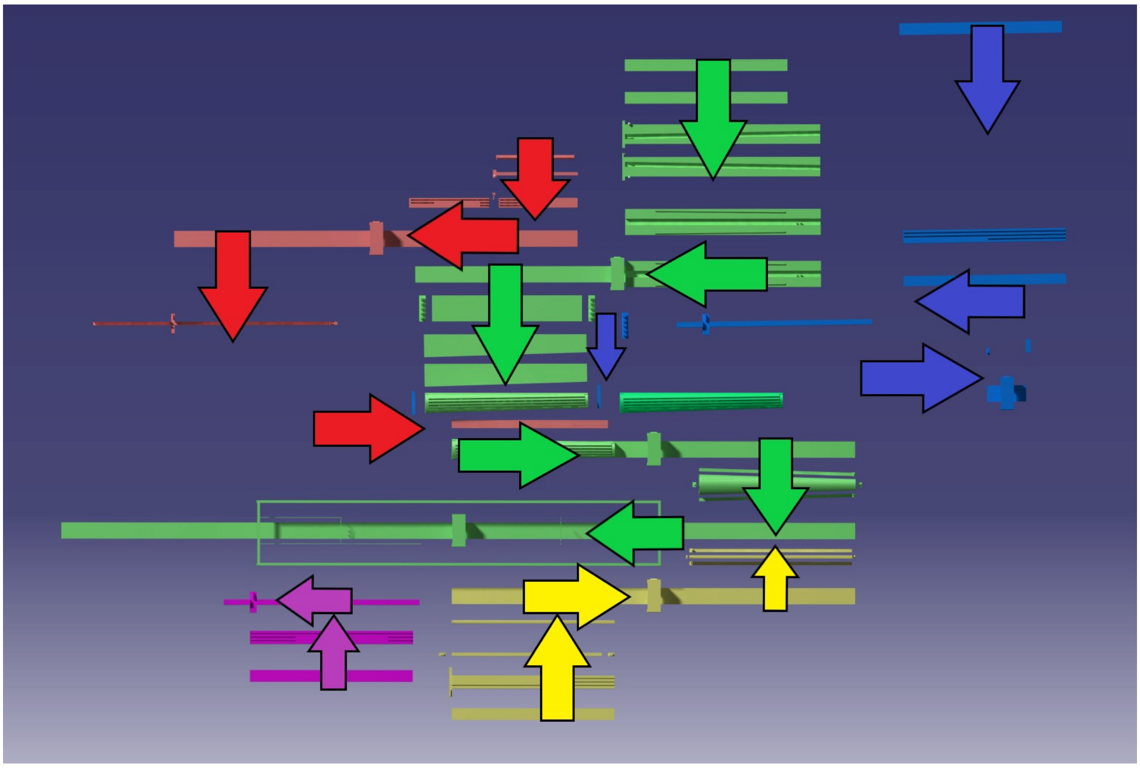


Figure 4.35: The layout of the plant

The total area of the layout shown in the figure is 15 150 square metres. This area is gained by treating the layout as a rectangle, multiplying the widest distance of the layout with the longest distance. Obviously, this is an oversimplification of the total area required for the production system but could act as a indication of the required size of the plant. In fact, the required area will be smaller since the dimensions of the rectangle are the longest and widest points of the production system.

5

Discussion

The final chapter of the thesis will include discussion about the results presented in chapter 4. Furthermore, the chapter will entail discussions about different design elements of the product, how they affect the production system as well as how they can be improved. This chapter will also discuss effects of the demand on the production system and the level of automation. The chapter will end by presenting the final conclusions of the thesis.

5.1 Overview of results

As shown in the results chapter, a production system able to produce wind turbine towers using Modvion modular design has been delivered. The presented system is able to deliver enough modules on a yearly basis to meet the demand set by Modvion as an objective, as all processes have cycle times equal or lower than the required takt time. The presented system has been complimented by a suggested layout as well. Thus, the purpose of the project has been fulfilled.

However, the suggested solution is not a finished concept, which it never was intended to be. Instead, it should be viewed as a base for future planning done by Modvion as the company continues to explore ways of increasing their production capacity. As such, the production system is not without it flaws, and in some cases entire key areas when it comes to production planning has been left out of the scope. Areas such as maintenance, the external supply chain of material and products and the order planning within the system have all been purposely left outside of the scope of the project but will all have a major impact on its performance. All these areas need to be further examined as the next step in the planning process of expanding the production capacity. Moreover, the suggested production system can be further optimised, with attempts of minimising the balancing losses and maximising the overall equipment efficiency (OEE), being recommend as future steps of research.

Even though the suggested solution should be viewed as a finished product, some take-aways from the suggested product system can be drawn, mainly dealing with the design of the product and what effects this has on the production flow. Other areas of discussion is the level of automation that should be used in the system and what effects the projected demand has on the system. Each of these areas will be reflected upon individually in the following sections.

5.2 Product design

The design of the module could be altered in favour of a more simplified and streamlined production with fewer and less complex processes. Different aspects of the product design will be discussed regarding how they are contributing to an overly complex and costly production.

5.2.1 Pillars

There are 32 pillars that are evenly spread out across the inside of each section. The purpose of the pillars are to provide stability and structural integrity to the tower according to Åkerström. However, as mentioned in chapter 4, the pillars will not be evenly spread out across each module in any section, leading to unique pillar positions for each module. Thus, 50 bending fixtures are needed to produce one 150-metre tower in the bending process. This makes the process complicated, expensive and space demanding. Note that only one of the 50 fixtures will be used at the station at a time, meaning that the other 49 will have to be stored somewhere else during this time. With each fixture being 25 metres long and between three to almost four metres wide, the required size of the storage area where the fixtures are to be stored during this time is not insignificant. Moreover, while the cost of each fixture has not been calculated in the project, one expert at Semcon estimated the cost of one fixture to be several million SEK. Hence, striving to minimise the number of fixtures should be prioritised by Modvion.

By standardising the number of pillars per module, as opposed to standardising the number of pillars per section, the number of fixtures required would be reduced. This is due to the positions of the pillars on one module not interfering with the positions of the adjacent module's pillars, as is the case currently. Thus, the pillars' position would be the exact same across all modules within the section. This would lead to the opportunity to use the same fixture to bend all the modules in a section, as they are identical in shape. This would mean that instead of 50 individual fixtures being required to build one 150-metres tower, it could be done with just six, as only one is needed per section. Obviously, the sequencing of the production orders would ultimately determine if it is possible to use a single fixture per section or more are needed to keep up with the takt. Nevertheless, the total number of fixtures would most definitely be reduced with this product design change.

5.2.2 Vertical joining

The male-to-male profile chosen for the vertical joining impacts the production system in several negative ways that could be avoided by redesigning it. Firstly, the design in it self requires the vertical lids to be added to help assemble the modules. This creates an additional flow in the production system as the lids will need to be constructed. Furthermore, by forcing the production to remove material, in order to create the male profile, time is spent on non-value adding processes which could be avoided. By having a design that avoids the usages of such lids, the additional flow could be removed and both money and layout space could be saved. Furthermore, the entire process of assembling the vertical lids at the site of the tower would be removed. Assembling the vertical lids at the site of the tower is a both long and complex process. This is because it involves lids, pillars and braces but more importantly it involves the complex process of bending the internal vertical lid while at the same time attaching the braces and pillars to it. By removing these strenuous processes from the assembly at the tower site it would be far easier, quicker and cheaper to erect a tower which is something desired by Modvion as mentioned in section 2.2.

An updated production layout that has implemented these changes can be seen in Figure 5.1.

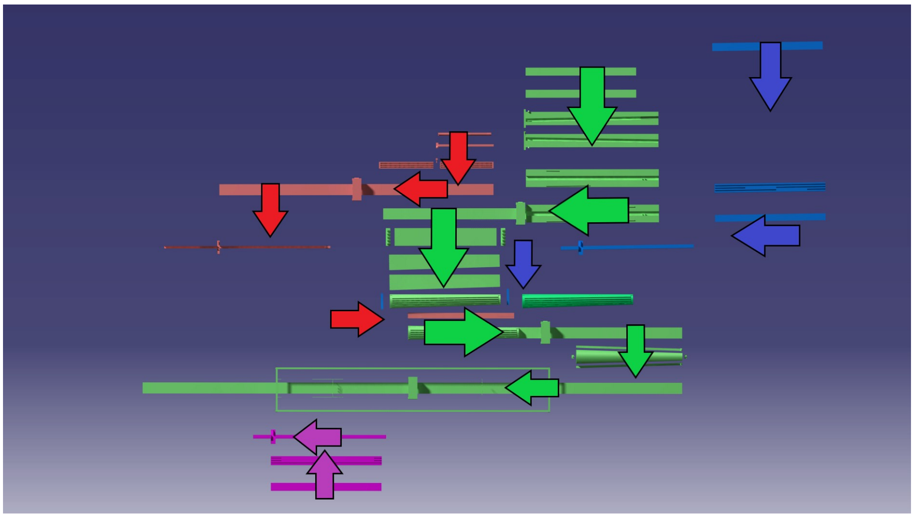


Figure 5.1: Layout of plant provided no vertical lids are required

A more logical solution would be to have a male-to-female profile, where each module has a male profile on one side and a female profile on the other. This can be achieved by displacing a number of layers of the module to one side in the gluing and bending process. This would result in a male profile on one side and a female profile on the other that would match each other. This is visualised in Figure 5.2. This approach would remove the need of the vertical lids entirely as the female profile would act as the lid instead. The removal of the lids would, as mentioned in the previous paragraph, remove an entire flow in the production system. Thereby reducing the initial cost of the production system, its running cost and save space. Thus, it would seem as there exist several benefits to removing the entire vertical lid by using a male-to-female profile.

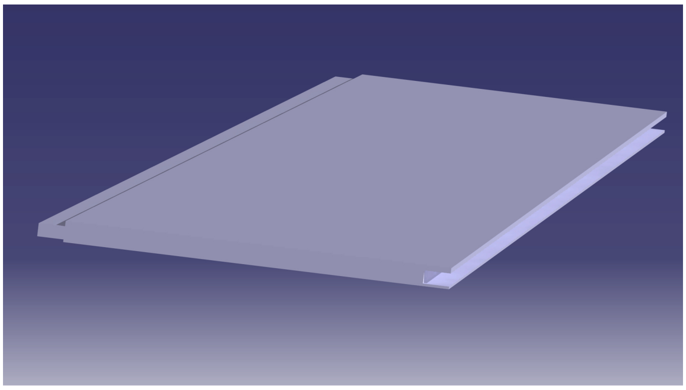


Figure 5.2: Alternative solution for bond between modules

5.2.3 Braces

The braces are added at the top and bottom of modules in order to give the perforated steel plates extra material as they are wider than the thickness of the module. In the production system, the creation of braces creates an extra flow that could be removed. As mentioned in the previous section, having extra flows leads to several large negative effects on the production system. Subsequently, the same type of improvements would be seen if the unwanted flow could be removed. This means that costs would be reduced and the required space of the plant would be reduced. Furthermore, it would simplify the gluing and bending process in the module flow as it would require less buffers around it, especially as the buffers for braces are at both the top and bottom of the bending fixture.

An option to having braces could be to increase the overall thickness of each module. By doing this, the extra material needed for the perforated steel plates that are to be inserted in each slit is achieved without the usage of any braces. Thus, the need for braces would be eliminated and therefore no additional flow for the manufacturing of the braces would be required in the system. An updated version of the plant layout without the flow of braces can be seen in 5.3.

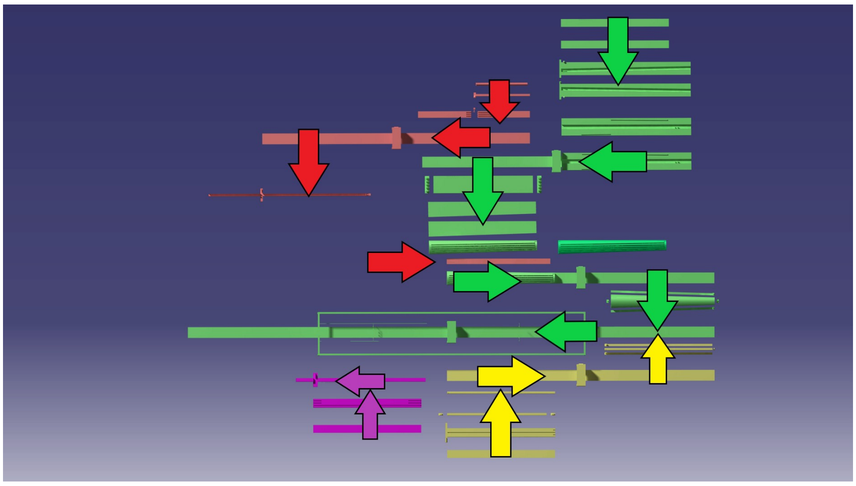


Figure 5.3: Alternative layout if flow of braces can be eliminated

This would bring several improvements to the production system, mainly reducing the investment cost as well as the running costs and save valuable facility space.

Furthermore, by increasing the thickness of the module, the stability and structural integrity would increase. Note that these are the reasons for why pillars are used in the module. Given that the extra thickness of the modules provides the same level of structural integrity as the pillars, it could be argued that the pillars are obsolete and could be removed from the product design which would remove the corresponding process flow in the production system. This would provide the same benefits as the removal of the braces flow from a production perspective. However, this would create a higher demand on several of the processes in the module flow as the modules would be thicker and made up of more layers, thus reducing the takt time of several processes in the flow. This means that the processes would be required to handle the extra demand in order for this solution to be viable. If it is concluded that no pillars are needed, the layout could be altered to the layout seen in Figure 5.4.

