Improving the production process of the Flap Wheels factory at Sundisc Abrasives

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Preface

This report is the result of my internship at Sundisc Abrasives as part of my master thesis in Industrial Engineering & Management with the specialization track of Production and Logistics Management. This thesis marks the end of five years of studying and the beginning of a new part of my life. For helping me come this far I would like to thank the people who supported me.

First of all I would like to thank the people at Sundisc Abrasives. I would like to thank Jan Enno Hofman for giving me this opportunity and for talking to me about what would be useful for the company to help me make sure that this report would be valuable to the company. I would like to thank Gino van Santen for being there for me on a daily basis, for keeping me in the loop about what is going on and for pointing me to the people with the right knowledge and for making me feel at home at Sundisc Abrasives. I would also like to thank the production team at Sundisc Abrasives, their knowledge and willingness to help me have greatly helped me during this project.

Aside from the people at Sundisc, I would like to thank the people at the University of Twente. My first supervisor, Ahmad al Hanbali, has helped me from the very beginning and from the start his feedback has allowed me to ensure that the quality of this thesis lives up to not only his, but also my expectations. My second supervisor, Martijn Mes, helped me greatly with my simulation model, which was a key part to my thesis. Both of them have helped me moving forward when difficulties arose during the project.

Lastly, I would like to thank my family and friends for supporting me during my thesis and during my studies too.

Yoeri Geurts
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Management summary

Sundisc Abrasives has recently started a new production line. Throughput at this new production line has been below expectations and in order for the production line to be profitable, the throughput has to be increased. To this end, the following research question is answered: *How can Sundisc improve the average throughput of their flap wheel production line to at least 5200 flap wheels per shift?*

First the layout of the production line and the flow of products through the system are analyzed. The process consists of a preparation station, two production machines, two gluing robots, a hand gluing station, two ovens and a packaging area. For this research the focus is on the production machines, the gluing robots and the hand gluing station, as these stations form the core of the production process. For each of these stations data is gathered and analyzed to determine the characteristics of the individual machines.

In order to evaluate the performance of the production line and how the performance can be improved, a simulation model is constructed. This model is verified by testing the behavior of the individual stations and validated using expert knowledge. The model is used for running experiments of different scenarios. The purpose of the first set of scenarios is to measure the impact of changes in the setup times and failure times at the production machines, the main bottleneck, on the throughput of the system. From these experiments we find that the current average throughput per shift is 3557, far below the goal of 5200. We find the following relations between setup time, failure time and throughput:

- A decrease in setup time of 25% leads to an increase in throughput of the system of 2-3% for a maximum throughput increase of approximately 13%. Leading to an average throughput of 5222 per shift, with a 95%-confidence interval of [5200-5246]
- A decrease in failure time of 25% leads to an increase in throughput of the system of approximately 1% for a maximum throughput increase of approximately 5%. Leading to an average throughput of 4846 per shift, with a 95%-confidence interval of [4827-4866]

This linear relationship also holds for increases in the setup times and failure times. Only the total elimination of the setup times leads to a throughput of 5200 flap wheels or higher. A combination of the reduction of setup times and failure times leading to the same throughput increase would also be enough to increase the average throughput per shift to 5200 but the total elimination of setup times, or something close to it, is not possible in practice.

Aside from changing the setup times and failure times, another option is to add different machines to increase the throughput. In order to do this, new experiments are conducted to find the average throughput of every individual machine. An incremental addition approach is then used to find the machines that have to be added in order to increase throughput. Each time a new machine is added to the previous addition, no changes to the previous addition are made. Each time there is only one option that improves the throughput for the current situation, no other options result in an improvement. The result of this approach is shown in Table M.0.1. In this table the layout of the configuration is p-g-h, with p refers to the production machines, g to the gluing robots and h to the hand gluing. With 1 machine added the configuration is 3-2-1, meaning 3 production machines, 2 gluing robots and 1 hand gluing machine.

Table M.0.1 Incremental machine addition summary, configuration p-g-h means p of production machines, g of gluing robots and h of hand gluing stations

Machines added	Configuration	Throughput	Throughput increase
0	2-2-1	3557	x
1	3-2-1	5237	1680
2	3-2-2	5335	98
3	4-2-2	6506	1170
4	4-3-2	7114	608
5	5-3-2	8892	1778
6	6-3-2	9758	866
7	6-4-2	10473	715
8	6-4-3	10670	197
9	7-4-3	12449	1778
10	8-4-3	13011	562

For each of these configurations the throughput for different types of products is also determined this way. This way the bottleneck for different types of products, which is located at different points in the system with different configurations, is found. This can also be used to calculate the new expected throughput in case of a change in the product mix that is sold by Sundisc Abrasives.

Based on these findings, the solution to the low throughput of the system is to add an additional production machine as this is the bottleneck of the system, for all of the products. Recommendations for future machine additions can also be found from this solution.

Further recommendations can be made based on the research:

- When the throughput requirements grow, add additional machines in the order shown in Table M.0.1.
- Change the performance measure for throughput at the production machines to include differences in the processing times due to product type. The current measure just counts the total number of products without taking into account that the operators have no control over the type of products they make.
- Add the following performance measures: number of setups at the production machine per different type (height change, width change or change of both), throughput at the hand gluing station, percentage of trays reworked at the hand gluing station for different product types, rate at which delivery schedules are met and difference between planned output and actual output.
- Continue gathering data regarding the processing times at the production machines, gluing robots and hand gluing station. This data would allow for more precise prediction of processing times for different products.
- Future research on a possible switch from Make to Order to Make to Stock, and on an improved resource driven planning system.

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1. Introduction

This project is a part of the author's master thesis. It is the conclusion of the Master of Industrial Engineering & Management with the specialization track of Production and Logistics Management at the University of Twente. It describes the research conducted at Sundisc Abrasives. The company description is given in Section 1.1, the project description is given in Section 1.2 and the design of the research is given in Section 1.3.

1.1. Company description

Sundisc Abrasives is a medium sized company that specializes in abrasives such as flap discs. The organization has been growing strongly for many years. Recently they acquired a factory in Malaysia for the production of clean & strip products. The company has a global yearly revenue of 22-23 million euros and has around 70 employees around the globe. Sundisc offers their products without its own label. This means that they produce for other companies who then sell the product as their own. Because of this there is a large product variety in their finished goods, which makes it challenging to meet the requirements of their customers on time. Their customers mainly consist of wholesalers.

1.2. Project description

Sundisc recently launched the production of a new product named the "flap wheel". Production levels have, however, been lower than expected, too low to have a profitable production line. Sundisc aims to improve the efficiency of their new production line to raise it to profitable levels. The production line has been set up only recently and up until a month before the start of this research, it was managed by the plant manager of their primary production plant. This means the plant manager had to pay attention to two factories at the same time. This means many things slipped through the cracks in the flap wheel factory, as the main factory was of prime concern. Approximately a month before the start of this project an employee was promoted to manage the flap wheel factory directly. This change, combined with the master thesis, is supposed to increase the production up to a profitable level.

In the current situation production takes place on a Make To Order basis (MTO). Orders have to be ready to be shipped within 10 working days after they are placed. The size of orders can vary from a few hundred products to a few thousand. Orders can be anticipated to a certain degree once the production line has been operational for a longer period. The lack of historical data is making this hard at the moment and possible rapid growth in the future further complicates this. The production planning is currently made by hand by the new plant manager, purely based on orders received. New orders are added to the planning as they arrive, usually on a day to day basis. The planning is based on the downtime at the production machines due to setup times and respecting the 10 working days deadline. Any further implications for the rest of the production line are not taken into account. While it is possible to produce to stock in practice this is not done yet, upper management is however open to the possibility of producing to stock in the future.

In the current situation there is a prevalent feeling within the organization that there are a lot of inefficiencies in the production line. They have identified some of these inefficiencies and are trying to solve them but they want the added insight of a more scientific approach to help identify other problems and what the impact of solving these problems would be.

In order to assess current inefficiencies and identify additional opportunities for improvement a model is made of the new production. The type of model that is selected is a part of the research. This model is validated and verified to make sure it is representative of the current situation. After this is done the model is used to identify areas of improvement that will have the biggest impact on production.

1.3. Research design

The company has already put a plant manager in charge of improving the situation by handling problems that arise during production. On top of that however they want someone to identify less obvious ways of improving production. A model can help identify the ways in which the system can be improved. The purpose of this model is to investigate and improve the system. This leads to the objective, research question and sub-questions in Section 1.3.1. The scope of the research is discussed in Section 1.3.2 and the problem approach in Section 1.3.3.

1.3.1. Objective

The objective of the master thesis is to improve the throughput of the production line up to an average of 10400 flap wheels per day, which translates to 5200 per shift; Sundisc has determined that this would be sufficient to make the production line profitable. Any further improvements are, of course, encouraged. The existing line will be used to reach this objective and while machines may be added, they may not be replaced.
To reach this objective the following research question will be answered:
How can Sundisc improve the average throughput of their flap wheel production line to at least 5200 flap wheels per shift?

To answer the main research question we formulated the following sub-questions:

1. What is the current situation at the production plant?
   For this sub-question a description of the current production plant is given. This includes order handling, inventory management and the flow of materials/products.

2. How can the data be used to construct a conceptual model?
   For this sub-question we construct a conceptual model. The variables that are included in the model and how the data is used to construct these variables is discussed. This serves as a translating step to be able to identify and construct the correct formal model.