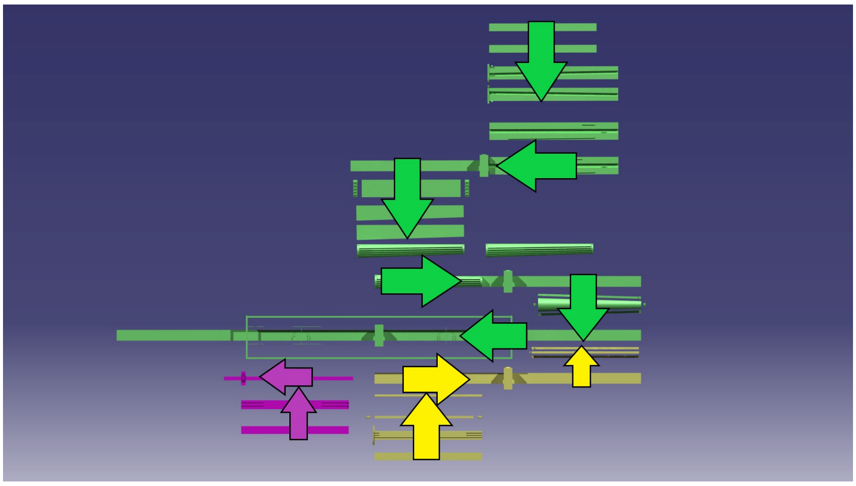


Figure 5.4: Alternative layout if flow of braces and flow of pillars can be eliminated

Finally, the additional thickness may prove costly and the economical benefits and downsides of said solution would need to be weighed against each other in order to establish if it is economically feasible. However, it seems likely that the extra material cost that comes with adding thickness to each module is outweighed by the economical benefits that comes from removing an entire separate line for braces as well pillars.

5.3 The effects of demand on production system

Due to the high demand of 100 150-metres towers annually, the takt times in the production system are all fairly short, as can be seen in section 4.2. Moreover, the large demand restricts which production layout options are viable for the system, as it more or less singles out a line layout as the sole realistic option. A lower annual demand would lead to longer takt times, which would have direct effects on how the production system operates.

For instance, lowering the demand would lead to more processes being able to be performed during the same takt, leading to a lower number of WIPs and less separate stations. Due to performing several processes at fewer stations, less time will be spent lifting parts or products from station to station. Thereby, the percentage of value adding time would be increased. The facility size would also be able to be decreased, leading to a smaller upfront investment being needed from Modivon. If the demand is lowered enough, perhaps even alternative layouts are viable again. This would allow for a completely different production system to be developed.

As touched upon in section 4.2, it is unlikely that Modvion will experience a demand of 100 towers annually from the start, but rather that the demand will slowly climb towards this figure as time progresses. This sentiment is based on comments from experts at Modvion, and could prove to be crucial when expanding the production capacity of the company. If a production system is built with capacity for a higher demand than needed, the system will be unnecessarily expensive. This is especially true if the capacity is gained through investments made in structural decision categories, such as facilities and equipment [24]. Thus, effort has been taken in the suggested solution to decrease the required investments in the structural decision categories and instead lean on the infrastructural categories, such as work force management. At the same time, building a production system where the structural decision categories are equally ignored could prove just a damaging in the long run for a company [24]. If a large increase in demand occurs, it is likely that investments into the structural categories are needed to keep up. Hence, developing a production system designed for the perhaps low initial demand could prove equally harmful as designing it for the in this case stated demand of 100 towers annually, which could prove too high. As such, it is recommended that any company that plans to expand their production capacity does a thorough market analysis and performs a detailed order prognosis for their future demand before any investments are made.

5.4 Level of automation

Furthermore, Modvion has had a desire to create a production system with a high level of automation. This might be due to them building their prototype by using hand-driven and hand-held tools to a high degree and therefore wish to move towards a higher level of automation. However, the aim should not simply be to create a production system with the highest level of automation. Instead the level of automation should be chosen to align with the chosen manufacturing strategy [25]. The risk of having a too high level of automation could be a production system that struggles with overcapacity and has lower flexibility, in combination with high investment costs [17].

Additionally, since Modvion has so far only created a prototype and not built a full-scale tower there is a large chance that the design of the product may change or that the requirements of the production system are changed. Thus, having a high level of automation may prove ill-advised as automated systems are worse than operators at handling variability [19]. Additionally, it may prove costly to do large changes to a production system with a high level of automation. Furthermore, having a higher level of automation also comes with higher initial cost as the robots, machines and advanced tools needed to be purchased are more expensive than hiring operators with regular tools.

5.5 Discussion of methods

The methodology used in the project heavily relies on the input of various industry experts. While no reason has been given to doubt the validity of these inputs, these statements have not been thoroughly examined and complimented with several other opinions in all cases, as this proved to be a much too time consuming process. Attempts of balancing out these biases with other expert voices, as well as using literature and bench marks whenever possible, were made in most cases though. Thus, there exists a certain risk within the project that some of the personal biases of the various experts influenced the final result of the project.

Furthermore, the capacity of the system is proved through cycle time calculations, without taking into account balancing losses or other flow characteristics. By building a simulation module of the production system, these characteristics could have been included in the results, thus allowing the project to provide data on possible bottlenecks in the system as well as buffer capacities. However, it was deemed that while this data would allow for a more detailed result, the actually validity of the results would be worsen with this approach. The thought process behind this decision was that the performance of the flow would be heavily affected by the break downs of the different processes within the system. As no accurate data concerning these break down patterns were attainable for the project due to the production system being a true *greenfield factory*, the true consequences of the break downs could not be determined. Hence, for example proclaiming one specific process within the system the bottleneck station without taking the break downs into account will most likely result in the wrong process being singled out. Thus, any analysis of the production system that does not take into account the break downs would be based on fundamentally incorrect data, leading to the conclusions drawn being incorrect as well. Instead, by being transparent that these factors have not influenced the results nor making any analysis of the flow characteristics demonstrated by the production system, the goal is to make the reader aware of the future work needed before the production system could become a reality.

5.6 Summary

The research questions of the project were "How can the future production of Modvion's wind turbine towers be performed?" and "How can a plant layout for Modvion's future production look like?", both of which have been answered. However, the suggested solutions are not perfect, and additional research needs to be done in a number of areas before any investments are made. That said, the production system presented has the capability to produce the 150-metre towers at a rate that meets the desired demand. With the production system, a potential layout has been proposed. The suggested layout has an area of 15 150 square metres.

Before the production is begun, it is recommended that the product design is further developed with a production-oriented perspective. Several advantages in a production environment can be gained by altering the design of the product. These benefits can perhaps best be seen when comparing the layout of the current production system with the layout that would be possible if the previously mentioned product changes are all implemented. This layout can be seen in Figure 5.5.

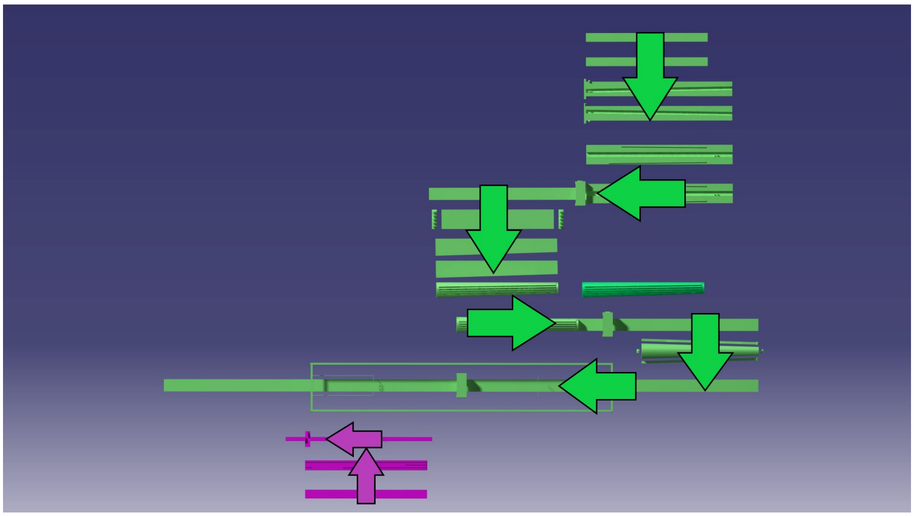


Figure 5.5: Alternative layout if all suggested product design changes are implemented

Furthermore, a detailed market analysis of the company's future demand needs to be made in order to calculate the actual required capacity of the system. This capacity has large effects on the size of the initial investments that has to be made, as well as which level of automation that is required.

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A

Appendix - Demand calculations

A.1 Module Demand

The module demand was calculated by multiplying the annual demand of towers with the amount of modules in each section of a 150 metre tower. This can be seen in equation A.1

$$D_m = D_t * \sum_{i=1}^{s} m_i \tag{A.1}$$

Where D_m = annual demand of modules, D_t = annual demand of 150 metre towers and $\sum_{i=1}^{s} m_i$ = the sum of all modules in a 150 metre tower. The amount of modules in each section in a 150 metre tower, as well as full dimensions of such a tower, is presented in Appendix B.1.

The annual module demand for each section, and in total, is presented below in Table A.1.

Table A.1: Module Demand

Section [#]	**Annual module demand**
1	500
2	600
3	800
4	900
5	1000
6	1200
Total	**5000**

B

Appendix - Dimensions

B.1 Module dimensions

Table B.1: Module dimensions

	Section 1	**Section 2**	**Section 3**	**Section 4**	**Section 5**	**Section 6**	**Section 7**
Modules per section [#]	5	6	8	9	10	12	13
Length [m]	25	25	25	25	25	25	25
Top outer diameter [m]	4	5.42	6.83	8.25	9.67	11.08	12.50
Bottom outer diameter [m]	5.42	6.83	8.25	9.67	11.08	12.50	13.92
Thickness [m]	0.192	0.192	0.192	0.192	0.192	0.192	0.192
Arc length [m]	3.40	3.58	3.24	3.37	3.48	3.27	3.36
Cord length [m]	3.18	3.42	3.16	3.31	3.42	3.24	3.33

C

Appendix - Distances in production system

C.1 Module flow

Table C.1: Cutting process

Points	**Distance [m]**
From input buffer to Cutting process (d_{mic})	10
From Cutting process to scrap buffer (d_{mcs})	10
From Cutting process to Vertical joining process (d_{mcv})	13

Table C.2: Vertical joining process

Points	**Distance [m]**
From Vertical joining process to Harden glue vertically process (d_{mvh})	8

Table C.3: Harden glue vertically process

Points	**Distance [m]**
From Harden glue vertically process to Make slits process (d_{mhm})	6

Table C.4: Make slits process

Points	**Distance [m]**
From Make slits process to Gluing and bending process layer buffer (d_{mmg})	11

Table C.5: Glueing and bending process

Points	**Distance [m]**
From Gluing and bending process layer buffer to Gluing and bending process (d$_{mglg}$)	9
From Gluing and bending process braces buffer to Gluing and bending process (d$_{mgbg}$)	2
From Gluing and bending process pillar buffer to Gluing and bending process (d$_{mgpg}$)	5
From Gluing and bending process to Harden glue process (d$_{mgh}$)	8
From Gluing and bending process fixture buffer to Gluing and bending process (d$_{mgfg}$)	30

Table C.6: Harden glue process

Points	**Distance [m]**
From Harden glue process to Surface treatment process (d$_{mhs}$)	5

Table C.7: Surface treatment process

Points	**Distance [m]**
From Surface treatment process to Coating process (d$_{msco}$)	6

Table C.8: Coating process

Points	**Distance [m]**
From Coating process to output storage (d$_{mcoo}$)	5

C.2 Vertical lid flow

Table C.9: Cut vertical lids

Points	**Distance [m]**
From input storage to cutting station (d$_{vic}$)	5
From cutting station to slits station (d$_{vcs}$)	5

Table C.10: make slits vertical lids

Points	**Distance [m]**
From slit station to bending station (d$_{vsb}$)	5

Table C.11: Bending external vertical lids

Points	**Distance [m]**
From bending station to start of furnace line (d_{vbf})	5

Table C.12: Harden glue and surface finish

Points	**Distance [m]**
From furnace line to surface finish area(d_{vfs})	7
From surface finish to coating station (d_{vsco})	5

C.3 Pillar flow

Table C.13: Prepare edges of beams

Points	**Distance [m]**
From input storage to milling station (d_{pim})	2.645
From milling station to joining station (d_{pmj})	13

Table C.14: Gluing and joining of beams

Points	**Distance [m]**
From joining station to furnace (d_{pjf})	5
From platform buffer to joining station (d_{ppj})	10

Table C.15: Hardening of pillars

Points	**Distance [m]**
From furnance to bending station (d_{pfb})	35
From furnace to cutting station (d_{pfc})	10

C.4 Brace flow

Table C.16: Vertical cutting process

Points	**Distance [m]**
From input buffer to Vertical cutting process (d_{bivc})	30
From Vertical cutting process to Horizontal cutting process buffer (d_{bvchcb})	6.5
From Vertical cutting process to scrap buffer (d_{bvcs})	10

Table C.17: Horizontal cutting process

Points	**Distance [m]**
From Horizontal cutting process buffer to Horizontal cutting process (d$_{bhcbhc}$)	30
From Horizontal cutting process to Slits process (d$_{bhcs}$)	10

Table C.18: Slits process

Points	**Distance [m]**
From Slits station to Gluing and bending process braces buffer (d$_{bsgb}$)	35

Table C.19: Bending process

Points	**Distance [m]**
From Bending station to furnace (d$_{bbf}$)	5
From furnace to Surface treatment process (d$_{bfs}$)	5

C.5 Horizontal lid flow

Table C.20: Vertical cut

Points	**Distance [m]**
From input storage to vertical cut station (d$_{hiv}$)	5
From vertical cut station to horizontal cut station (d$_{hvh}$)	5

Table C.21: Horizontal cut

Points	**Distance [m]**
From horizontal cut station to output storage (d$_{hho}$)	5