3. How can the current situation at the production plant be modelled in a formal model?
   Based on the conceptual model a formal model is chosen. This formal model is used for numerical analysis of the production line. In theory there are many different types of formal models. Determining the formal model that is selected is part of this sub-question. This model is developed, experiments are conducted and the results are discussed.

1.3.2. Scope

The scope of the research is the main production. This means it does not include the preparation for production or the packaging. Anything else relating to the production, for example inventory management, does not have to be changed during this research but any changes that are required to support the outcome are mentioned. The main focus is on the production machines, the gluing robots and the hand-gluing station. These machines cannot be replaced, they can only be improved or additional machines can be added.

1.3.3. Problem approach

1. Line description:

The purpose of the line description is to provide an overview of the production system and its different components. It also shows the practices in the production line and how this all fits together. It can be used as a basis for the conceptual model and to provide an easy introduction to the production process for readers.

For the line description informal conversations with employees at the production plant have been used. Time has been spent to monitor the production process and to ask questions. After the line description was formulated this description was presented to individual employees and the plant manager to verify the accuracy of the line description.

2. Conceptual model and data:

The purpose of the conceptual model is to translate the line description into more scientific terms in order to link the production process to the formal model. This can then be used to identify possible formal models and limitations of these formal models when it comes to modeling the production line.

For a model with the purpose of investigating and improving the system the conceptualization is very important (Pidd, 2010). The conceptualization is done by regular interactions with the plant manager and the employees working in the plant. Preceding the formation of the conceptual model, data was also gathered through observation of the system for an extended period of time, during which interactions with the employees were possible. The main focus of the conceptual model is on the variables included in the formal model and how these variables can be constructed from the gathered data.

3. Formal model:

The purpose of the formal model is to represent the production line in such a way that it will allow numerical and/or mathematical analysis. This model can then be used for experimentation, for example by changing different input variables. These input variables are mostly on an operational or tactical level. Decisions at the strategic level are only counted as constraints, not as variables that can be altered.

The formal model representing the system is made based on the conceptual model. The nature of this formal model is established based on the findings of the conceptual model. This formal model is validated by the plant managers and operators and the accuracy is verified by analyzing output and product pathing. The results of the formal model and the validation techniques are presented to, and discussed with, the supervisors in order to ensure they support the model and any findings derived from it.

Through experimentation, the formal model is used to identify the impact of certain measures on the throughput of the whole system. These impacts are then presented and conclusions are drawn from them.

2. What is current situation at the production plant?

To answer this sub-question this chapter is split in five sections. In Section 2.1 an introduction of the product is made, then in Section 2.2 the handling of orders is discussed, after that the handling of raw material inventory is explained in Section 2.3, the production process is discussed in Section 2.4 and finally an overall overview is shown in Section 2.5.

Packaging is left out as it falls outside of the scope of this project and it takes place after the rest of production so it has little effect on it.

2.1. Product description

The product consists of four components:

- A spindle (Figure 2.1)
- A cardboard label (Figure 2.2)
- Sandpaper (Figure 2.3)
- Glue (Figure 2.4)

Figure 2.1: A spindle

Figure 2.2: A carboard label

Figure 2.3: Sandpaper

Figure 2.4: Glue

This sounds relatively simple but there is a large variety in the actual product. Currently Sundisc is offering, on their website, 67 different product variations in their regular assortment with 257 additional product variations available on request. Internally even more variations are possible; these are not advertised on their website but are regularly being made. Even internally they are unsure about the number of possible variations in their product. The main variety comes from the sandpaper; there are two properties in which the sandpaper can change. The roll of sandpaper can have a different width or the grain can be smaller or larger (fine or rough). The machine can also cut the sandpaper to parts of different sizes which further contributes to the variety of final products that can be made. There are also a few different kinds of spindles. The labels are different for each size of product and in the future it is possible that the same size product may have varying labels too.

Figure 2.5: Flap wheel

The final product is called a flap wheel (Figure 2.5). It is flaps of sandpaper that are glued to a spindle. This product is used for cleaning surfaces that are hard to reach with the regular flap discs, for example cleaning inside of pipes.

2.2. Order handling & planning

The production of flap wheels is based on Make To Order (MTO). A customer places an order at the sales department, which is then sent to the planning department. At the planning department an internal production order and packaging order list is produced which is then sent to the plant manager. Based on these production orders and packaging orders a planning is made by the junior plant manager by hand. This means that for the flap wheel production the planning department does not actually do the planning and scheduling, this is done at a lower level in the organization by the junior plant manager.

The planning is made based on perceived optimal production machine downtime due to setup; other forms of downtime are not included. There is no actual data for this but there are general rules that make it somewhat predictable which setup is longer and which is shorter. Furthermore the order has to be finished and be ready to be shipped within 10 workdays after the order is received. If this conflicts with downtime optimization, changes to the planning are made again by hand by the junior plant manager to make sure the deadline is met. The planning just consists of the order in which the different production orders have to be produced. If production is delayed all orders are simply pushed back and produced later, unless this violates the 10 work-day deadline.

2.3. Raw material inventory

The inventory of raw material is managed by the Pilmanager. The handling of this inventory is done purely at the Pilmanager's discretion. For every type of raw material the Pilmanager takes the mean amount used per week and decides how many weeks' worth of inventory the minimum and maximum inventory is. For example for a certain piece of sandpaper the minimum is two weeks of inventory and the maximum is six. When the inventory reaches the two weeks' worth an order is placed to reach the six weeks' worth of inventory, or as little over it as possible, due to order size rules. The Pillmanager keeps track of the average amount used per week and the numbers are altered every few weeks.

2.4. Production process

To start describing the production process first the materials that are used during production are revisited. Four components are used for the product as described in Section 2.1. The product consists of sandpaper, a spindle, a cardboard label and glue. During production four more tools are needed to make the product, a ring to hold the sandpaper (Figure 2.8), a cup so that the product is formed correctly (Figure 2.9), a tray to hold all the cups (Figure 2.6) and a cart to hold all the trays (Figure 2.7). There is a limited amount of all of these, with the amount of cups being the most restrictive for production.

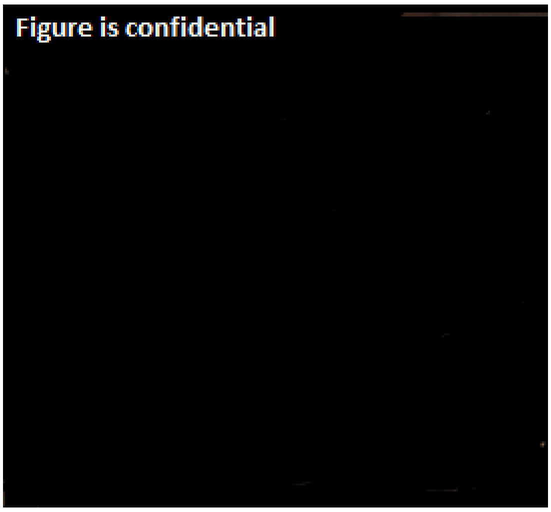

Figure 2.6: Tray

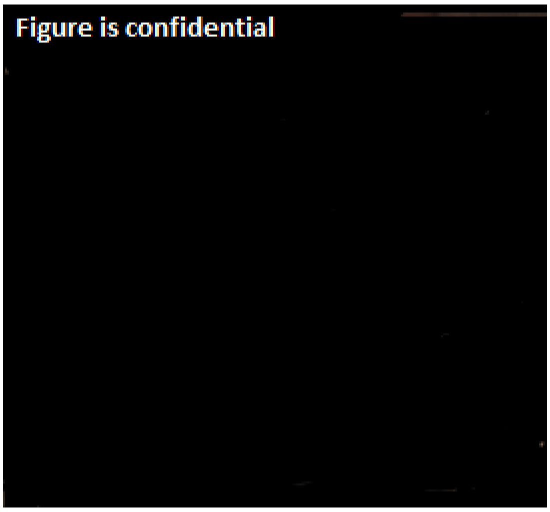

Figure 2.8: Ring

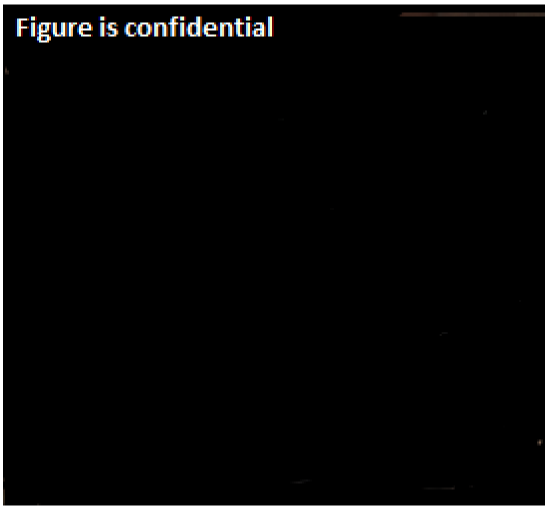

Figure 2.9: Cup

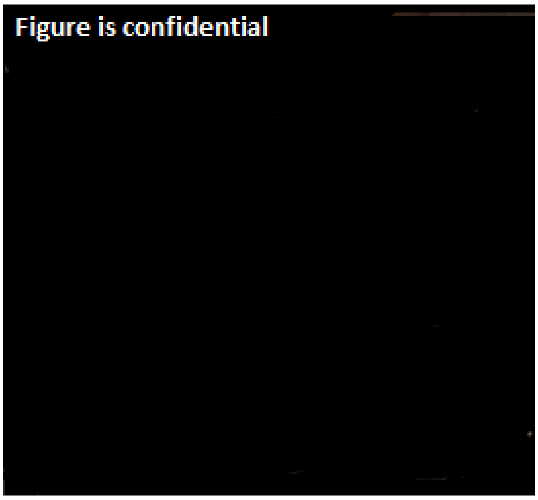

Figure 2.7: Cart

The production process consists of six steps with one additional step being added if needed.