D

Appendix - Process calculations

Table D.1: Bench-marked traverse speeds and lift height

Traverse speed vertically (V$_{tv}$)	0.208 [m/s]
Traverse speed horizontally (V$_{th}$)	0.5 [m/s]
Vertical lift height (H$_t$)	2 [m]

D.1 Cycle time module cutting and milling

Time to lift sheet from input storage to cutting station

$$T_{pickupsheet} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.1}$$

$$T_{movesheettostation} = \frac{d_{mic}}{V_{th}} = \frac{10}{0.5} = 20[sec] \tag{D.2}$$

$$T_{putsheetdown} = T_{pickupsheet} \tag{D.3}$$

$$T_{bringtraverseback} = T_{movesheettostation} \tag{D.4}$$

$$\begin{aligned} T_{untilsheetatstation} &= T_{pickupsheet} + T_{movesheettostation} + \frac{T_{putsheetdown}}{2} \\ &= 19.2 + 20 + \frac{19.2}{2} = 48.8[sec] = 0.813[min] \end{aligned} \tag{D.5}$$

Time to lift scarp from cutting station to scarp buffer

$$T_{pickupsheet} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.6}$$

$$T_{movescraptobuffer} = \frac{d_{mcs}}{V_{th}} = \frac{10}{0.5} = 20[sec] \tag{D.7}$$

$$T_{putsheetdown} = T_{pickupsheet} \tag{D.8}$$

$$T_{bringtraverseback} = T_{movescraptobuffer} \tag{D.9}$$

$$\begin{aligned} T_{untilscrapisgonefromstation} &= T_{pickupsheet} + T_{movescraptobuffer} + \frac{T_{putsheetdown}}{2} \\ &= 19.2 + 20 + \frac{19.2}{2} = 48.8[sec] = 0.813[min] \end{aligned} \tag{D.10}$$

Time to lift sheet from cutting station to glue vertically station

$$T_{pickupsheet} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.11}$$

$$T_{movetostation} = \frac{d_{mcg}}{V_{th}} = \frac{13}{0.5} = 26[sec] \tag{D.12}$$

$$T_{putsheetdown} = T_{pickupsheet} \tag{D.13}$$

$$T_{bringtraverseback} = T_{movescraptobuffer} \tag{D.14}$$

$$\begin{aligned} T_{untilsheetatstation} &= T_{pickupsheet} + T_{movetostation} + \frac{T_{putsheetdown}}{2} \\ &= 19.2 + 26 + \frac{19.2}{2} = 54.8[sec] = 0.913[min] \end{aligned} \tag{D.15}$$

Total time spent lifting at process

$$\begin{aligned} T_{lift} = T_{untilsheetatstation} + T_{untilscrapisgonefromstation} + T_{untilsheetatstation} = \\ 0.813 + 0.813 + 0.913 = 2.54[min] \end{aligned} \tag{D.16}$$

Cut time¨

Table D.2: Bench-marked cut speed

Cut speed (V$_c$)	1 [m/s]
Cut Length (L$_c$)	25 [m]

$$T_{cut} = \frac{L_c}{V_c} = \frac{25}{1} = 25[sec] = 0.416[min] \tag{D.17}$$

Milling time

Table D.3: Bench-marked mill speed

mill speed (V$_m$)	1 [m/s]
mill Length (L$_m$)	25 [m]

$$T_{mill} = \frac{L_m}{V_m} = \frac{25}{1} = 25[sec] = 0.416[min] \tag{D.18}$$

Cycle time for cut and milling process

$$T_{cycletime} = T_{lift} + max(T_{cut}, T_{mill}) = 2.54 + 0.416 = 2.96[min] \tag{D.19}$$

D.2 Cycle time module vertical joining of sheets

Time to drill guiding holes

$$T_{drill} = 60[sec] = 1[min] \tag{D.20}$$

Time to move layer from station to start of furnace line

$$T_{pickupsheet} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.21}$$

$$T_{movetostation} = \frac{d_{mvh}}{V_{th}} = \frac{8}{0.5} = 16[sec] \tag{D.22}$$

$$T_{putsheetdown} = T_{pickupsheet} \tag{D.23}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.24}$$

$$\begin{aligned} T_{lift} &= T_{pickupsheet} + T_{movetostation} + \frac{T_{putsheetdown}}{2} \\ &= 19.2 + 16 + \frac{19.2}{2} = 44.8[sec] = 0.746[min] \end{aligned} \tag{D.25}$$

Time to press sheets together

Table D.4: Press variables

Distance to press (d$_{press}$)	1 [m]
Pressure speed (V$_{press}$	0.05 [m/s]

$$T_{press} = \frac{d_{press}}{V_{press}} = \frac{1}{0.05} = 0.33[min] \tag{D.26}$$

Glue time
T$_{taktlayer} = 4.4[min]$

$$T_{lefttoglue} = T_{taktlayer} - T_{press} - T_{lift} = 4.4 - 0.33 - 0.746 = 3.32[min] \tag{D.27}$$

Cycle time for vertical joining process

$$\begin{aligned} T_{cycletime} &= T_{lift} + T_{press} + max(T_{drill}, T_{lefttoglue}) \\ &= 0.746 + 0.33 + 3.32 = 4.4[min] \end{aligned} \tag{D.28}$$

D.3 Cycle time module harden glue vertically

Time to move layer from end of furnace line to next station

$$T_{pickupsheet} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.29}$$

$$T_{movetostation} = \frac{d_{mhm}}{V_{th}} = \frac{6}{0.5} = 12[sec] \tag{D.30}$$

$$T_{putsheetdown} = T_{pickupsheet} \tag{D.31}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.32}$$

$$\begin{aligned} T_{lift} &= T_{pickupsheet} + T_{movetostation} + \frac{T_{putsheetdown}}{2} \\ &= 19.2 + 12 + \frac{19.2}{2} = 40.8[sec] = 0.68[min] \end{aligned} \tag{D.33}$$

Hardening time
$\mathrm{T}_{taktlayer} = 4.4[min]$

$$T_{lefttoharden} = T_{taktlayer} - T_{lift} = 4.4 - 0.68 = 3.72[min] \tag{D.34}$$

$\mathrm{D}_{furnace} = 33[meter]$

$$V_{furnace} = \frac{D_{furnace}}{T_{lefttoharden}} = \frac{33}{3.72} = 8.87[\frac{m}{min}] \tag{D.35}$$

Cycle time harden glue vertically

$$T_{cycletime} = T_{lift} + T_{lefttoharden} = 0.68 + 3.72 = 4.4[min] \tag{D.36}$$

D.4 Cycle time module make slits

Time to move layer from slits station to buffer ahead of bending process

$$T_{pickupsheet} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.37}$$

$$T_{movetostation} = \frac{d_{mmg}}{V_{th}} = \frac{11}{0.5} = 22[sec] \tag{D.38}$$

$$T_{putsheetdown} = T_{pickupsheet} \tag{D.39}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.40}$$

$$\begin{aligned} T_{lift} &= T_{pickupsheet} + T_{movetostation} + \frac{T_{putsheetdown}}{2} \\ &= 19.2 + 22 + \frac{19.2}{2} = 50.8[sec] = 0.84[min] \end{aligned} \tag{D.41}$$

Time to cut slits

Number of blades operating at the same time (N_B) $= 5$

Maximum number of slits to be cut by each blade per module:

$$N_{slits} = \frac{\frac{ModuleWidth_{max}}{SlitsDistance}}{N_B} = \frac{\frac{3.58}{0.04}}{5} = 17 \tag{D.42}$$

slits depth = 0.22 [m]

slits length (D_{slits}) = 0.35 [m]

V$_{cut}$ $= 0.1[\frac{m}{sec}]$

Initial setup (time to move blade to work piece) (T_{si}) = 10 [sec]

Setup between cuts (time to move blade between cuts) (T_{sc}) = 2 *N_{slits} = 34 [sec]

Setup redacting blades from cut (T_{sr}):

$$T_{sr} = \frac{N_{slits} * D_{slits}}{V_{cut}} = \frac{17 * 0.35}{0.1} = 59.5[sec] \tag{D.43}$$

Total setup time (T_{sTot}):

$$T_{sTot} = \frac{T_{si} + T_{sc} + T_{sr}}{60} = \frac{10 + 34 + 59.5}{60} = 1.725[min] \tag{D.44}$$

Cut time (T_c):

$$T_c = \frac{\frac{N_D * D_{slits}}{V_{cut}}}{60} = \frac{\frac{17*0.35}{0.1}}{60} = 0.99[min] \tag{D.45}$$

Total cut time (T_{cTot}):

$$T_{cTot} = T_c + T_{sTot} = 0.99 + 1.725 = 2.716[min] \tag{D.46}$$

Cycle time make slits

$$T_{cycletime} = T_{cTot} + T_{lift} = 2.176 + 0.84 = 3.56[min] \tag{D.47}$$

D.5 Cycle time module gluing and bending

Time to lift layers to station

$$T_{pickupsheet} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.48}$$

$$T_{movetostation} = \frac{d_{mglg}}{V_{th}} = \frac{9}{0.5} = 18[sec] \tag{D.49}$$

$$T_{putsheetdown} = T_{pickupsheet} \tag{D.50}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.51}$$

$$\begin{aligned} T_{ModuleLift} &= T_{pickupsheet} + T_{movetostation} + T_{putsheetdown} + T_{bringtraverseback} \\ &= 19.2 + 18 + 19.2 + 18 = 74.4[sec] = 1.24[min] \end{aligned} \tag{D.52}$$

$$T_{ModuleLiftAllLayers} = T_{ModuleLift} * 8 = 9.92[min] \tag{D.53}$$

$$T_{UntilAllLayersAtStation} = T_{ModuleLiftAllLayers} - \frac{\frac{T_{putsheetdown}}{2} + T_{bringtraverseback}}{60} = 9.46[min] \tag{D.54}$$

Time to lift braces to station

$$T_{pickupbrace} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.55}$$

$$T_{movetostation} = \frac{d_{mgbg}}{V_{th}} = \frac{2}{0.5} = 4[sec] \tag{D.56}$$

$$T_{putbracedown} = T_{pickupbrace} \tag{D.57}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.58}$$

$$\begin{aligned} T_{BraceLift} &= T_{pickupbrace} + T_{movetostation} + T_{putbracedown} + T_{bringtraverseback} \\ &= 19.2 + 4 + 19.2 + 4 = 46.4[sec] = 0.77[min] \end{aligned} \tag{D.59}$$

Time to lift pillars to station

$$T_{pickuppillar} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.60}$$

$$T_{movetostation} = \frac{d_{mgpg}}{V_{th}} = \frac{5}{0.5} = 10[sec] \tag{D.61}$$

$$T_{putpillardown} = T_{pickuppillar} \tag{D.62}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.63}$$

$$\begin{aligned} T_{PillarLift} &= T_{pickuppillar} + T_{movetostation} + T_{putpillardown} + T_{bringtraverseback} \\ &= 19.2 + 10 + 19.2 + 10 = 58.4[sec] = 0.97[min] \end{aligned} \tag{D.64}$$

Average amount of pillars per module = 6

$$T_{PillarLiftAll} = T_{PillarLift} * 6 = 5.84[min] \tag{D.65}$$

Time to move module to next process

$$T_{pickupmodule} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.66}$$

$$T_{movetostation} = \frac{d_{mgh}}{V_{th}} = \frac{8}{0.5} = 16[sec] \tag{D.67}$$

$$T_{putsmoduledown} = T_{pickupmodule} \tag{D.68}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.69}$$

$$\begin{aligned} T_{liftmodule} &= T_{pickupmodule} + T_{movetostation} + T_{putmoduledown} \\ &= 19.2 + 16 + 19.2 = 54.4[sec] = 0.906[min] \end{aligned} \tag{D.70}$$

Time to move next fixture to bending station

$$T_{pickupfixture} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.71}$$

$$T_{movetostation} = \frac{d_{mgfg}}{V_{th}} = \frac{30}{0.5} = 60[sec] \tag{D.72}$$

$$T_{putfixturedown} = T_{pickupfixture} \tag{D.73}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.74}$$

$$\begin{aligned} T_{liftFixture} &= T_{bringtraverseback +} T_{pickupfixutre} + T_{movetostation} + T_{putfixturedown} \\ &= 60 + 19.2 + 60 + 19.2 = 158.4[sec] = 2.64[min] \end{aligned} \tag{D.75}$$

Time to glue layers into module
Glue feed rate (V_g= 1 [m/s]
Layer length (D_L) = 25 [m]

$$T_{GlueLayer} = \frac{D_L}{V_g} = \frac{25}{1} = 25[sec] \tag{D.76}$$

$$T_{GlueAllLayers} = \frac{T_{GlueLayer} * 8}{60} = \frac{25 * 8}{60} = 3.33[min] \tag{D.77}$$

Time to glue braces onto module
Glue feed rate (V_g= 1 [m/s]

Brace length (D_B) = 25 [m]

$$T_{GlueBrace} = \frac{D_B}{V_g} = \frac{25}{1} = 25[sec] \tag{D.78}$$

$$T_{GlueAllBraces} = \frac{T_{GlueBrace} * 4}{60} = 1.67[min] \tag{D.79}$$

Time to glue pillars onto module
Glue feed rate (V_g= 1 [m/s]
Pillar length (D_P) = 24 [m]

$$T_{GluePillar} = \frac{D_P}{V_g} = \frac{24}{1} = 24[sec] \tag{D.80}$$

Bending Module
Number of pressure points (N_P) = 9
Setup-time for each pressure point (T_{sp}) = 1 [min]

$$T_p = N_P * T_{sp} = 9[min] \tag{D.81}$$

Time to add parts to fixture

Time to add first layers of braces and all pillars

$$T_1 = T_{BraceLift} + T_{PillarLiftAll} = 0.77 + 5.84 = 6.61[min] \tag{D.82}$$

Time to add second layer of braces and glue braces

$$T_2 = max(T_{Bracelift}, T_{GlueBrace}) = 0.77[min] \tag{D.83}$$

Time to glue pillars and second layer of braces

$$T_3 = \frac{T_{BraceGlue} + T_{PillarGlue}}{60} = \frac{25 + 24}{60} = 0.816[min] \tag{D.84}$$