- Preparation
- Cutting sandpaper and putting the sandpaper in cups (called production internally)
- Gluing the sandpaper (using a gluing robot)
- Topping off the glue by hand
- Curing the glue in an oven
- Packing the product

Alternatively if the gluing of the sandpaper is expected to be insufficient after the first round of topping off the glue, the products are cured in the oven for a short time before they are glued again by hand. After that they can be put in the oven to cure for the last time.

There are four people on the work floor, two are production employees, also known as machine operators and two are production-supporting employees. The production-supporting employees handle the preparation, take the finished carts out of the oven and handle the hand gluing station. They also take care of packaging. The distribution of tasks for production-supporting employees is fluid, they regularly switch stations. The production employees handle the two production machines and the two gluing robots. Unlike the production supporting employees the production employees have a clear distribution of tasks; each production employee handles one production machine and one gluing robot. The ovens are not a part of this project, other than the extra time spent in between hand gluing, if applicable.

Packaging is ignored in the rest of this chapter as it has little effect on the rest of the production line and therefore is outside of the scope of this project.

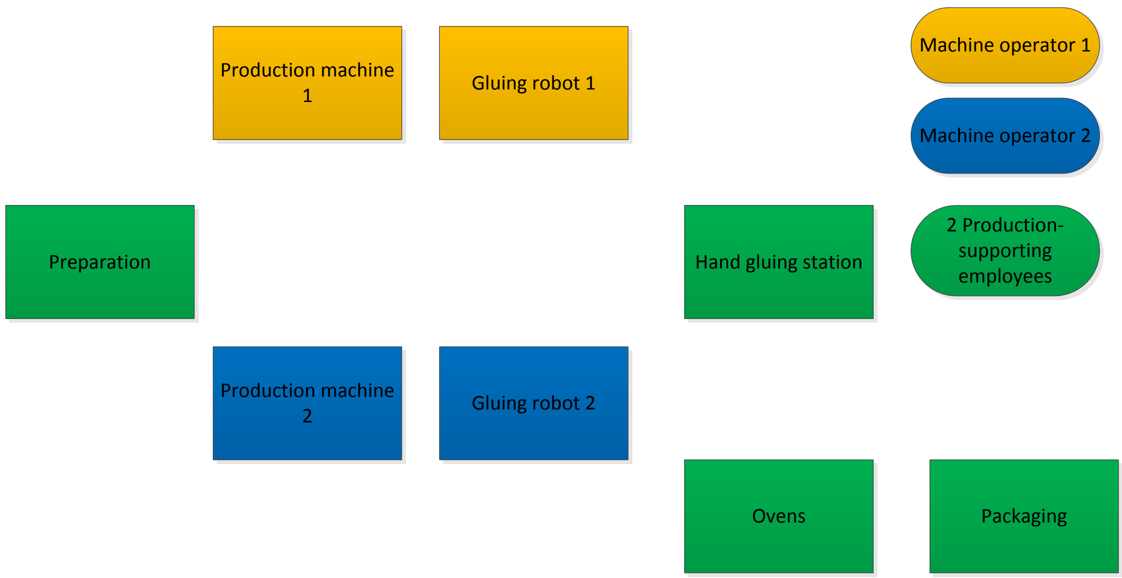

Figure 2.10: Production layout task distribution

The production layout as described above can be found in Figure 2.10. The workstations are represented by the rectangles and the employees are represented by the ellipses. The green color represents the production-supporting employees and the stations they are responsible for. The orange color represents machine operator 1 and the stations he is responsible for and the blue color represents machine operator 2 and the stations he is responsible for. From this figure you can clearly see the strict distribution of tasks for the machine operators and the fluid distribution of tasks for the production supporting employees.

Production takes place in multiple shifts. There are two shifts per day on Monday to Thursday and one morning shift on Friday. A morning shift is from 6AM to 3PM and an evening shift is from 3PM to midnight. Each shift has three breaks after every 2 hours of working. The first and third breaks are 15 minutes and the second break is 30 minutes.

The components of the production process are discussed in separate sections. The preparation is discussed in Section 2.4.1, the production is discussed in Section 2.4.2, the gluing robots are discussed in Section 2.4.3, the ovens are discussed in Section 2.4.4 and the hand gluing station is discussed in Section 2.4.5.

2.4.1. Preparation

For preparation the trays are prepared for production. This means that the trays with the cups are taken, a cardboard label is put on the spindle and the spindle is then put in the cup. At this point the tray is ready for the next step of production. All trays for a production order are put together next to the production machine together with the rolls of sandpaper that will be used during production. For certain types of spindles in smaller cups a magnetic tool has to be used to put the spindles in the cups, which makes the time needed a little longer.

Mistakes

The preparation is fairly straightforward but sometimes mistakes are made. Sometimes the cardboard labels are put on wrongly, sometimes the wrong spindles are used or the spindle is put in the cup upside down. These mistakes rarely have an impact at the final product as they rarely occur and most can be found later in the production process; however some do make it through.

Batching

For preparation the orders are batched per complete order. The order is prepared tray by tray until all trays for the order are made. They are stored next to the production machines and there are generally multiple orders worth of trays stored near the production machine to make sure it can keep producing.

Resources used and exiting resources

Used: tray with cups, spindle, cardboard label (Figure 2.11)

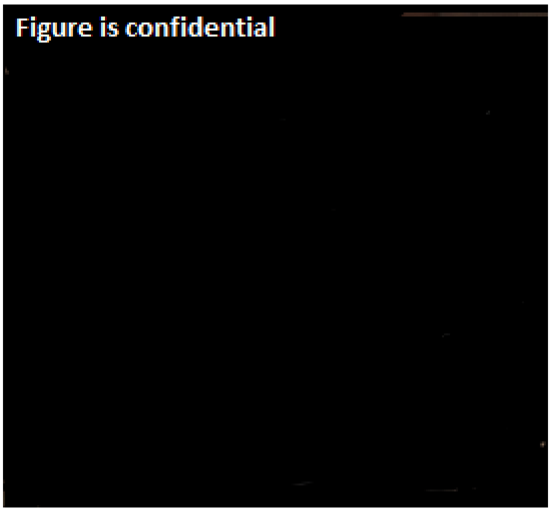

Figure 2.11: Materials entering preparation

Exiting: tray with cups filled with spindle and cardboard label (Figure 2.12)

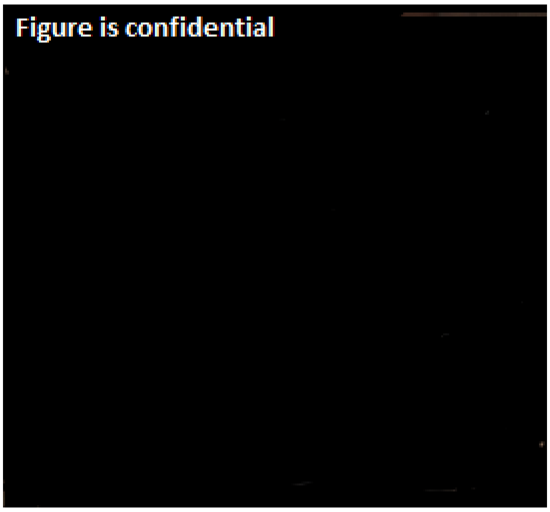

Figure 2.12: Materials exiting preparation

2.4.2. Production

The production machine is where the sandpaper is put in the cups to make them ready to be glued.

Setup

Since the roll of sandpaper has to be guided through the machine, the machine has to be altered in order to be able to properly guide the roll of sandpaper if the product changes. This has to be done by hand and may take a long time, between 15 minutes to an hour. As these setups have to be done manually and require changing parts in the machine the setup times are also highly variable and dependent on the operator's skill and knowledge of the machine. Setup times also vary according to the way the next order is different from the last. The main difference is in the height and the width of the product, as shown in Figure 2.13.

Figure 2.13: Height and Width

If the height of the product changes, extensive changes have to be made to the machine by hand. However, if only the width of the product changes, it takes a slightly shorter time. If both have to be changed naturally the setup time increases even more. This means that there is a ranking in which type of orders are better to put after a certain order. The most preferable is a product that requires no changes, then a product that is only different in width, then a product that is only different in height and last is a product that is different in width and height.

Downtime

Downtime for the machine can also be quite extensive. There are a lot of moving parts causing frequent downtime. The most frequent cause of downtime can happen multiple times a day and takes some time to fix, 15 to 30 minutes. On average this should happen after 2000 flap wheels have been produced but different sizes of flap wheels result in different wear on the machines resulting in highly variable times at which they break down. There are also various other common occurrences of downtime due to mechanical failure but these are quicker to remedy.

There is also regular downtime caused by resources that are running out. This is primarily caused by the roll of sandpaper ending. It is not possible to change the roll of sandpaper while the machine is running; this means every time a roll ends there is a few (one or two) minutes of downtime. This is not highly variable and only a short period of time.