Time to place all layers and glue them (gluing done in parallel)

$$T_4 = T_{UntilAllLayersAtStation} = 9.46[min] \tag{D.85}$$

Time to apply pressure to module (done in two pairs)

$$T_5 = \frac{T_p}{2} = 4.5[min] \tag{D.86}$$

Time to move module to next process

$$T_6 = T_{liftModule} = 0.906[min] \tag{D.87}$$

Time to move next fixture to bending station

$$T_7 = T_{liftFixture} = 2.64[min] \tag{D.88}$$

Cycle time for gluing and bending process

$$\begin{aligned} T_{cycletime} &= T_1 + T_2 + T_3 + T_4 + T_5 + T_6 + T_7 \\ &= 6.61 + 0.77 + 0.816 + 9.46 + 4.5 + 0.906 + 2.64 = 25.7[min] \end{aligned} \tag{D.89}$$

Time between first glue is applied and pressure applied

$$T_{assembly} = T_2 + T_3 + T_4 + T_5 = 0.77 + 0.816 + 9.46 + 4.5 = 15.5[min] \tag{D.90}$$

D.6 Cycle time module harden glue

Time to move fixture from furnace line to next station

$$T_{pickupfixture} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.91}$$

$$T_{movetostation} = \frac{d_{mhs}}{V_{th}} = \frac{5}{0.5} = 10[sec] \tag{D.92}$$

$$T_{putfixturedown} = T_{pickupfixture} \tag{D.93}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.94}$$

$$\begin{aligned} T_{lift} &= T_{pickupfixture} + T_{movetostation} + \frac{T_{putfixutredown}}{2} \\ &= 19.2 + 10 + \frac{19.2}{2} = 38.8[sec] = 0.646[min] \end{aligned} \tag{D.95}$$

Time to harden module
Takt time module ($T_{taktModule}$) = 35.2 [min]
Furnace length ($D_{Furnace}$) = 37 [m]

$$T_{reminingtoharden} = T_{taktModule} - T_{lift} = 35.2 - 0.646 = 34.53[min] \tag{D.96}$$

$$V_{Furnace} = \frac{D_{Furnace}}{T_{remainingtoharden}} = \frac{37}{34.53} = 1.07\frac{min}{meter} \tag{D.97}$$

Cycle time for harden glue process

$$T_{Cycletime} = T_{lift} + T_{remainingtoharden} = 0.646 + 34.53 = 35.2[min] \tag{D.98}$$

Time to harden without furnace
Hardening time (T_h)= 345 [min]
Takt time module ($T_{taktmodule}$ = 35.2 [min]
N_{takts} = number of takts per hardening time

$$N_{takts} = \frac{T_h}{T_{taktmodule}} = \frac{345}{35.2} = 9.8[takts] \tag{D.99}$$

D.7 Cycle time module surface treatment

Time to move fixture from furnace line to next station

$$T_{pickupmodule} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.100}$$

$$T_{movetostation} = \frac{d_{msc}}{V_{th}} = \frac{6}{0.5} = 12[sec] \tag{D.101}$$

$$T_{putmoduledown} = T_{pickupmodule} \tag{D.102}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.103}$$

$$\begin{aligned} T_{lift} &= T_{pickupmodule} + T_{movetostation} + \frac{T_{putmodule}}{2} \\ &= 19.2 + 12 + \frac{19.2}{2} = 40.8[sec] = 0.68[min] \end{aligned} \tag{D.104}$$

Surface treatment
Takt time module (T_{takt}) = 35.2 [min]
Set-up (T_s) = 20 [sec] = 0.33 [min]

$$\begin{aligned} T_{remainingforsurfacetreatment} &= T_{takt} - T_s - T_{lift} \\ &= 35.2 - 0.33 - 0.68 = 34.18[min] \end{aligned} \tag{D.105}$$

Surface distance to be treated (D_s) = 25 [meter]

$$V_s = \frac{D_s}{T_{remainingforsurfacetreatment} * 60} = \frac{25}{34.18 * 60} = 0.012\frac{m}{sec} \tag{D.106}$$

D.8 Cycle time module coating of module

Plug guiding holes
Time to plug one hole (T_p) = 30 [sec]
Number of holes to plug per module (P) = 2
walking speed (V_w) = 0.5 [m/sec]
walk distance (D_w) = 35 [meter]

$$T_{walk} = \frac{D_w}{V_w} = \frac{35}{0.5} = 70[sec] \tag{D.107}$$

$$T_{plugging} = T_p * P + T_{walk} = 30 * 2 + 70 = 130[sec] = 2.16[min] \tag{D.108}$$

Time to move fixture from coating line to end storage

$$T_{pickupmodule} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.109}$$

$$T_{movetostorage} = \frac{d_{msc}}{V_{th}} = \frac{5}{0.5} = 10[sec] \tag{D.110}$$

$$T_{putmoduledown} = T_{pickupmodule} \tag{D.111}$$

$$T_{bringtraverseback} = T_{movetostorage} \tag{D.112}$$

$$\begin{aligned} T_{lift} = T_{pickupmodule} + T_{movetostorage} + \frac{T_{putmodule}}{2} \\ = 19.2 + 10 + \frac{19.2}{2} = 38.8[sec] = 0.646[min] \end{aligned} \tag{D.113}$$

Coating

As both the vertical lids and the modules are to be coated using the same station, the number of products that needs to be processed at the station are doubled that of the rest of the flow. Thus, the takt time is halved compared to the other stations in the module flow.

T_{takt} = 17.6 [min]

$$T_{remainingforcoating} = T_{takt} - (T_{plugging} + T_{lift}) = 14.78[min] \tag{D.114}$$

Length of coating line (D_c) = 115 [meter]

$$V_{coating} = \frac{D_c}{T_{remainingforcoating}} = \frac{115}{14.78} = 7.77[m/min] \tag{D.115}$$

Cycle time

$$T_{cycletime} = T_{plugging} + T_{remainingforcoating} + T_lift = 2.16 + 14.78 + 0.646 = 17.6[min] \tag{D.116}$$

D.9 Cycle time Vertical lids cut and guiding holes

Time to move sheet from input storage to station

$$T_{pickupsheet} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.117}$$

$$T_{movetostation} = \frac{d_{vic}}{V_{th}} = \frac{5}{0.5} = 10[sec] \tag{D.118}$$

$$T_{putsheetdown} = T_{pickupsheet} \tag{D.119}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.120}$$

$$\begin{aligned} T_{lift1} &= T_{pickupsheet} + T_{movetostation} + \frac{T_{putsheetdown}}{2} \\ &= 19.2 + 10 + \frac{19.2}{2} = 38.8[sec] = 0.646[min] \end{aligned} \tag{D.121}$$

Time to move sheet from cutting station to next process

$$T_{pickupsheet} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.122}$$

$$T_{movetostation} = \frac{d_{vcs}}{V_{th}} = \frac{5}{0.5} = 10[sec] \tag{D.123}$$

$$T_{putsheetdown} = T_{pickupsheet} \tag{D.124}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.125}$$

$$\begin{aligned} T_{lift2} &= T_{pickupsheet} + T_{movetostation} + \frac{T_{putsheetdown}}{2} \\ &= 19.2 + 10 + \frac{19.2}{2} = 38.8[sec] = 0.646[min] \end{aligned} \tag{D.126}$$

Cut sheet and drill holes
Speed of cut (V_c) = 1 [m/s]
Length of cut (D_c) = 25 [meter]

$$T_c = \frac{D_c}{V_c} = \frac{25}{1} = 25[sec] = 0.416[min] \tag{D.127}$$

Time to drill guiding hole (T_{drill}) = 1 [min]

Cycle time
As each sheet can be generate three separate vertical lids layers and one scrap piece, in total four pieces must be lifted away from the station each takt.

$$T_{cycletime} = T_{lift1} + max(T_c, T_{drill}) + (T_{lift2} * 4) = 5.956[min] \tag{D.128}$$

D.10 Cycle time Vertical lids slits

As the slits of the inner and outer layer of the vertical lids cannot be cut at the same due to different placements, the process will have to handle each of them separately. This means that each step needs to be repeated twice within the process, in order to guarantee that both layers are processed properly.

Number of slits per lid (N_s) = 12
Length of slits (D_s) = 0.35 [meter]
Time it takes to move blade between cuts (T_{sc}) = 2 [sec]
Initial setup of moving the blade to the work piece (T_si) = 10 [sec]

$$T_{movebladebetweencuts} = N_s * T_{sc} = 12 * 2 = 24[sec] \tag{D.129}$$

Speed of cut (V_c)= 0.1 [m/s]

$$T_{redactblade} = \frac{N_s * D_s}{V_c} = \frac{12 * 0.35}{0.1} = 42[sec] \tag{D.130}$$

$$\begin{aligned} T_{setup} &= (T_si + T_{movebladebetweencuts} + T_{redactblade}) * 2 \\ &= (10 + 24 + 42) * 2 = 152[sec] = 2.53[min] \end{aligned} \tag{D.131}$$

Cutting slits

$$T_{cut} = \frac{D_s * N_s}{V_s} = \frac{0.35 * 12}{0.1} = 42[sec] = 0.7[min] \tag{D.132}$$

Time to move lids from slits station to next process

$$T_{pickupsheet} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.133}$$

$$T_{movetostation} = \frac{d_{vsb}}{V_{th}} = \frac{5}{0.5} = 10[sec] \tag{D.134}$$

$$T_{putsheetdown} = T_{pickupsheet} \tag{D.135}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.136}$$

$$\begin{aligned} T_{lift} &= (T_{pickupsheet} + T_{movetostation} + T_{putsheetdown} + T_{bringtraverseback}) * 2 \\ &= (19.2 + 10 + 19.2 + 10) * 2 = 116.8[sec] = 1.94[min] \end{aligned} \tag{D.137}$$

Cycle time

$$T_{cycletime} = T_{setup} + T_{cut} + T_{lift} = 2.53 + 0.7 + 1.94 = 5.17[min] \tag{D.138}$$

D.11 Cycle time bending vertical lids

Glue time
Glue feed $V_g = 1$ [m/s]
Glue distance $D_g = 25$ [meter]

$$T_{Glue} = \frac{D_g}{V_g} = \frac{25}{1} = 25[sec] = 0.41[min] \tag{D.139}$$

Bending time
Number of pressure points $N_p = 9$
Set-up time for each pressure point $T_{setup} = 1$ [min]

$$T_{bend} = N_p * T_{setup} = 9[min] \tag{D.140}$$

Time to move lids from slits station to next process

$$T_{pickupsheet} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.141}$$

$$T_{movetostation} = \frac{d_{vbf}}{V_{th}} = \frac{5}{0.5} = 10[sec] \tag{D.142}$$

$$T_{putsheetdown} = T_{pickupsheet} \tag{D.143}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.144}$$

$$\begin{aligned} T_{lift} &= T_{pickupsheet} + T_{movetostation} + T_{putsheetdown} + T_{bringtraverseback} \\ &= 19.2 + 10 + 19.2 + 10 = 58.4[sec] = 0.973[min] \end{aligned} \tag{D.145}$$

Cycle time

$$T_{cycletime} = T_{Glue} + T_{bend} + T_{lift} = 0.41 + 9 + 0.973 = 10.383[min] \tag{D.146}$$

D.12 Cycle time hardening and surface treatment of vertical lids

Hardening of glue
Furnace distance (D_f) = 35 [meter]
Hardening speed (V_f) = 6 [m/min]

Remember, the much lower thickness of the vertical lids (2 layers) compared to the module (8 layers) allows for a much quicker hardening time.

$$T_{hardening} = \frac{D_f}{V_f} = \frac{35}{6} = 5.83[min] \tag{D.147}$$

Time to move lids from end of furnace line to surface finish area

$$T_{pickupsheet} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.148}$$

$$T_{movetostation} = \frac{d_{vfs}}{V_{th}} = \frac{7}{0.5} = 14[sec] \tag{D.149}$$

$$T_{putsheetdown} = T_{pickupsheet} \tag{D.150}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.151}$$

$$\begin{aligned} T_{lift1} &= T_{pickupsheet} + T_{movetostation} + T_{putsheetdown} + T_{bringtraverseback} \\ &= 19.2 + 14 + 19.2 + 14 = 66.4[sec] = 1.106[min] \end{aligned} \tag{D.152}$$

Time to move lids from surface treatment station to coating process

$$T_{pickupsheet} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.153}$$

$$T_{movetostation} = \frac{d_{vsco}}{V_{th}} = \frac{5}{0.5} = 10[sec] \tag{D.154}$$

$$T_{putsheetdown} = T_{pickupsheet} \tag{D.155}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.156}$$

$$\begin{aligned} T_{lift2} &= T_{pickupsheet} + T_{movetostation} + T_{putsheetdown} + T_{bringtraverseback} \\ &= 19.2 + 10 + 19.2 + 10 = 58.4[sec] = 0.973[min] \end{aligned} \tag{D.157}$$

Surface treatment

T_{takt} = 35.2 [min]

$$\begin{aligned} T_{leftforsurface} &= T_{takt} - (T_{hardening} + T_{lift1} + T_{lift2}) \\ &= 35.2 - (5.83 + 1.106 + 0.973) = 27.28[min] \end{aligned} \tag{D.158}$$

Max grind length (D_{grind}) = 25 [meter]

$$V_{grind} = \frac{D_{grind}}{T_{leftforsurface} * 60} = \frac{25}{27.28 * 60} = 0.015[m/s] \tag{D.159}$$

Cycle time

$$\begin{aligned} T_{cycletime} &= T_{lift1} + T_{hardening} + T_{leftforsurface} + T_{lift2} \\ &= 1.106 + 5.83 + 27.28 + 0.973 = 35.2[min] \end{aligned} \tag{D.160}$$

D.13 Cycle time pillar preparation of edges of beams

Time to move beams from input storage to milling station

$$T_{pickupbeam} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.161}$$

$$T_{movetostation} = \frac{d_{pim}}{V_{th}} = \frac{2.645}{0.5} = 5.29[sec] \tag{D.162}$$

$$T_{putbeamtdown} = T_{pickupbeam} \tag{D.163}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.164}$$

$$\begin{aligned} T_{lift1} &= T_{pickupbeam} + T_{movetostation} + T_{putsbeamdown} + T_{bringtraverseback} \\ &= 19.2 + 5.29 + 19.2 + 5.29 = 48.98[sec] = 0.816[min] \end{aligned} \tag{D.165}$$

Time to mill edge
Milling speed (V_m) = 1 [m/s]
Milling distance (D_m) = 0.215 [m]

$$T_m = \frac{D_m}{V_m} = \frac{0.215}{1} = 0.215[sec] = 0.0035[min] \tag{D.166}$$

Time to move beam from milling station to next process in flow

$$T_{pickupbeam} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.167}$$

$$T_{movetostation} = \frac{d_{pmj}}{V_{th}} = \frac{13}{0.5} = 26[sec] \tag{D.168}$$

$$T_{putbeamtdown} = T_{pickupbeam} \tag{D.169}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.170}$$

$$\begin{aligned} T_{lift2} &= T_{pickupbeam} + T_{movetostation} + T_{putsbeamdown} + T_{bringtraverseback} \\ &= 19.2 + 26 + 19.2 + 26 = 90.4[sec] = 1.51[min] \end{aligned} \tag{D.171}$$

Cycle time

$$T_{cycletime} = T_{lift1} + T_m + T_{lift2} = 0.816 + 0.0035 + 1.51 = 2.32[min] \tag{D.172}$$

D.14 Cycle time joining of beams into pillars

Glue time
Since the fixture used at the station will join in total six beams into three separate pillars, glue will have to be applied to half, meaning three, of the beams.

Pillar width (D_p) = 0.215 [m]

$$D_{glue} = D_p * 3 * 2 = 0.215 * 3 * 2 = 1.29[m] \tag{D.173}$$

Glue feed (V_{glue}) = 0.1 [m/s]

$$T_{glue} = \frac{D_{glue}}{V_{glue}} = \frac{1.29}{0.1} = 12.9[sec] = 0.215[min] \tag{D.174}$$

Press beams togeheter
Distance to press (D_{press}) = 1.5 [m]
Pressure speed (V_{press}) = 0.05 [m/s]

$$T_{press} = \frac{D_{press}}{V_{press}} = \frac{1.5}{0.05} = 30[sec] = 0.5[min] \tag{D.175}$$

Time to move fixture from joining station to start of hardening furnace

$$T_{pickupfixture} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.176}$$

$$T_{movetostation} = \frac{d_{pjf}}{V_{th}} = \frac{5}{0.5} = 10[sec] \tag{D.177}$$

$$T_{pufixturedown} = T_{pickupfixture} \tag{D.178}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.179}$$

$$\begin{aligned} T_{lift1} = T_{pickupfixture} + T_{movetostation} + T_{putfixturedown} + T_{bringtraverseback} \\ = 19.2 + 10 + 19.2 + 10 = 58.4[sec] = 0.97[min] \end{aligned} \tag{D.180}$$

Time to move new fixture from buffer to joining station

$$T_{pickupfixture} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.181}$$

$$T_{movetostation} = \frac{d_{ppj}}{V_{th}} = \frac{10}{0.5} = 20[sec] \tag{D.182}$$

$$T_{putfixturedown} = T_{pickupfixture} \tag{D.183}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.184}$$

$$\begin{aligned}T_{lift2} = T_{pickupfixture} + T_{movetostation} + T_{putfixturedown} + T_{bringtraverseback} \\ = 19.2 + 20 + 19.2 + 20 = 78.4[sec] = 1.31[min]\end{aligned} \tag{D.185}$$

Cycle time

$$\begin{aligned}T_{cycletime} = T_{glue} + T_{press} + T_{lift1} + T_{lift2} \\ = 0.215 + 0.5 + 0.97 + 1.31 = 2.99[min]\end{aligned} \tag{D.186}$$

D.15 Cycle time harden pillars

As the fixture with the now glued, both not hardened, pillars contains in total three pillars as they arrive at the start of the hardening process, the takt time for each of these fixture is tripled compared to if just one pillar was handled at a time. Thus,

$$T_{takt} = T_{pillartakt} * 3 = 9.167 * 3 = 27.5[min] \tag{D.187}$$

Time to move fixture from end of furnace line to buffer ahead of module bending station

$$T_{pickupfixture} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.188}$$

$$T_{movetostation} = \frac{d_{pfb}}{V_{th}} = \frac{35}{0.5} = 70[sec] \tag{D.189}$$

$$T_{putfixturedown} = T_{pickupfixture} \tag{D.190}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.191}$$

$$\begin{aligned}T_{lift} = T_{pickupfixture} + T_{movetostation} + T_{putfixturedown} + T_{bringtraverseback} \\ = 19.2 + 70 + 19.2 + 70 = 178.4[sec] = 2.97[min]\end{aligned} \tag{D.192}$$

Time remaining for furnace
Furnace line distance (D_f) = 34 [m]

$$T_{remainingforfurnace} = T_{takt} - T_{lift} = 27.5 - 2.97 = 24.56[min] \tag{D.193}$$

$$V_{furnace} = \frac{D_f}{T_{remainingforfurnace}} = \frac{34}{24.56} = 1.38[min] \tag{D.194}$$

Cycle time

$$T_{cycletime} = \frac{T_{remainingforfurnace} + T_{lift}}{3} = \frac{24.56 + 2.97}{3} = 9.167[min] \tag{D.195}$$

D.16 Cycle time braces vertical cut

As this process will deal with entire sheets of LVL that are than cut into "columns of braces", the takt time for the process will be larger than the takt time for one single brace (8.8 min), as multiple braces can be extruded from one sheet.

Sheet width (D_s) = 1.8 [m]
Brace length (D_b) = 0.5 [m]

$$N_{bracecolumnspersheet} = rounddown(\frac{D_s}{D_b}) = 3 \tag{D.196}$$

Column length (D_{bc}) = 25 [m]
Average brace width (D_{ab})= 2.96 [m]

$$N_{bracespercolumn} = rounddown(\frac{D_{bc}}{D_{ab}}) = rounddown(\frac{25}{2.96}) = 8 \tag{D.197}$$

However, important to note is that the braces all require two layers. Hence, each column of braces does not contain eight braces, but rather eight brace layers, or four braces.

$$N_{bracespersheet} = \frac{bracecolumnspersheet * N_{bracespercolumn}}{2} = \frac{8*3}{2} = 12 \tag{D.198}$$

Time to make cut
Cut speed (V_c) = 1 [m/s]
Cut length (D_c) = 25 [m]

$$T_{cut} = \frac{D_c}{V_c} = \frac{25}{1} = 25[sec] = 0.416[min] \tag{D.199}$$

Note that the station uses three saw blades at once, meaning that all columns are cut at the same time.

Time to drill guiding holes
Time it takes to drill one hole (T_d) = 1 [min]
Maximum number of holes per column (N_d) = 9
Time it takes to move the drill between each hole (T_{ds}) = 1[min]

$$T_{drill} = T_d * N_d + T_{ds} * N_d = 1*9 + 1*9 = 18[min] \tag{D.200}$$

Time to move sheet from input storage to cutting station

$$T_{pickupsheet} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.201}$$

$$T_{movetostation} = \frac{d_{bivc}}{V_{th}} = \frac{30}{0.5} = 60[sec] \tag{D.202}$$

$$T_{putsheetdown} = T_{pickupsheet} \tag{D.203}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.204}$$

$$\begin{aligned} T_{lift1} &= T_{pickupsheet} + T_{movetostation} + T_{putsheetdown} + T_{bringtraverseback} \\ &= 19.2 + 60 + 19.2 + 60 = 158.4[sec] = 2.64[min] \end{aligned} \tag{D.205}$$

Time to move columns from cutting station to next process within the flow

$$T_{pickupcolumn} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.206}$$

$$T_{movetostation} = \frac{d_{bvchc}}{V_{th}} = \frac{6.5}{0.5} = 13[sec] \tag{D.207}$$

$$T_{putcolumndown} = T_{pickupcolumn} \tag{D.208}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.209}$$

$$\begin{aligned} T_{lift2} &= T_{pickupcolumn} + T_{movetostation} + T_{putcolumndown} + T_{bringtraverseback} \\ &= 19.2 + 13 + 19.2 + 13 = 64.4[sec] = 1.07[min] \end{aligned} \tag{D.210}$$

Time to move scarp from cutting station to scrap buffer

$$T_{pickupscrap} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.211}$$

$$T_{movetobuffer} = \frac{d_{bvcs}}{V_{th}} = \frac{10}{0.5} = 20[sec] \tag{D.212}$$

$$T_{putscrapdown} = T_{pickupscrap} \tag{D.213}$$

$$T_{bringtraverseback} = T_{movetobuffer} \tag{D.214}$$

$$\begin{aligned} T_{lift3} &= T_{pickupscrap} + T_{movetobuffer} + T_{putscrapndown} + T_{bringtraverseback} \\ &= 19.2 + 20 + 19.2 + 20 = 78.4[sec] = 1.30[min] \end{aligned} \tag{D.215}$$

Cycle time

$$\begin{aligned} T_{cycletimesheet} &= T_{cut} + T_{drill} + T_{lift1} + T_{lift2} * N_{bracecolumnspersheet} + T_{lift3} \\ &= 0.416 + 18 + 2.64 + 1.07 * 3 + 1.3 = 25.56[min] \end{aligned} \tag{D.216}$$

$$T_{cycletimebrace} = \frac{T_{cyletimesheet}}{N_{bracespersheet}} = \frac{25.56}{12} = 2.13[min] \tag{D.217}$$

D.17 Cycle time braces horizontal cut

Lift from buffer to horizontal cutting station

$$T_{pickupbracecolumn} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.218}$$

$$T_{movetostation} = \frac{d_{bhcbhc}}{V_{th}} = \frac{30}{0.5} = 60[sec] \tag{D.219}$$

$$T_{putbraccolumndown} = T_{pickupbracecolumn} \tag{D.220}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.221}$$

$$\begin{aligned} T_{lift1} &= T_{pickupbracecolumn} + T_{movetostation} + T_{putbracecolumndown} + T_{bringtraverseback} \\ &= 19.2 + 60 + 19.2 + 60 = 158.4[sec] = 2.64[min] \end{aligned} \tag{D.222}$$

Cut time
Cut length (D_c) = 0.5 [meter]
Cut speed (V_c) = 1 [m/s]
Number of brace layers per column (N_b) = 8

Since each brace column contains eight brace layers, the total cutting time per brace column is the time it takes to cut one layer from a brace column multiplied eight times.

$$T_{cut} = \frac{D_c}{V_c} * N_b = \frac{0.5}{1} * 8 = 4[sec] = 0.067[min] \tag{D.223}$$

Lift from buffer to horizontal cutting station

$$T_{pickupbrace} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.224}$$

$$T_{movetostation} = \frac{d_{bhcs}}{V_{th}} = \frac{10}{0.5} = 20[sec] \tag{D.225}$$

$$T_{putbracedown} = T_{pickupbrace} \tag{D.226}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.227}$$

$$\begin{aligned} T_{lift2} &= T_{pickupbrace} + T_{movetostation} + T_{putbracedown} + T_{bringtraverseback} \\ &= 19.2 + 20 + 19.2 + 20 = 78.4[sec] = 1.30[min] \end{aligned} \tag{D.228}$$

As each brace layer that is cut at the station needs to be moved, this time needs to be taken into consideration.

$$T_{lift2tot} = T_{lift2} * N_b = 1.30 * 8 = 10.4[min] \tag{D.229}$$

Station line feed
T_{takt} = 35.2 [min]

$$\begin{aligned} T_{remainingtofeed} &= T_{takt} - (T_lift1 + T_{cut} + T_{lift2tot}) \\ &= 35.2 - (2.64 + 0.067 + 10.4) = 22.09[min] \end{aligned} \tag{D.230}$$

Average brace length ($D_{average}$) = 2.96 [m]

$$V_{linefeed} = \frac{D_{average} * N_b}{T_{remainingtofeed}} = \frac{2.96 * 8}{22.09} = 1.071[m/min] = 0.017[m/s] \tag{D.231}$$

Cycle time

$$\begin{aligned} T_{cycletime} &= T_{lift1} + T_{cut} + T_{remainingtofeed} + T_{lift2tot} \\ &= 2.64 + 0.067 + 22.09 + 10.4 = 35.2[min] \end{aligned} \tag{D.232}$$

D.18 Cycle time braces slits

Setup required ahead of cut
Maximum number of slits per brace (N_{slits}) = 12
Slits length (D_{slits}) = 0.35 [meter]
Cut speed (V_{cut}) = 0.1 [m/s]
Initial setup (time to move blade to work piece) (T_{si}) = 10 [sec]
Setup between cuts (time to move blade between cuts) (T_{sc}) = 2 [sec]

$$T_{sctot} = T_{sc} * N_{slits} = 2 * 12 = 24[sec] \tag{D.233}$$

Setup redacting blades from cut (T_{sr}):

$$T_{sr} = \frac{N_{slits} * D_{slits}}{V_{cut}} = \frac{12 * 0.35}{0.1} = 42[sec] \tag{D.234}$$

Total setup time:

$$T_{setup} = T_{si} + T_{sctot} + T_{sr} = 10 + 24 + 42 = 76[sec] = 1.26[min] \tag{D.235}$$