Another source of downtime is if an operator is busy taking care of the gluing robot and the production machine runs out of rings to put the sandpaper in.

Batching

Batching at the production machine takes place per tray. Once a tray is finished it is sent to the gluing robot. If the gluing robot has already finished the last tray, the new tray is immediately entered into the gluing robot. If the last tray is still being glued the new tray is put on a cart until the gluing robot is done.

Resources used and exiting resources

Used: tray with cups filled with spindle and cardboard label, roll of sandpaper (Figure 2.14)

Exiting: tray with cups filled with spindle, cardboard label and pieces of sandpaper (Figure 2.15)

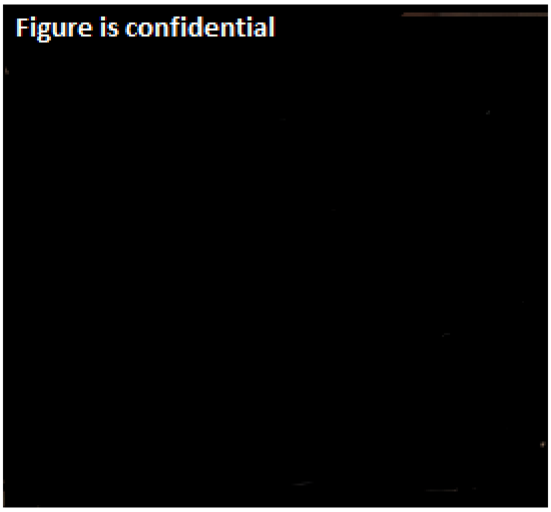

Figure 2.14: Materials entering production

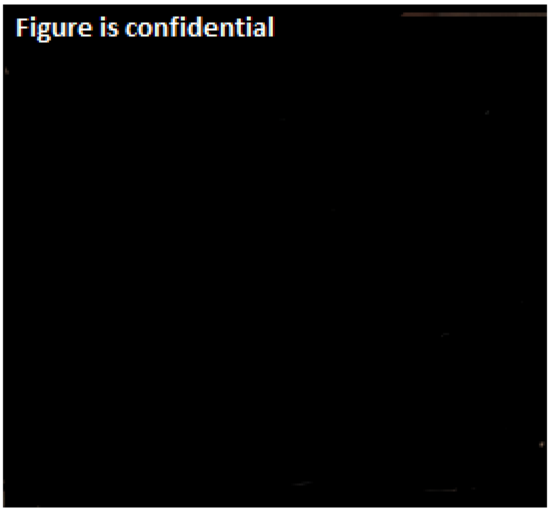

Figure 2.15: Materials exiting production

2.4.3. Gluing

At the gluing robot the hole in the middle of the flap wheel is filled with glue to keep the sandpaper in place and to fix the sandpaper to the spindle. This is done by placing a tray in the gluing robot and letting it fill the cups one by one with glue. For the smaller sizes this is done in two cycles to account for the fact that the glue needs to settle in. For these smaller sizes this may cause the level of glue to drop so significantly that a second cycle of filling is needed. If, even after the second cycle, the glue settles and it turns out that another cycle of filling is needed, this is then done by hand and not in the gluing robot. See Section 2.4.5 for more details on this. Different sized flap wheels take different amounts of time to fill, the smaller products take two cycles, which obviously takes more time. This means for varying products either the production is slower or the gluing is slower.

<u>Setup</u>

The setup times for the gluing machine are rather short. There are no mechanical parts that have to be manually changed like in the production machines; it is just about adjusting settings in the software. Then after a testing round, or letting the machine fill a few products, further minor adjustments are made to the settings until the result is satisfactory. There is a trade-off that has to be made here as there are multiple options for how to find the right settings. The operator can make the robot only fill one or a few cups and adjust settings based on that, this requires the operator to be present but means this tray will deviate from the optimum less, possibly meaning less rework that has to be done after. Additionally the operator can decide to let the first tray fill fully and then inspect the tray to identify how to change the settings, giving a larger sample size, allowing the operator to tend to his other duties on the work floor but also giving the possibility that the entire tray has to go to the hand-gluing station.

<u>Downtime</u>

Downtime at the gluing robot mainly consists of having to switch out the glue barrel for a new one when they are empty. This takes a significant amount of work and often requires two people. It takes around 30 minutes to replace the glue barrels. After that the glue barrels have to be mixed and brought up to the right temperature. The mixing takes longer than the heating.

Another source of downtime is due to operators being busy at the production machine while the gluing robot has finished and needs a new tray to be put in. This can simply be because the operator does not have time to put one of the trays that are waiting in the machine but can also happen because the tray has not been filled yet and is still at the production machine.

Batching
Batching at the gluing robot takes place per cart. Once a tray has been glued it is put on a cart with other trays until the operators decide the right amount of trays is on the cart. This can differ per size of product since there are more small products on one tray than there are large products. The main consideration here is that the cart needs to be available again soon and that handling a very large amount of small products at the hand gluing station and the packaging station takes a very long time. This means that for smaller products the operators prefer to only put a very small amount of products on the carts, even if this means the oven is far from full. For example a cart can hold up to 24 trays, but for the smaller sizes only 8 trays are put on the cart before it is sent to the next stations.

Resources used and exiting resources:
Used: tray with cups filled with spindle, cardboard label and pieces of sandpaper, glue (Figure 2.16)

Exiting: tray with cups filled with spindle, cardboard label and pieces of sandpaper glued together (Figure 2.17)

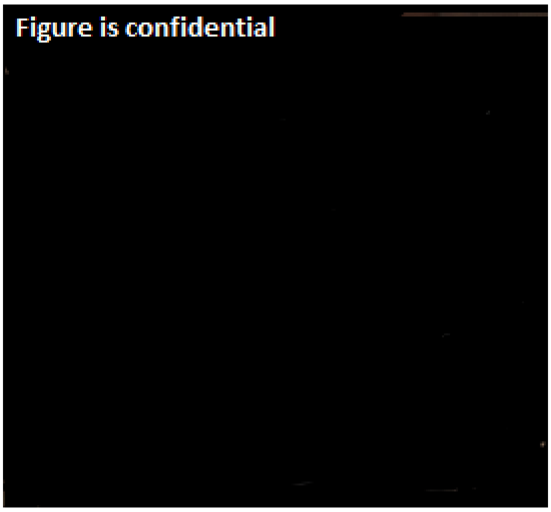

Figure 2.16: Materials entering gluing

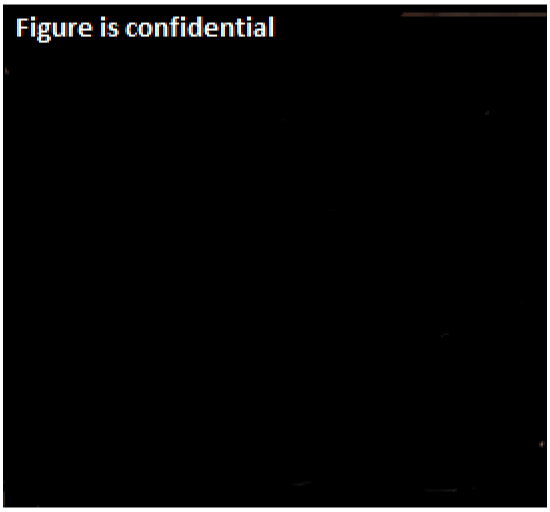

Figure 2.17: Materials exiting gluing

2.4.4. Oven
At the oven the flap wheels are cured. The glue is hardened and the flap wheels should come out as finished products. The oven first has to be pre-heated to 90 degrees. The cart with trays can be put in the oven before but the timer only starts to run when the oven hits 90 degrees. After one hour the oven starts cooling down and when the oven reaches 80 degrees the cart can be taken out. At this point either the product is finished or it is found out that the glue settled down further than expected, in this case the product has to be fixed at the hand-gluing station. If the product is finished it is sent to be packed.

Setup
In the oven every product is treated the same, they get the same amount of time and use the same settings. At the beginning of each day there is a period of time where the ovens need to heat up before they can be used. The carts can already be put in the oven during this time so there’s no extra effort required of operators but it does mean it takes a small amount of time for ovens to be able to be used.

Downtime
There is practically no downtime for the ovens. The main downtime arrives when either an oven is empty and there is no cart available to be put in the oven, or when there is a cart in the oven that can be taken out and nobody takes it out.

Batching
Batching in the oven is not changed. The same cart that enters the oven leaves the oven again.