Lift from slits station to bending station

$$T_{pickupbrace} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.236}$$

$$T_{movetostation} = \frac{d_{bhcs}}{V_{th}} = \frac{35}{0.5} = 70[sec] \tag{D.237}$$

$$T_{putbracedown} = T_{pickupbrace} \tag{D.238}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.239}$$

$$\begin{aligned} T_{lift} &= T_{pickupbrace} + T_{movetostation} + T_{putbracedown} + T_{bringtraverseback} \\ &= 19.2 + 70 + 19.2 + 70 = 178.4[sec] = 2.97[min] \end{aligned} \tag{D.240}$$

Time to cut
(T_{takt}) = 4.4 [min]

$$T_{remainingtocut} = T_{takt} - (T_{setup} + T_{lift}) = 4.4 - (1.26 + 2.97) = 0.159[min] \tag{D.241}$$

Speed of cut required:

$$V_{cut} = \frac{D_{slits} * N_{slits}}{T_remainingtocut} = \frac{0.35 * 12}{0.159} = 26.4[\frac{m}{min}] = 0.44[\frac{m}{sec}] \tag{D.242}$$

Cycle time

$$T_{cycletime} = T_{setup} + T_{remainingtocut} + T_{lift} = 1.26 + 0.159 + 2.97 = 4.4[min] \tag{D.243}$$

D.19 Cycle time braces bending and hardening

Glue time
Glue feed (V_{glue}) =1 [m/s]
Brace length $(D_{brace}$ = 0.5 [m]

$$T_{glue} = \frac{D_{brace}}{V_{glue}} = \frac{0.5}{1} = 0.5[sec] = 0.0083[min] \tag{D.244}$$

Bending time for brace
Number of pressure points (N_{press}) = 1
Time per pressure point (T_{press}) = 1 [min]

$$T_{press} = N_{press} * T_{press} = 1 * 1 = 1[min] \tag{D.245}$$

Lift from bending station to furnace

$$T_{pickupbrace} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.246}$$

$$T_{movetostation} = \frac{d_{bbf}}{V_{th}} = \frac{5}{0.5} = 10[sec] \tag{D.247}$$

$$T_{putbracedown} = T_{pickupbrace} \tag{D.248}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.249}$$

$$\begin{aligned} T_{lift1} &= T_{pickupbrace} + T_{movetostation} + T_{putbracedown} + T_{bringtraverseback} \\ &= 19.2 + 10 + 19.2 + 10 = 58.4[sec] = 0.97[min] \end{aligned} \tag{D.250}$$

Lift from furnace to surface treatment station

$$T_{pickupbrace} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.251}$$

$$T_{movetostation} = \frac{d_{bfs}}{V_{th}} = \frac{5}{0.5} = 10[sec] \tag{D.252}$$

$$T_{putbracedown} = T_{pickupbrace} \tag{D.253}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.254}$$

$$\begin{aligned} T_{lift2} &= T_{pickupbrace} + T_{movetostation} + T_{putbracedown} + T_{bringtraverseback} \\ &= 19.2 + 10 + 19.2 + 10 = 58.4[sec] = 0.97[min] \end{aligned} \tag{D.255}$$

Harden glue
Takt time (T_{takt}) = 8.8 [min]
Length of furnace line ($D_{furnace}$) = 6 [meter]

$$\begin{aligned} T_{remainingtoharden} &= T_{takt} - (T_{glue} + T_{press} + T_{lift1} + T_{lift2}) \\ &= 4.4 - (0.0083 + 1 + 0.97 + 0.97) = 5.84[min] \end{aligned} \tag{D.256}$$

$$V_{furnace} = \frac{D_{furnace}}{T_{remainingtoharden}} = \frac{6}{5.84} = 1.02[m/min] \tag{D.257}$$

Cycle time

$$\begin{aligned} T_{cycletime} &= T_{glue} + T_{press} + T_{lift1} + T_{remainingtoharden} + T_{lift2} \\ &= 0.0083 + 1 + 0.97 + 5.84 + 0.97 = 8.8[min] \end{aligned} \tag{D.258}$$

D.20 Cycle time braces surface treatment

Grind time short side of brace
Length of short side (D_{short}) = 0.5 [meter]
Grind feed (V_{grind}) = 0.02 [m/s]

$$T_{grindshort} = \frac{D_{short}}{V_{grind}} = \frac{0.5}{0.02} = 25[sec] = 0.416[min] \tag{D.259}$$

Grind time long side of brace
Maximum length of long side (D_{long}) =3.38 [meter]
Grind feed (V_{grind}) = 0.02 [m/s]

$$T_{grindlong} = \frac{D_{long}}{V_{grind}} = \frac{3.38}{0.02} = 169[sec] = 2.81[min] \tag{D.260}$$

Cycle time

$$T_{cycletime} = T_{grindshort} + T_{grindlong} = 0.416 + 2.81 = 3.22[min] \tag{D.261}$$

D.21 Cycle time Horizontal lids vertical cut

Lift from input storage to vertical cut station

$$T_{pickupsheet} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.262}$$

$$T_{movetostation} = \frac{d_{hiv}}{V_{th}} = \frac{5}{0.5} = 10[sec] \tag{D.263}$$

$$T_{putsheetdown} = T_{pickupsheet} \tag{D.264}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.265}$$

$$\begin{aligned} T_{lift1} &= T_{pickupsheet} + T_{movetostation} + T_{putsheetdown} + T_{bringtraverseback} \\ &= 19.2 + 10 + 19.2 + 10 = 58.4[sec] = 0.97[min] \end{aligned} \tag{D.266}$$

Time to cut
Horizontal lid width (D_{lid}) =0.7 [meter]
Sheet width(D_{sheet}) = 1.8 [meter]
Sheet length (D_{length}) = 25 [meter]

$$N_{lidcolumnspersheet} = rounddown(\frac{D_{sheet}}{D_{lid}}) = rounddown(\frac{1.8}{0.7}) = 2 \tag{D.267}$$

Cutting speed (V_{cut}) = 1 [m/s]

$$T_{cut} = \frac{D_{length}}{V_{cut}} = \frac{25}{1} = 25[sec] = 0.416[min] \tag{D.268}$$

Lift from vertical cut station to horizontal cut station

$$T_{pickupsheet} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.269}$$

$$T_{movetostation} = \frac{d_{hvh}}{V_{th}} = \frac{5}{0.5} = 10[sec] \tag{D.270}$$

$$T_{putsheetdown} = T_{pickupsheet} \tag{D.271}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.272}$$

$$\begin{aligned} T_{lift2} &= T_{pickupsheet} + T_{movetostation} + T_{putsheetdown} + T_{bringtraverseback} \\ &= 19.2 + 10 + 19.2 + 10 = 58.4[sec] = 0.97[min] \end{aligned} \tag{D.273}$$

Cycle time

$$T_{cycletime} = T_{lift1} + T_{cut} + T_{lift2} = 0.97 + 0.416 + 0.97 = 2.35[min] \tag{D.274}$$

D.22 Cycle time Horizontal lids horizontal cut

How many lids per column?
Minimum lid width (D_{minlid}) = 3.24 [meter]
Lid column length ($D_{lidcolumn}$) = 25 [meter]

$$N_{maxlidspercolumn} = rounddown(\frac{D_{lidcolumn}}{D_{minlid}}) = rounddown(\frac{25}{3.24}) = 7 \tag{D.275}$$

Lift from horizontal cut station to output storage

$$T_{pickuplid} = \frac{H_t}{V_{tv}} * 2 = \frac{2}{0.208} * 2 = 19.2[sec] \tag{D.276}$$

$$T_{movetostation} = \frac{d_{hho}}{V_{th}} = \frac{5}{0.5} = 10[sec] \tag{D.277}$$

$$T_{putliddown} = T_{pickuplid} \tag{D.278}$$

$$T_{bringtraverseback} = T_{movetostation} \tag{D.279}$$

$$\begin{aligned} T_{lift} &= T_{pickuplid} + T_{movetostation} + T_{putliddown} + T_{bringtraverseback} \\ &= 19.2 + 10 + 19.2 + 10 = 58.4[sec] = 0.97[min] \end{aligned} \tag{D.280}$$

Since each separate lid needs to be lifted off the station, the total lift time needs to consider the number of lids per lid column.

$$T_{lifttot} = T_{lift} * N_{maxlidspercolumn} = 0.97 * 7 = 6.79[min] \tag{D.281}$$

Time to cut
Takt time (T_{takt}) = 17.6 [min]

$$T_{remainingtocut} = T_{takt} - T_{lifttot} = 17.6 - 6.79 = 10.81[min] \tag{D.282}$$

Distance to feed line forward between cuts = $D_{minlid} = 3.29$ [meter]
Number of lids per column $N_{lidspercolumn} = 7$

$$T_{percut} = \frac{T_remainingtocut}{N_{lidspercolumn}} = \frac{10.81}{7} = 1.54[min] \tag{D.283}$$

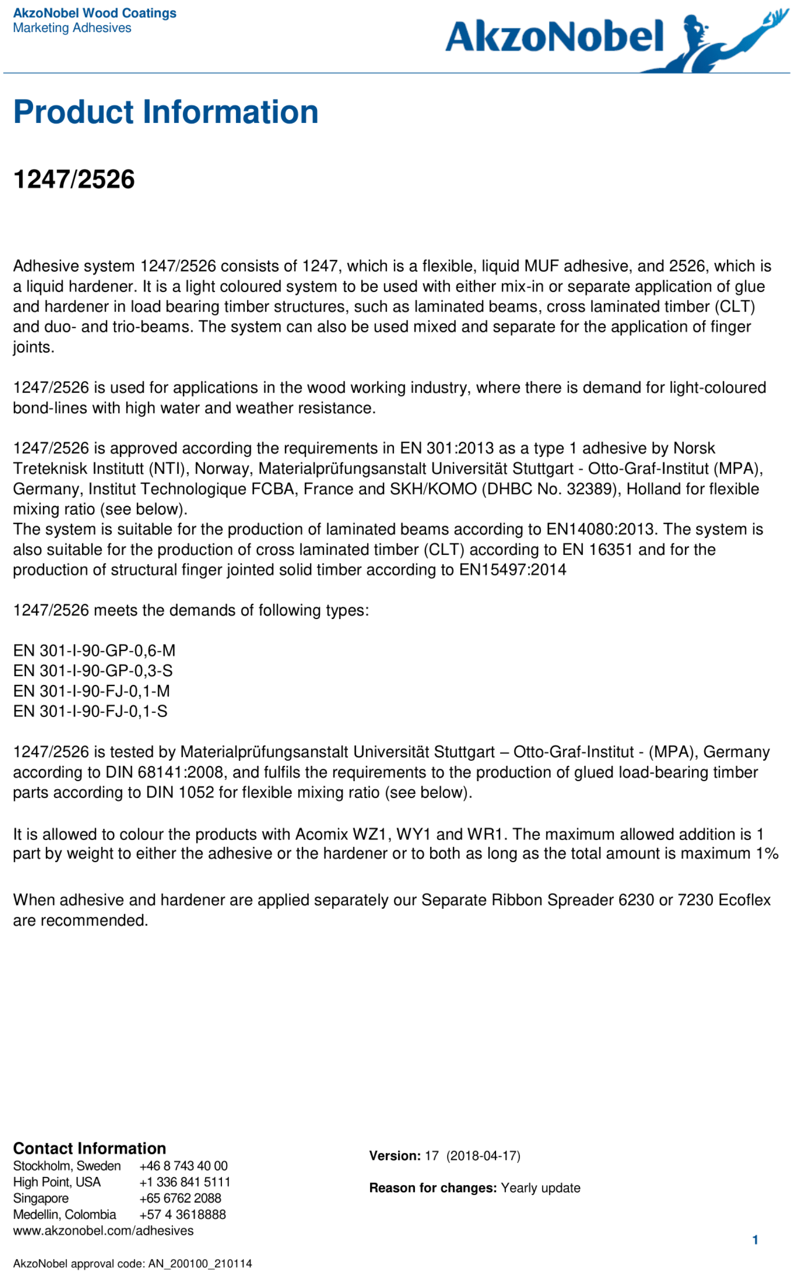
$$V_{line} = \frac{D_{minlid}}{T_{percut}} = \frac{3.29}{1.54} = 2.13[m/min] = 0.035[m/s] \tag{D.284}$$

Cycle time

$$T_{cycletime} = T_{lifttot} + T_{remainingtocut} = 17.6[min] \tag{D.285}$$

E

Appendix - AzkoNobel 1247/2526 adhesive system



AkzoNobel Wood Coatings
Marketing Adhesives

Product Information

1247/2526

Adhesive system 1247/2526 consists of 1247, which is a flexible, liquid MUF adhesive, and 2526, which is a liquid hardener. It is a light coloured system to be used with either mix-in or separate application of glue and hardener in load bearing timber structures, such as laminated beams, cross laminated timber (CLT) and duo- and trio-beams. The system can also be used mixed and separate for the application of finger joints.

1247/2526 is used for applications in the wood working industry, where there is demand for light-coloured bond-lines with high water and weather resistance.

1247/2526 is approved according the requirements in EN 301:2013 as a type 1 adhesive by Norsk Treteknisk Institutt (NTI), Norway, Materialprüfungsanstalt Universität Stuttgart - Otto-Graf-Institut (MPA), Germany, Institut Technologique FCBA, France and SKH/KOMO (DHBC No. 32389), Holland for flexible mixing ratio (see below).
The system is suitable for the production of laminated beams according to EN14080:2013. The system is also suitable for the production of cross laminated timber (CLT) according to EN 16351 and for the production of structural finger jointed solid timber according to EN15497:2014

1247/2526 meets the demands of following types:

EN 301-I-90-GP-0,6-M
EN 301-I-90-GP-0,3-S
EN 301-I-90-FJ-0,1-M
EN 301-I-90-FJ-0,1-S

1247/2526 is tested by Materialprüfungsanstalt Universität Stuttgart – Otto-Graf-Institut - (MPA), Germany according to DIN 68141:2008, and fulfils the requirements to the production of glued load-bearing timber parts according to DIN 1052 for flexible mixing ratio (see below).

It is allowed to colour the products with Acomix WZ1, WY1 and WR1. The maximum allowed addition is 1 part by weight to either the adhesive or the hardener or to both as long as the total amount is maximum 1%

When adhesive and hardener are applied separately our Separate Ribbon Spreader 6230 or 7230 Ecoflex are recommended.

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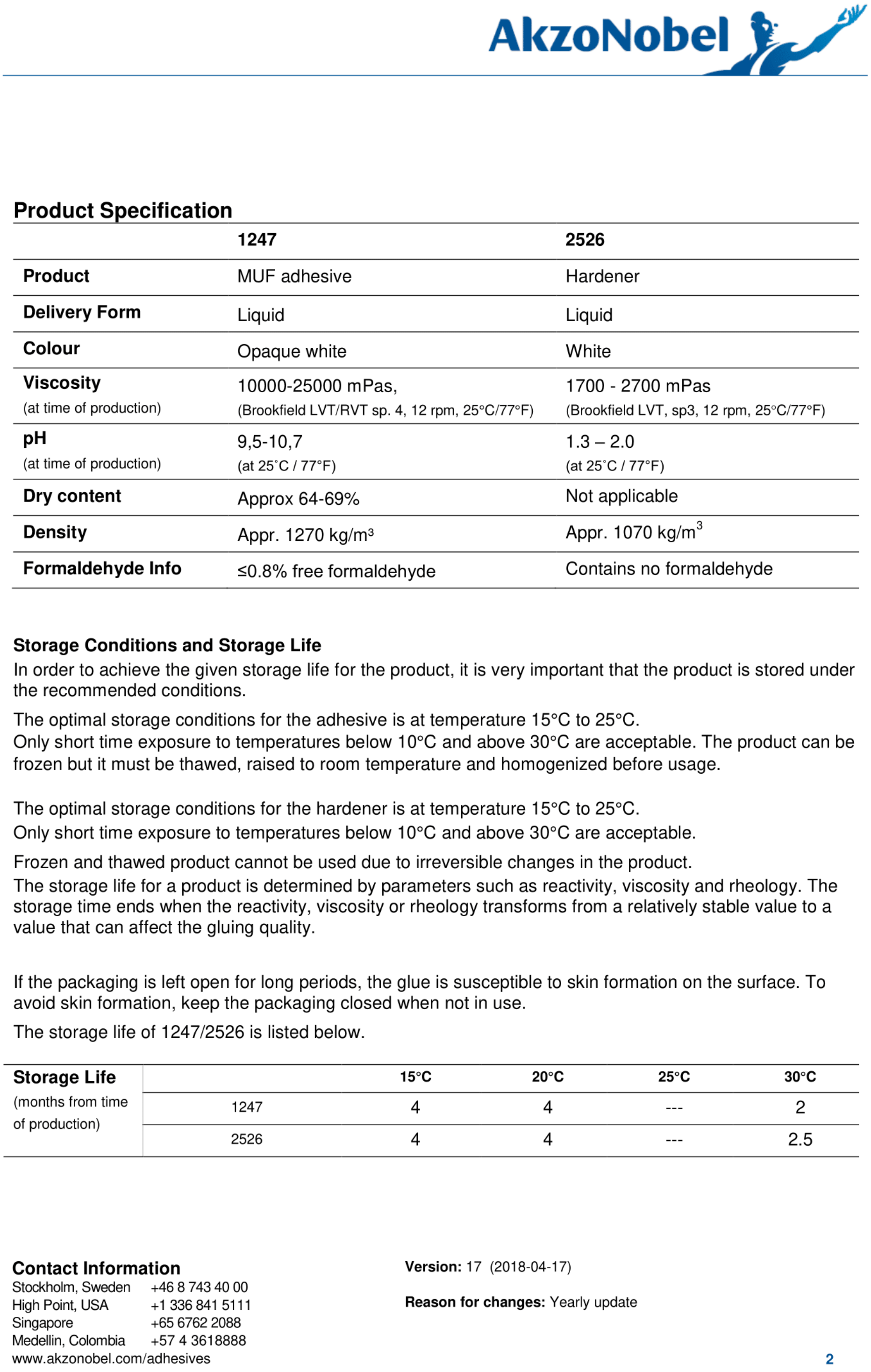

Product Specification

	1247	2526
Product	MUF adhesive	Hardener
Delivery Form	Liquid	Liquid
Colour	Opaque white	White
Viscosity (at time of production)	10000-25000 mPas, (Brookfield LVT/RVT sp. 4, 12 rpm, 25°C/77°F)	1700 - 2700 mPas (Brookfield LVT, sp3, 12 rpm, 25°C/77°F)
pH (at time of production)	9,5-10,7 (at 25°C / 77°F)	1.3 – 2.0 (at 25°C / 77°F)
Dry content	Approx 64-69%	Not applicable
Density	Appr. 1270 kg/m³	Appr. 1070 kg/m³
Formaldehyde Info	≤0.8% free formaldehyde	Contains no formaldehyde

Storage Conditions and Storage Life

In order to achieve the given storage life for the product, it is very important that the product is stored under the recommended conditions.

The optimal storage conditions for the adhesive is at temperature 15°C to 25°C.
Only short time exposure to temperatures below 10°C and above 30°C are acceptable. The product can be frozen but it must be thawed, raised to room temperature and homogenized before usage.

The optimal storage conditions for the hardener is at temperature 15°C to 25°C.
Only short time exposure to temperatures below 10°C and above 30°C are acceptable.

Frozen and thawed product cannot be used due to irreversible changes in the product.
The storage life for a product is determined by parameters such as reactivity, viscosity and rheology. The storage time ends when the reactivity, viscosity or rheology transforms from a relatively stable value to a value that can affect the gluing quality.

If the packaging is left open for long periods, the glue is susceptible to skin formation on the surface. To avoid skin formation, keep the packaging closed when not in use.

The storage life of 1247/2526 is listed below.

Storage Life (months from time of production)		15°C	20°C	25°C	30°C
	1247	4	4	---	2
	2526	4	4	---	2.5

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Gluing Operation Information

1247/2526 is intended for use in the wood working industry, for applications such as laminated beam production according to EN14080:2013, CLT, Duo- and Trio-beams as well as I-beams.

Mixing ratio

1247/2526 is approved according to EN301:2013 to be used in the following mixing ratios:

Spruce, Pine, Fir, European Larch, Sibirian Larch (by weight)	Mixed for fingerjointing	100 : 20-100 (glue:hardener)
	Separate for fingerjointing	100 : 100 (glue:hardener)
	Mixed and Separate for face lamination	100 : 20-100 (glue:hardener)

The adhesive and hardener shall be used in between the mixing ratio provided above. If other mixing ratios are used, various factors including press times, pot lives, assembly times, and glue line quality will be affected.

In the production of structural timber constructions the maximum allowed deviation from the given hardener ratio is ±2 parts by weight.

If a mixed system is used it is important to ensure that the adhesive and hardener have been thoroughly mixed before the mixture is used. If mixing the hardener and adhesive by hand, add the hardener to the adhesive.

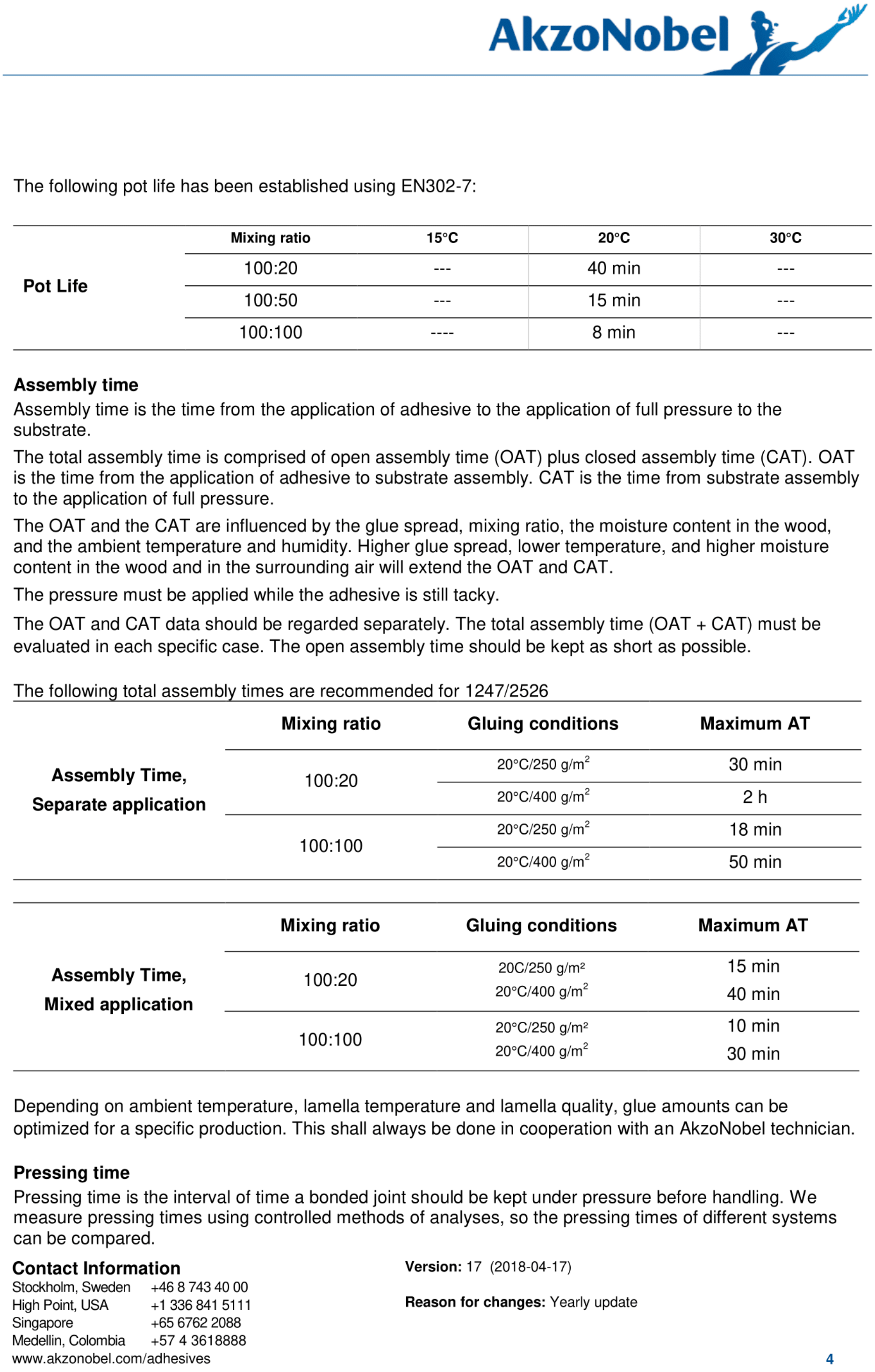
Separate application of glue and hardener

1247/2526 is optimal for use of separate application of glue and hardener for face gluing, preferably with our separate ribbon spreader 6230 or 7230 Ecoflex. These machines ensure correct ratio of glue and hardener is applied. Assembly times are prolonged while keeping short press times.
The use of other separate application spreader is only allowable if the suitability of these machines has been proven for the intended use.
When glue and hardener are used in separate application no problem with pot life will occur since the glue and hardener are not mixed until being applied on the surfaces to be bonded.

The maximum allowable bond line when using separate application of resin and hardener for face lamination is 0.3 mm.

Mixed application of glue and hardener

1247/2526 can also be used as a mix-in system for finger jointing, preferably with our mixers. Here it is important to have control of the pot life, as this limits the working life with which the system can be used.
Pot life is defined as the period of time during which the mixture of glue and hardener can be used. We measure pot lives using controlled methods of analyses, so the pot lives of different systems can be compared.



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The following pot life has been established using EN302-7:

	Mixing ratio	15°C	20°C	30°C
Pot Life	100:20	---	40 min	---
	100:50	---	15 min	---
	100:100	----	8 min	---

Assembly time

Assembly time is the time from the application of adhesive to the application of full pressure to the substrate.

The total assembly time is comprised of open assembly time (OAT) plus closed assembly time (CAT). OAT is the time from the application of adhesive to substrate assembly. CAT is the time from substrate assembly to the application of full pressure.

The OAT and the CAT are influenced by the glue spread, mixing ratio, the moisture content in the wood, and the ambient temperature and humidity. Higher glue spread, lower temperature, and higher moisture content in the wood and in the surrounding air will extend the OAT and CAT.

The pressure must be applied while the adhesive is still tacky.

The OAT and CAT data should be regarded separately. The total assembly time (OAT + CAT) must be evaluated in each specific case. The open assembly time should be kept as short as possible.

The following total assembly times are recommended for 1247/2526

	Mixing ratio	Gluing conditions	Maximum AT
Assembly Time, Separate application	100:20	20°C/250 g/m^2	30 min
		20°C/400 g/m^2	2 h
	100:100	20°C/250 g/m^2	18 min
		20°C/400 g/m^2	50 min

	Mixing ratio	Gluing conditions	Maximum AT
Assembly Time, Mixed application	100:20	20C/250 g/m² 20°C/400 g/m^2	15 min 40 min
	100:100	20°C/250 g/m² 20°C/400 g/m^2	10 min 30 min

Depending on ambient temperature, lamella temperature and lamella quality, glue amounts can be optimized for a specific production. This shall always be done in cooperation with an AkzoNobel technician.

Pressing time

Pressing time is the interval of time a bonded joint should be kept under pressure before handling. We measure pressing times using controlled methods of analyses, so the pressing times of different systems can be compared.