Resources used and exiting materials:
Used: tray with cups filled with spindle, cardboard label and pieces of sandpaper glued together (Figure 2.18)

Exiting: Finished product (Figure 2.19)

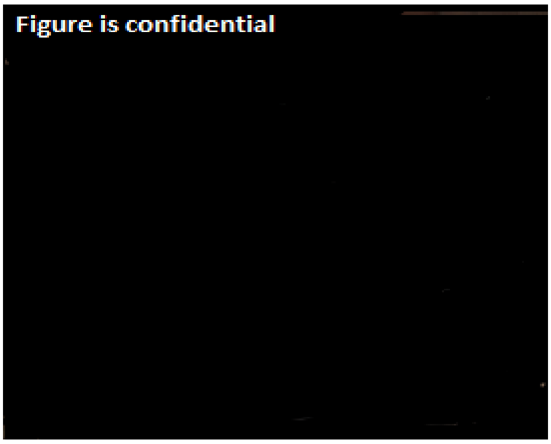

Figure 2.18: Materials entering oven

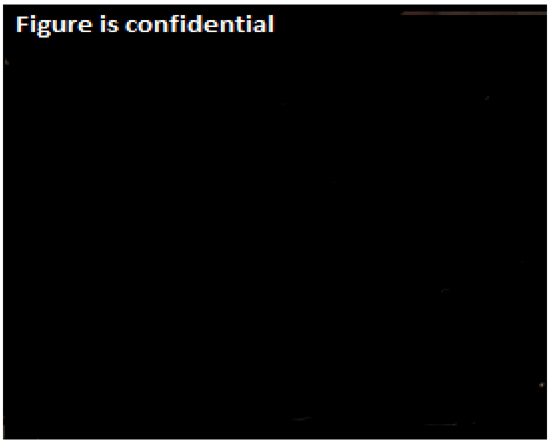

Figure 2.19: Materisla exiting oven

2.4.5. Hand gluing

The hand gluing station is meant to make sure the glue reaches to the edge of the product. This was initially intended to be purely for cosmetic purposes so that the product would look flat at the bottom if the level of glue dropped a little. The operator of the hand gluing machine adds a little bit of glue to every product that needs some tray by tray manually.

In practice for some sizes of the flap wheels the glue drops so much that the product would be unusable without being hand glued. Almost every product has to be hand glued at least once and a lot of products have to be glued twice. If a product has to be glued twice it is put in the oven for 15 minutes before they are glued for a second time. After this the product still has to go into the oven again for the regular amount of time. How much the glue drops differs from flap wheel to flap wheel, even on the same tray. Some flap wheels have slightly bigger gaps between the sandpaper which makes a little more glue seep through. Sometimes there are a little more bubbles in the glue which make the glue drop a little bit more. This makes it possible for only a few products needing extra glue in the final round instead of all the products in the tray.

Figure 2.21 shows the intended use of the hand gluing station. The flue has slightly dropped down and needs a little extra glue to make the top of the glue line up with the flaps. Figure 2.20, however, shows how the hand gluing station is often used. The flap wheels arriving still need a lot of glue, you can even see the spindles still in the wheel. Without the hand gluing stations these products would not be usable.

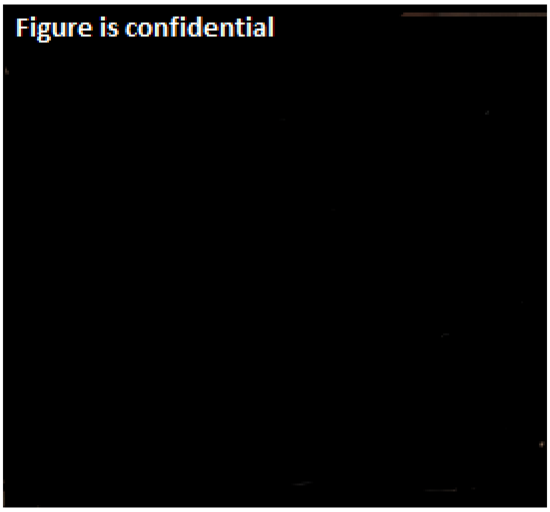

Figure 2.21: Intended use of hand gluing

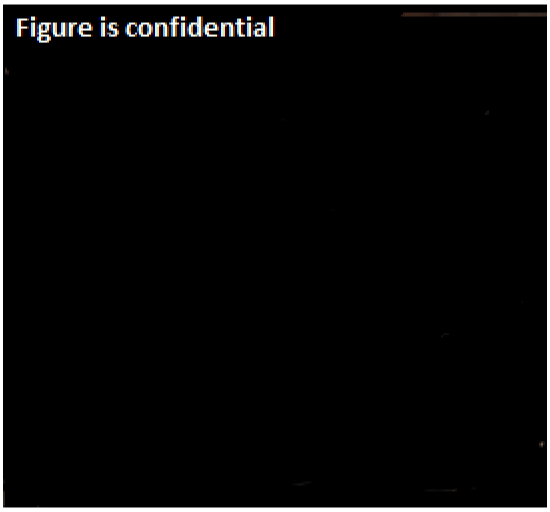

Figure 2.20: Actual use of hand gluing

Setup

For every size of product certain settings have to be changed. This however can be done fairly quickly. For different amounts of glue different pressure settings have to be used. For small amounts of glue a lower pressure is needed as more accuracy is needed. For high amounts of glue a higher pressure can be used to speed up the process as less accuracy is needed. If the station is not used for a while there is a setting that makes some glue come out after a little while, this is to avoid the glue in the mixing tubes of the gluing machine from hardening. If this is not done while the machine is not used this part has to be replaced. These parts are fairly cheap and very quickly replaced.

Downtime

The main source of downtime for the hand gluing machine is changing the glue barrel. This barrel is a lot smaller and easier to change than the barrel at the gluing robot. The mixing and bringing the glue up to temperature coincides with the cleaning of the empty barrel and is much shorter than at the gluing robot too.

Batching

The hand gluing station does not alter the batching done. The same cart that enters the station leaves the station. Sometimes a cart is sent to the hand gluing station before it is filled if the hand gluing station is idle. The new trays are then added as they finish until the cart is considered filled. This is only done if the cart has not been in the oven yet as only filled carts are sent to the oven.

2.5. Overview

The amount of product variation of flap wheels requires a flexible production facility. Despite all this simple planning based on the reduction of setup times at one production station is being used, as long as this does not conflict with the lead-time target of 10 working days. The planning is done by the plant manager and not by the planning department. The inventory management is also relatively simple and based on experience.

When putting all of the pieces of the production system from the previous sections together you get the flow of products as can be seen in Figure 2.22.

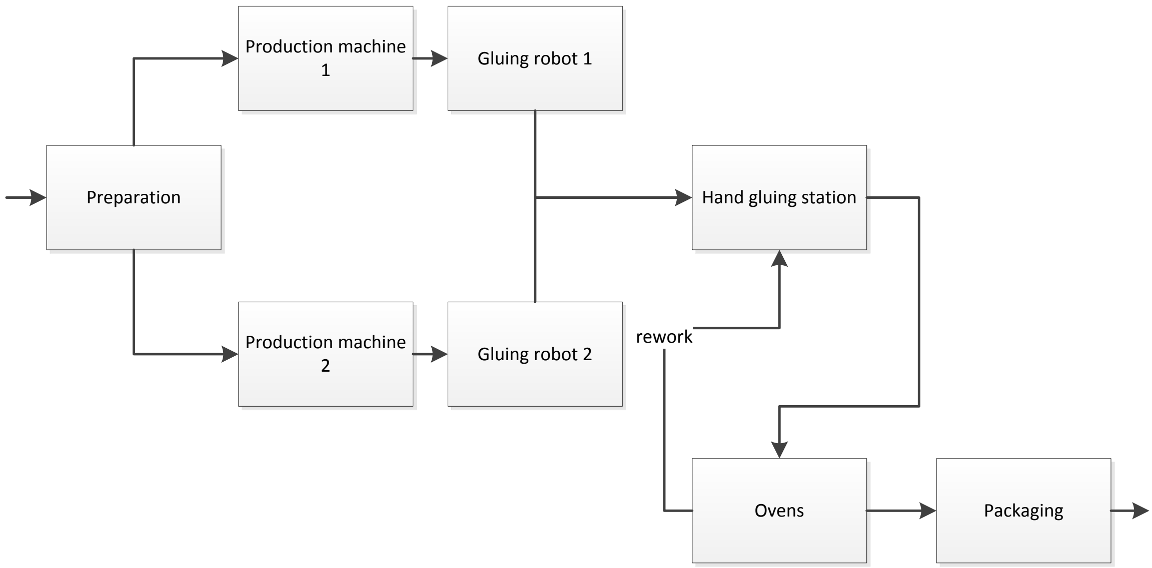

Figure 2.22: Product flow of the production line

The production starts with preparation, where the spindles and cardboard label are put in the cups. The production machines follow where the sandpaper is put in the circular form and then pushed into the cups. After that the gluing robot fills the gap in the middle with glue. After that the products are sent to the hand gluing station, where extra glue is added after the glue has slowly dropped. The products are then sent to the oven to cure the glue, if the glue levels are expected to drop even further, rework is expected and they are in the oven for a shorter time and afterwards are sent back to the hand gluing station. If the glue is not expected to drop even further, or if the product has been reworked, they are sent to the ovens for a longer period. When the products come out with the right level of glue they are then sent to packaging.

The main downtime is at the production machines. Mechanical failures and setup times here are much higher than in the rest of the production. The gluing robot mainly suffers from inconsistency and sub-par quality of the glue, which regularly results in rework at the hand-gluing station even though this station was only meant for cosmetic fixes. The different times for varying product types at the production and gluing stations also mean that the bottleneck can shift based on the product mix of the orders being made.

3. How can the data be used to construct a conceptual model?

An important part of any model in the Operations Research domain is the conceptual model (Oral & Ketani, 1993; Bertrand & Fransoo, 2002). In this chapter a conceptual model for the production plant is made. We discuss the conceptual model in terms of which variable are included in the formal model and how these variables are represented through the use of data, for example in terms of the level of aggregation. In Section 3.2 the characteristics of the data are discussed, such as how it was collected and what impact this has on the usability of the data. In Section 3.2 the individual machines are analyzed. In Section 3.3 the individual machines are combined into a system and the properties of the system are discussed. In Section 3.4 the measurements of interest are discussed. This is the data that the formal model needs to produce. In Section 3.5 the conclusions of this chapter are presented

3.1. Data characteristics and analysis

For the conceptual model assumptions are needed. There is a distinct lack of data, and where there is data there is not enough to perform statistical tests. However based on the knowledge of the properties of the production system and the data that is available we make some realistic assumptions.

Data for the production machines and gluing machines has been gathered per tray. This means that there is no data available on individual products, only per tray. For the hand gluing station, only data relating to an entire cart is available, not even per individual tray. The data was gathered per minute and not per second as there was not enough time for such detail. The data was gathered over a period of approximately one month, more time was not available. This means that a lot of data is missing.

The data for the time to repair at the production machines is a special case. This data was first collected along with the other data. This did not lead to enough data points. As such it was continued to be collected over a month by the operators themselves. The data collected during the first month was exact to the minute while the data collected by the operators was only exact to five minutes. The operators simply did not have time to be more specific.

174 data points were collected for the processing time at the production machines. 259 data points were collected for the processing time at the gluing robots. 62 data points were collected for the setup times for the production machines. 31 data points have been collected for the hand gluing station. 103 data points were collected for the meant time to repair at the production machines and 47 data points were collected for the mean time to failure.

When using data to construct a model there are different ways in which it can be used. Law (2006) identifies three different options:

- Use historical data directly: Data gathered is used directly. This can for example be the processing times for a machine. In this case the exact time that was used to make that specific product in the simulation is used in the model. This can for example be applied to historical order arrivals.
- Use an empirical distribution: The data that has been gathered is used to construct an empirical distribution. For example with the processing time for a machine we would take a sample from this distribution and use the drawn sample as the processing time for the product. With each new product another sample is drawn and used.

- Use a theoretical distribution: In this case the data is used to identify the theoretic distribution. The data is "fitted" with a theoretical distribution. If a theoretical distribution fits to the data, this distribution is then used to draw samples from.

Each of these options has its advantages and disadvantages. The historical data is generally only used if the use of the other two is (nearly) impossible. The theoretical distribution is almost always preferred because of limitations on the empirical distribution. If the data set is small then irregularities can make an empirical distribution less representative of the actual situation. Furthermore, there may be extreme situations that have not been observed due to the rare nature of them, meaning if an empirical distribution is used then these will never occur. For each of the input data we determine what kind of distribution to use. For the fitting of theoretical distributions the program Easyfit 5.6 is used. The data is compared to the following distributions: Beta, Normal, Erlang, Exponential, Gamma, Lognormal and Weibull. Easyfit provides three different goodness-of-fit tests: The Kolmogorov Smirnov test, the Anderson Darling test and the Chi-Squared test. The Chi-Squared test combined with possible applications from Law (2006) is used as justification for a theoretic distribution. If the p-value from the Chi-squared test is below 0.05 the theoretical distribution is rejected. Further explanation can be found in Appendix A.

3.2. Individual machines

Each of the machines is analyzed using Kendall's notation as well as the additions made by Zijm (2012). Kendall's notation contains order arrival, processing times, number of servers and number of places in the system. To this list, Zijm (2012) adds failures, setup times, rework and batching. Batching represents both the process batch and the move batch, a process batch is the batch used during the processing of the products and a move batch is the batch used to move the products from one station to the next, these do not have to be the same. These are the aspects on which the individual machines are analyzed.

The machines analyzed are the production machines (Section 3.2.1), the gluing robots (Section 3.2.2) and the hand gluing machine (Section 3.2.3). The way that these stations fit into the system can be found in Figure 2.22.

3.2.1. Production machines

The production at the machines only start after the completion of the preparation, as stated in Section 2.4.1 and Section 2.4.2. Because the preparation is not within the scope of the project, this step is omitted.

Order arrival

The order arrival at the production machine is based on the planning made by the plant manager. This means that the arrival of orders is pre-determined. Customer orders consist of the product in question and the amount of products that have to be made. These are then split into production orders of one type of product, each with an amount to be made. The sequence in which orders arrive and the size of these orders is determined by historical data. This is because of the fact that a customer order contains multiple types of products which, as Law (2006) states, makes it very hard if not impossible to use the other approaches.

The trays are handled at the production machines one at a time; this means that there is no arrival distribution. Products appear in the production machines as though it is a pull system. Once the first product is finished the next one is created, until a tray is filled. When a tray is filled it leaves the production machines and an empty one arrives.

Processing time
The data acquired for the processing times is not enough to be used to determine a distribution for many of the products, empirical or theoretical. One type of product has 60 data points, another has 43 data points and the next largest has 26 data points. Three products have less than 10 data points and many others have 0 data points. In order to be able to include products with no data points products will have to be put together and treated as one and the same type of product. "Buckets" are constructed and products are placed in these buckets based on the characteristics that influence the processing times the most.

The processing time of the production machines largely depends on the width of the product. Depending on the width of the product, 25, 36, 49 or 81 products can be put on a tray (Table 3.1). This has the biggest impact on the processing time. Within these buckets there is also a slight difference in processing time but there is not enough data available to make this distinction. As such the products are put together in buckets depending on the amount of products per tray. The exception to this is the bucket of 36 products per tray. For this bucket there is no data at all and it only consists of around 1% of the actual production. As such this bucket is put together with the bucket for 49 products per tray. While not correct in practice, the impact on the results is expected to be negligible.

Table 3.1: Number of products per tray

Product width	Products per tray
20mm, 25mm, 30mm, 40mm, 1inch and 1-1/2inch	81 products
50mm, 60mm and 2 inch	49 products
2-1/2 inch	36 products
80mm and 3 inch	25 products

Within these buckets the number of data points is still a problem. The bucket of 36 & 49 products per tray still only has 25 data points and the bucket of 25 products per tray still only has 30 data points. The bucket for 81 products per tray, however, has 119 data points and can therefore be used to fit a theoretical distribution.

When fitting the data to a distribution as specified in Section 3.1 the distribution that fits best with the data using the chi-squared test is the gamma distribution. This distribution is rejected (p-value of 0.0056). The results of the test can be found in Appendix A.

While the gamma distribution is often used to model the time it takes to perform a task (Law, 2006) the rejection by the chi-squared test means an empirical distribution is used. The characteristics of these empirical distributions can be found in Table 3.2.

Table 3.2: Processing times production machines, mean and standard deviation

Production	Confidential
Bucket 81	[redacted]
Bucket 36&49	
Bucket 25	

Number of machines
The production machines consist of two (near) identical parallel production machines. Both produce different orders at the same time. This means that while there are multiple machines these are to be

treated as two separate machines in the model. They are two different stations, not one station of two machines in parallel.

Number of places in the system
The number of places in the machine is 1. Only one tray of products can be produced at a time per machine. The number of products per tray (processing batch) depends on the properties of the specific product. The options for this number are 25, 36, 49 and 81. There is no queue before the machine; trays arrive in a pull fashion, only after the previous tray is finished. To make the products in the machine, cups are needed. There are different cups for different sizes. The amount of cups of each size can be seen in Table 3.3. If there are no cups left, no more products of that size can be produced at the machine. The amount of products is also capped by the amount of trays but this is larger than the amount of cups so there will always be more trays than cups.

Table 3.3: Number of cups per size of product

Width	Number	Width	Number
20mm	1300 cups	1 inch	4170 cups
25mm	735 cups	1-1/2 inch	2000 cups
30mm	1300 cups	2 inch	2050 cups
40mm	2061 cups	2-1/2 inch	1020 cups
50mm	2078 cups	3 inch	2014 cups
60mm	2080 cups		
80mm	900 cups		

Setup times
Both machines have setup times between different orders due to different product specifications. These setup times occur often as there are rarely multiple identical orders. There are two distinct types of setups: changing the height of the product and changing the width of the product. It is also possible for both of these changes to occur for the next order. This makes the setup times sequence dependent. The setup times depend on the previous and the new product properties. For the actual setup times an empirical distribution is used since there is insufficient data to fit a theoretical distribution (19, 11 and 25 data points respectively).

At the beginning of the day there is no setup for the production machines. If the same order is continued, the production can begin immediately. If a new order is started it is just a regular setup in between orders.

Failures
The production machines are prone to failure. There is one main source of these failures, there are other sources but these occur less often. In 44 of the 57 recorded failures the "Forming blade" was among the reasons, in 38 of these even being the sole reason of the failure. This is not unexpected as it is the most strained part of the machine. According to the supplier specifications, the forming blade should on average be able to produce 2000 products before failing. However, in practice the number is widely variable. There is no preventative replacement; production is run until a failure occurs.

An empirical distribution is used for the time to repair. When trying to fit a theoretical distribution with Easyfit all possibilities were rejected. The distribution that was found to fit best with the data was the exponential distribution and this was rejected with a p-value of less than $2.57*10^{-12}$. The goodness-of-fit test can be found in Appendix A.

For the time to failure, Easyfit was able to fit a Weibull distribution with a p-value of 0.82369. The characteristics of the distribution are alpha 0.96158 and beta 19620. More distributions were a possible fit to the data but the Weibull distribution was the closes fit, aside from that this distribution also makes sense to use as Law (2006) states that this distribution is often used to model the mean time to failure and is a rough model in the absence of data. As such this distribution is used in the model. The goodness-of-fit test can be found in Appendix A.