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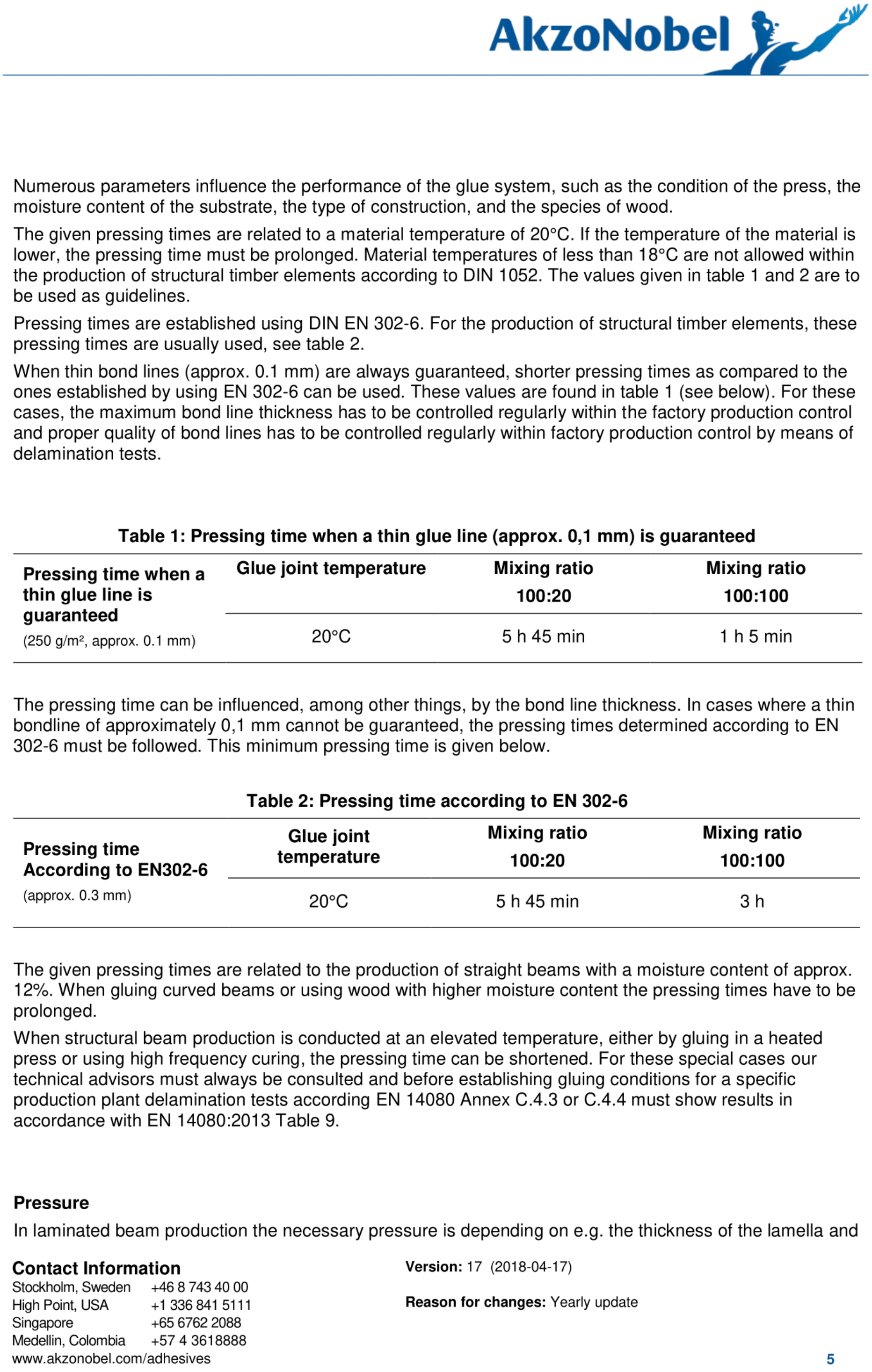

Numerous parameters influence the performance of the glue system, such as the condition of the press, the moisture content of the substrate, the type of construction, and the species of wood.

The given pressing times are related to a material temperature of 20°C. If the temperature of the material is lower, the pressing time must be prolonged. Material temperatures of less than 18°C are not allowed within the production of structural timber elements according to DIN 1052. The values given in table 1 and 2 are to be used as guidelines.

Pressing times are established using DIN EN 302-6. For the production of structural timber elements, these pressing times are usually used, see table 2.

When thin bond lines (approx. 0.1 mm) are always guaranteed, shorter pressing times as compared to the ones established by using EN 302-6 can be used. These values are found in table 1 (see below). For these cases, the maximum bond line thickness has to be controlled regularly within the factory production control and proper quality of bond lines has to be controlled regularly within factory production control by means of delamination tests.

Table 1: Pressing time when a thin glue line (approx. 0,1 mm) is guaranteed

Pressing time when a thin glue line is guaranteed (250 g/m², approx. 0.1 mm)	**Glue joint temperature**	**Mixing ratio 100:20**	**Mixing ratio 100:100**
	20°C	5 h 45 min	1 h 5 min

The pressing time can be influenced, among other things, by the bond line thickness. In cases where a thin bondline of approximately 0,1 mm cannot be guaranteed, the pressing times determined according to EN 302-6 must be followed. This minimum pressing time is given below.

Table 2: Pressing time according to EN 302-6

Pressing time According to EN302-6 (approx. 0.3 mm)	**Glue joint temperature**	**Mixing ratio 100:20**	**Mixing ratio 100:100**
	20°C	5 h 45 min	3 h

The given pressing times are related to the production of straight beams with a moisture content of approx. 12%. When gluing curved beams or using wood with higher moisture content the pressing times have to be prolonged.

When structural beam production is conducted at an elevated temperature, either by gluing in a heated press or using high frequency curing, the pressing time can be shortened. For these special cases our technical advisors must always be consulted and before establishing gluing conditions for a specific production plant delamination tests according EN 14080 Annex C.4.3 or C.4.4 must show results in accordance with EN 14080:2013 Table 9.

Pressure

In laminated beam production the necessary pressure is depending on e.g. the thickness of the lamella and

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the wood species.

Lamella thickness of under 35 mm requires pressure between 0.6 – 0.8 MPa. If lamellas have thickness between 35 - 45 mm, pressure should be 0.8 MPa (grooved lamellas) or 1.0 MPa (non-grooved lamellas). For lamella thickness between 45 - 80 mm, pressure should be 0.8 - 1.0 MPa. Bear in mind that lamella thicknesses of more than 45 mm are not allowed in glulam production. Same pressure can be used when separate application of resin and hardener is used for face lamination.

Too high pressure may cause excessive adhesive squeeze out, resulting in a starved glue line.

Too low pressure may result in poor contact between the two surfaces, causing a weak bond.

Glue spread

The glue spread may vary, depending on wood specie, wood moisture content, relative humidity, room temperature, press types, assembly times, and planing quality. The minimum glue spread should not be lower than the values stated in the table below:

The glue spread should not be below 220 g/m² for curing at room temperature.

The glue spread should not be below 180 g/m² for curing with radio frequency.

For the production of structural timber constructions a reduction of the glue spread, e.g. at very short assembly times, is only allowed to be done together with our Technical Advisors and depends on the production parameters for the production line in question. The optimization implies that the set parameters are followed and that a continuous control of the bonding quality is made by means of delamination tests. For these cases signed written statements from AkzoNobel and the adhesive approval institute are mandatory.

A slight squeeze out of adhesive along the edge of all the joints when pressure is applied indicates adequate glue spread and that the total assembly time has not been exceeded.

A high squeeze out indicates excessive glue spread, very high press pressure, or a combination of these two factors.

Higher glue spread can be used when long assembly times are required.

An evenly applied glue spread is important.

Moisture content of Wood

The moisture content of the wood will affect the gluing result. High moisture content can slow down the system, and for some adhesive systems, excessively high moisture content will negatively affect the glue line quality.

In some cases, excessively low moisture content can accelerate the gluing process.

The moisture content of the wood will also affect the overall quality of the end product. Moisture content that is uneven, excessively low or high, can cause the material to warp, cup and become uneven.

For laminated beam production, moisture content should be preferably 10 - 12%, or at least within 6 - 15%. The maximum allowable difference of the moisture content between two boards is 5% according to EN14080, Annex I.

Preparation of wood

For best result the wood must be smoothly planed. For optimum bond strength the bonding operation shall take place within 24 hours after preparation.

The surface must be free from dust, grease, oil, and other contaminants.

The substrate must be carefully selected so an optimum bond line quality is achieved. In order to meet the pressing times given above, lamella temperature must be at least 20°C. Material temperatures of less than 18°C are not allowed within the production of structural timber elements according to DIN 1052.

1247/2526 is approved for following wood species: Spruce, Fir, Pine, European Larch and Sibirian Larch.

Post curing

After the pressing time, the bond line has enough strength for the construction to be handled. Full strength will be reached after a certain time, depending on the pressing time and the pressing temperature.

Post curing is the time needed for the bond line to build enough strength to reach final strength and water resistance.

The specific post curing time depends on the pressing time, the pressing temperature, lamellae temperature, and the post curing temperature.

Curing at temperatures other than 20°C will change the required post curing time. The relevant post curing time must be provided by an AkzoNobel technical advisor.

At 20°C, the post curing time is 20 hours for 100:20, and 10 hours for 100:100.

Formaldehyde emission information

The glue system has been tested according to EN14080 and has passed E1 at worst level conditions.

To determine the emission level of your glued product, a product sample must be sent to a testing institute for measurement.

For more information on emissions norms, post treatments, and related information, please contact your technical representative.

Additional information for finger jointing

For the production of finger joints the requirements given in DIN1052 and EN14080:2013 must be followed. Mix-in or separate application can be used. When using separate application the requirements of Z-9.1-730 bust be followed. The table below highlights important bonding information:

Nominal mixing ratio	Mixed application: 100:20 to 100 Separate application: 100:100
Glue spread	Recommended between 250 -350g/m^2
Maximum assembly time	5 min
Curing time	100:20 5 h 45 min 100:50 2 h 100:100 1 h 5 min
Pressure	According to EN 14080:2013

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Mixed application of finger joints
When a glue mixture is used, profiled rollers or similar equipment is recommended. Mix ratios between 100:20 (glue:hardener) and 100:100 part by weight can be used. The accuracy of the ratio between glue and hardener shall be ±3 pbw. 75% of the area of the fingers needs to be covered with glue mixture.
It is important here to check pot life, as it limits the usage of a glue mixture. The table listed under "Pot life" can be used to check the pot life at 20°C for different mix ratios. A cooled glue mixture will have longer pot life. Higher temperature will shorten the pot life.

Separate application of finger joints
When using separate application on finger joints, double application of glue and hardener, and continuous surveillance of the glue and hardener application in accordance with the technical specification Z-9.1-730 (DIBt) must be ensured. The nominal mix ratio is 100:100 (glue:hardener) with a machine system inherent deviation of ± 3pbw hardener. Deviations on the flanges of the fingers due to application issues shall be less than ±30 pbw of hardener. At least 75% of the area of the fingers must be covered with glue and also with hardener.

Curing of finger joints
The minimum pressing temperature shall be +20°C, when producing according to EN14080:2013.
If Radio frequency curing (RF) is used, the temperature in the zone of the finger joint should reach a temperature of minimum 65°C.

Further treatment of finger joints
Finger jointed lamellae can be further processed directly after the finger jointing operation if the transportation equipment and the planing of the lamellae do not expose the joints for any damaging stresses. Otherwise the pressing time in the table above shall be followed.

End strength of finger joints
The time of final strength of a finger joint will depend on curing conditions and adhesive system used. For 1247/2526 used with a mixing ratio of 100:20 this time is 20 hrs., for 100:100 this time is 10 hrs.

Quality control of finger joints
The quality control of the finger joints must be in line with the respective product standard.

Handling and HSE info

Cleaning Agent 2704;

It is highly recommended to use Cleaning Agent 2704 to clean the adhesive ribbon spreader. Add a 50/50 (by weight) solution of warm water and Cleaning Agent 2704 to the spreader. Let the solution pump around the spreader for four minutes, then wash with warm water

Cleaning

Equipments must be cleaned with lukewarm water before the adhesive has cured. Cured adhesive must be removed mechanically.

Handling

Avoid direct contact with adhesives and hardeners. Always use gloves and goggles. If adhesive or hardener comes in contact with skin, immediately wash the affected area with soap and lukewarm water.

Due to its low pH the hardener is corrosive to copper and copper-containing alloys. Steel or plastic is therefore recommended for use in direct contact with the product.

The Safety Data Sheet provides information regarding health and safety. Study this information carefully.

Miscibility

Whether a product can be mixed with another product (for example when changing the glue or the hardener to another product) must be determined in each specific case. Please contact your technical representative for more information.

Waste Handling

Glue - Is normally classified as hazardous waste (contains free formaldehyde).

Hardener - Depending on classification hardeners may be considered as hazardous waste, check the SDS (section 13).

Mixed glue and hardener – Can normally be treated as not hazardous waste when fully cured.

NOTE! There might be national and/or local regulatory differences, therefore always keep a dialogue with the local authorities

Waste water treatment

Mechanical Precipitation → municipal sewage with biological treatment

Mechanical precipitation (sedimentation) is used to lower the solid content of the waste water in order to minimize the risk of clogging of pipes. Sedimentation of the waste water can easily be carried out in an empty barrel or IBC container depending on the amount of wash water used. When the container is full of sludge it should be left to dry (preferably above 50°C) and can after that normally be treated as not hazardous industrial waste. The water phase can normally not be let out directly into the drain without permission from the local authorities.

NOTE! There might be national and/or local regulatory differences, therefore always keep a dialogue with the local authorities. If assistance is needed, contact our technical representative.

Health and Safety

For more information, see SDS

Legal clause

The information is based on laboratory tests and practical experience. It is introductory and intended to help the user find the most suitable method of working. Since the user's production conditions are beyond our control, we cannot be held responsible for the results of the work which is affected by local circumstances. In each particular case testing and continuous control are recommended.

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