Rework

There is no rework on the machines. Very rarely a product that leaves the machine is of insufficient quality but these products are then destroyed and an extra one is simply made in the machine.

Batching

As stated before in Section 3.2.1, trays are produced with different amounts of products. This processing batch can be of size 25, 36, 49 or 81. The size of the trays always stays the same (see Figure 2.6) so as the products get bigger the number of products per tray the batch of products becomes smaller. Only after an entire tray is processed is it allowed to proceed to the next station. This means that the size of the move batch is identical to the processing batch for the production machine. We assume that there are no exceptions to this.

3.2.2. Gluing robots

In this section the gluing robots are analyzed according to the way specified in Section 3.1.

Order arrival

Zijm (2012) states that the arrival rate at a station depends on the arrival process and the distribution for the processing time of the previous station. In this case that means that the arrival rate at the gluing robots depends on the arrival process and distribution for the processing time at the production machines. If the utilization of the production machines is high, it mostly depends on the distribution of the processing time. As the production machine does not have a queue in front of the machine this is the case for this system. This means that the arrival rate at the gluing robots depends on the processing time distribution of the production machine. As such the inter arrival time is based on the empirical distribution from the production machines.

Processing time

The data for the processing time for the gluing robots has been gathered per tray. The processing time of the gluing robots is deterministic. It takes the same amount of time for the machine to finish an entire tray of products. When we incorporate the time it takes for the operator to notice a batch is done, take out the batch and put in a new batch the processing times seem to become a distribution with a relatively small standard deviation. Hopp & Spearman (2008) give the measure of Coefficient of Variation (CV) for the variability of a random variable. They classify variables as low variability if the CV is below 0.75, as moderate variability if the CV is between 0.75 and 1.33 and high variability if the CV is over 1.33. The CV is the standard deviation divided by the mean. As can be seen in Table 3.4 the Coefficient of Variation for the processing times of the gluing robot is far below the 0.75. Therefore we assume the processing times are deterministic.

As mentioned in Section 2.4.3, a product can be glued in one or two cycles in the gluing machine. Every product that is 30mm or smaller in width and 20mm or more in height is glued in two cycles, as are all products that are 40mm or 1-1/2 inch wide; all other products are glued in one cycle. This makes that when using the same buckets as the production machines for the gluing robots, the bucket for the products with 81 per tray has to be split to account for the products that have to be glued in two cycles. Aside from that, the buckets for products with 49 and 36 products per tray can ,again, be put together as their means only differed by 2 seconds. There are other factors that influence the processing times to a lesser extent, such as the grain of the sandpaper, but there is not enough data to incorporate these.

As such, the means of the buckets are used as the deterministic processing time for all products within these buckets. The means and standard deviations can be found in Table 3.4. In this table the processing time for one cycle is presented, this means that in the case of the products with two cycles this processing time occurs twice.

Table 3.4: Processing times gluing robot, mean, standard deviation and Coefficient of Variations

Gluing	Confidential	CV:
Bucket 81 2x	[redacted]	0.14
Bucket 81 1x	[redacted]	0.07
Bucket 49&36	[redacted]	0.15
Bucket 25	[redacted]	0.25

Number of machines

Much like the production machines, the gluing robots consist of two (near) identical gluing robots. These gluing robots are tied to a specific production machine and they mostly handle the orders of this single production machine. While this rule is not set in stone, this is the normal practice by the operators. As such the gluing robots are also two separate stations with one machine.

Number of places in the system

The number of places in the system depends on the number of products in a batch. The system can hold exactly one batch of products. This means depending on the size of the product there can be 25, 36, 49 or 81 products in the system at a time. The waiting area has practically unlimited capacity. Theoretically the waiting area has 6 carts that can each hold 24 batches. In practice however this capacity restriction is never even remotely reached.

Setup times

The setup times for the gluing robots in between orders mostly do not depend on the properties of the product. The setup time is equal to zero only if the next order is identical. If the orders differ the setup, time takes between 2 and 4 minutes. The impact of this setup on the results is expected to be so marginal that we assume that there are no set-ups in between orders. At the beginning of the day the gluing robot does need to be warmed up before it can be used. This is usually done before production even begins; meaning in practice there is no setup at the beginning of the day.

Failures

During the time the data was collected there were no failures at the gluing robots. This is not unexpected because there are very few moving parts that could fail regularly.

Rework

There is no rework on the gluing robot station. A significant number of products need to be processed twice but this is determined in advance and according to plan (as mentioned in the processing times). It is a step that is required to increase the quality of the product but it is not done after an inspection of any kind. It simply depends on the properties of the product and is therefore not considered rework.

Batching
While before the gluing robot a move batch consists of a tray of products, after the gluing robot a move batch consists of a cart of trays. The amount of trays that is put on a cart depends on the amount of products on a tray. For example, a cart full of trays with 81 products would take a very long time to fill up. After that, this cart would also take a very long time to process at the hand gluing station. Alternatively a cart full of trays with only 25 products per tray would be significantly faster at both. Carts are batched according to what the operators believe is best for the flow of products. This means carts are rarely completely full. There is no fixed methodology for when a cart is finished and sent to the next station but there are general numbers that can be used in a model (Table 3.5). In practice, deviations from these numbers are common but it is impossible to incorporate these in the model.

Table 3.5: Number of trays per cart

product width	number of trays per cart	product width	number of trays per cart
30mm	8	1 inch	8
40mm	6	1-1/2 inch	10
50mm	12	2 inch	12
60mm	12	2-1/5 inch	6
80mm	6	3 inch	12

In the model the carts are filled according to this rule unless the product dimensions change before the number is reached (for example if a new order starts). In that case the cart is sent forward before it is filled and a new cart is started for the new order. Table 3.5 is not complete, it misses the 20mm and 25mm products but these are only produced in very small orders so they would be sent forward regardless as soon as the product changes. The gluing robots glue the products per tray; a processing batch for the gluing robots is therefore one tray of products.

3.2.3. Hand gluing

In this section the hand gluing is analyzed according to the way specified in the introduction of chapter 3.

Order arrival
The order arrival for the hand gluing station is a difficult thing to determine. The trays from the gluing robots are batched together on carts that can carry up to 24 trays. In practice, as can be seen in Table 3.5, the carts carry less than 24 trays. These trays are collected from the gluing robots. Sometimes the trays from both gluing robots go on the same cart. Sometimes they each make use of a different cart. For simplicity, however, we assume the trays are never collected on a combined cart.

Processing time
The data for the processing times were gathered per cart, not per tray. The number of trays on that cart can be found in Table 3.5 so an average time per tray can be determined. Since there are only 31 data points, any meaningful statistical analysis of factors that influence the processing time, such as product dimensions or number of times glued before at the hand gluing station, is impossible. As such the average time per tray glued is taken all together without regard for any altering factors. This leads to a mean processing time of 3:55 with a standard deviation of 2:11. The high variability somewhat comes from the fact that the gluing is done by hand but a large portion also comes from the lack of data. Due to this lack of data an empirical distribution is used as distribution fitting on such a small amount of data points is pointless, especially when there are so many obvious factors contributing to the variance that cannot be accounted for in the data.

Number of machines
There is one hand gluing machine.

Number of places in the system
The number of places in the system depends on the number of products per tray. The gluing robot can hold exactly one tray of products, with the rest of the move batch in a queue on the cart. This means there can be as many trays in the queue as there are carts, theoretically. In practice this never occurs.

Setup times
There are practically no setup times for the hand gluing station. The pressure may need to be adjusted depending on the amount of glue that has to be used but the amount of time it takes is negligible.

Failures
During the time where data was gathered the hand gluing station did not have a single failure. The system is very basic so no regular downtime is expected.

Rework
Trays regularly have to be reworked in the hand gluing station. The rework takes approximately the same time as the normal processing time as the whole tray has to be checked again. After the first time at the hand gluing station the carts are put in the oven for 15 minutes. If rework is needed this means it takes 15 minutes before the cart re-enters the hand gluing station. At which point it has to wait before the new cart is finished (if there is one).

We assume that a product with a lower width has a higher chance of rework. If this low width product has a higher height this chance increases even more. While there is not enough data to prove this statistically, only one instance of a 2 inch product being hand glued was found, with all the other instances being products with a width of 1 inch of lower. This was confirmed by the operators on the work floor. As a general rule they never have to rework products that are larger in diameter than 1-1/2 inch. For the products that are 1-1/2 inch or smaller they only have to rework the products that are more than 20mm in height. This is used as a general rule in the model.

Batching
Batches enter the hand gluing station in carts of trays of products. The same way they leave the gluing robots. These carts are then processed one tray at a time and returned to the same cart. Once an entire cart has been processed it leaves the hand gluing station in the same batch that it arrived in.

3.3. System characteristics and boundaries

For the scope of this project the system consists of two production machines, two gluing robots and one hand-gluing machine as mentioned in Chapter 2 and Section 3.2. In this section the system is discussed in overarching principles and their effects on the system as a whole.

Product routing
The products start at production machine 1 or 2 and then travel to the corresponding gluing robot in batches of trays. After the gluing robots, move batches of carts are formed that proceed to the hand gluing station. Here a product can be hand glued once, at which point it leaves the system. It is also possible that rework is needed, with a 15 minute delay in between (oven time).

Maximum amount of WIP
The system's WIP is bounded by the fact that the production machines can only produce one product at a time which eliminates the threat of exploding WIP due to arriving orders, as long as the production machines are the bottleneck. The system's WIP is further bounded by the lower bound of the number of carts available, the number of trays available and the number of cups for that specific product available.

WIP is capped in theory; in practice this cap can be largely ignored. A cap in WIP that is reached sometimes is the number of cups available for certain product sizes. For most products this cap is also almost never reached but if the throughput of the system is to be increased and the cycle time is not reduced then this could become a problem.

Complexity
As can be seen in Section 3.2.1 and Section 3.2.2, most of the complexity in the system is due to the wide variety of products. Product dimensions determine a lot of things, from maximum amount of WIP in the system to processing times and amount of rework at the hand gluing station. It also determines the batching on the trays and on the carts. It even determines the setup time at the production machines. However, the impact of the product dimensions also differs greatly in the system. For example, the height of a product does not matter in the batching on trays or on carts, yet it has a bigger impact on setup times at the production machines than width does. On the other hand width has a huge impact on the batching and the need for rework at the hand gluing station.

The rest of the complexity comes from the hand gluing machine. Not all products have to go to this station, but it is uncertain which products do and how many times they have to enter this station for rework until they are done. This causes complexity due to uncertainty that is hard to gather from the data.

Continuous or discrete
The system is a discrete system. Products are made at an event with a clear beginning and an end. The products and batches also only move at the beginning and end of an event. The system has no continuous characteristics.

3.4. Measures of interest

The main measure of interest is the average throughput of the system. Since the main goal of the project is to improve throughput two things are of particular interest; the time during which the production machine is not running and reasons the machine is running slower than expected when it is running. This means that of particular interest are the downtime at the production machines due to failures and the downtime due to setups. Also of interest is the maximum number of trays and the maximum number of carts in the system, this is to monitor if there are blockages in the system; it is not an interesting measure for the results.

Other measures of interest are the downtime at the gluing robot and hand gluing station due to a lack of products to better map inefficiencies.

All of the above measures are of course interesting under normal operation circumstances but it is also be interesting to look into them during extreme product mixes to see what extreme circumstances can be handled the system, this helps to identify weak points. Since different product dimensions have different effects on the system, it is interesting to see what an excess of one product would cause on the system.

3.5. Conclusion

The system consists of two parallel production machines with empirically distributed processing times, two parallel gluing robots that are dedicated to a production machine each, with deterministic processing times and one hand gluing machine with empirical distribution times. An overview of these distributions can be found in Table 3.6. Together these machines form a system with a theoretical maximum WIP that in practice is never reached. The main uncertainty of the system originates from the product dimensions having a different impact on certain parts of the system. Another source of uncertainty is the hand gluing machine, where there is not enough data to describe the uncertainty in a meaningful statistical way.

Table 3.6: Distribution type per station

	Processing time	Time to failiure	Time to repair	Set-up time
Production machines	Empirical	Weibull	Empirical	Empirical
Gluing robots	Deterministic	x	x	x
Hand gluing station	Empirical	x	x	x

4. How can the current situation be modelled in a formal model?

In this chapter we determine what formal model is to be used to model the production system and the model is constructed. In Section 4.1 a formal model is selected based on a literature review, the characteristics of the system and the goals of the project. In Section 4.2, a model is constructed and in Section 4.3 the conclusions of this chapter are presented.

4.1. Which formal model fits the project requirements

In this section the formal model type is determined. In Section 4.1.1 the analytical option is compared to the simulation option. In Section 4.1.2 the type of simulation model to be employed is determined.

4.1.1. Analytical vs Simulation

When choosing a formal model we consider two main options: the analytical model (Zijm, 2012) and the simulation model (Law, 2006). Law (2006) states that the choice between the analytical model and the simulation model mostly depends on the complexity of the system. Winston & Goldberg (2004) simulations are preferable to analytical models when the analytical models require too many simplifying assumptions. Simulation models allow for more flexibility in representing the real production line. Much of the system is not overly complex, and the complexity due to the product diversity, mentioned in Section 3.3, can be offset by putting them in buckets. The problem starts at the sequence dependent setup times at the production machine. Even when the products are put in buckets there are multiple factors that determine the setup times, for example the product height. In an analytical model this would mean a simplifying assumption would have to be made, while a simulation model allows for sequence dependent setup times to be included. Another problem is that the processing time for the production machines and the hand gluing station are empirically distributed, among other variables. While this is acceptable in a simulation model, it is more difficult in an analytical model. As such a simulation model is used as the formal model.

4.1.2. Type of simulation model

Law (2006) classifies simulation models along three different dimensions:

1. <u>Static vs dynamic models</u>: In a static model, the system is represented at a particular time, or time simply plays no role. A dynamic model represents a system that is changing over time.
2. <u>Deterministic vs stochastic models</u>: Simply put if there is no probability in the system at all it can be represented with a deterministic model. A stochastic model represents a system with probabilistic components.
3. <u>Continuous vs discrete models</u>: This distinction is a bit less clear-cut. A discrete model presents a model where changes occur at specific events after certain intervals. In a continuous model changes do not have to be dependent on such events, changes are continuous.

For this project a dynamic, stochastic and discrete model needs to be used. The state of the production process can change according to the product mix that enters it. As such it is important to be able to monitor these changes and the effects they have on the performance of the system. A static model would not be able to provide these insights. A deterministic model does not fit as there are probability distributions that are needed to represent the processes in some parts of the system. This means a stochastic model is used. For this project a continuous model is not suitable.

Now that we know the characteristics of our model, we can look for a suitable form of simulation. Law (2006) identifies five forms of simulation:

1. Discrete-event simulation: the system is monitored as it changes over time. These changes occur at a finite number of points in time. These points are called "events". The time of occurrence of these events can be stochastic.
2. Continuous simulation: the state of the system changes continuously over time.
3. Combined discrete-continuous simulation: the state of the system changes continuously over time but can also be altered due to events.
4. Monte Carlo simulation: with the use of random inputs many experiments take place and the outcomes of these experiments are analyzed.
5. Spreadsheet simulation: drawing random numbers from distributions in, for example, Excel this simulation can be used for relatively simple systems.

Since the production system can be represented by a discrete model, the continuous simulation and combined discrete-continuous simulation are not required for this project. The problem is also too complex for Monte Carlo simulation and spreadsheet simulation. Therefore, we decided to use the Discrete-event simulation, which can accommodate all of the required characteristics of the simulation for this project.

Law (2006) also offers different options for the types of simulations regarding output analysis. He states that simulations can be either terminating or nonterminating:

1. Terminating simulation: In the case of a terminating simulation there is a natural event that marks the end of a simulation run. Such a natural event can, for example, be that the whole production line has to be emptied at a scheduled time. This means that individual simulation runs between two of those events are independent of each other. Since such events actually have a big impact on the performance of the system the impact of these events has to be included in the simulation model and in the output of the model.
2. Nonterminating simulation: A nonterminating simulation is a simulation where such an event does not occur. In nonterminating simulation runs the output of interest is often related to the performance of the system under normal circumstances, in a steady state. Winston & Goldberg (2004) refer to nonterminating simulations as steady- state simulations for this reason. One problem with this approach is that in general there is no such thing as a steady state in the actual production system, since these systems change over time. There is also no clear point where the simulation ends.

The production system has no natural events where a simulation can end. Every shift proceeds where the last shift ended; there is no event in the system where what occurred before that event is independent from what occurs after. This means that the simulation model will be a nonterminating simulation model. The performance measures aim to measure the steady state parameters of the system and a point where the simulation ends has to be chosen.

4.2. Model construction

In this section the construction of the model is discussed. First in Section 4.2.1 the assumptions are discussed, then the simulation model is described in Section 4.2.2 and the experimental design is discussed in Section 4.2.3.

4.2.1. Assumptions

The following assumptions are made with regards to the manufacturing system:

- The number of trays per cart, when they are sent to the hand gluing station, is described in Table 3.5.
- Each tray in the system is always fully filled, as mentioned in Section 3.2.1.

- Processing times at the gluing robots are deterministic. The Coefficient of Variation is so low that this is a reasonable assumption (See section 3.2.2)
- There are no set-up times on the gluing robot. Since this has an insignificant effect on the results (See Section 3.2.2).
- Trays from different gluing robot are not combined on the same cart; each is assigned to their own separate cart for that gluing robot. This is mentioned in Section 3.2.3.
- Hand gluing rework is done according to the product specifications mentioned in Section 3.2.3. . No rework has to be done on products that are larger in diameter than 1-1/2 inch. For the products that are 1-1/2 inch or smaller rework is only needed for the products that are more than 20mm in height.
- There are always enough raw materials in stock. Accounting for raw material management is outside of the scope of this project.
- All components required to repair a failure are on stock. Accounting for spare parts availability is outside of the scope of this project.
- There is no downtime due to massive failures that require the attention of an outside party. Due to lack of data on this type of failure, only failures that can be fixed in-house are incorporated in the model.
- It takes no time to move the trays and the carts. While technically not true this time is negligible.
- Each station always has an operator. While not true in practice, the intricacies of the workplace are too complex to fully model. The operators not always being able to fully juggle their responsibilities is also already somewhat accounted for in the way the data was gathered due to the aggregation to the tray level.
- There are an infinite number of cups, trays and carts in the system. While not true in practice, the limited number of cups available is already taken into account at the historic production schedule. If there were not enough cups available to continue production a new order would be started. After that new order is finished the old order would be continued. When this happens it is shown in the production history and thus incorporated in the order arrival.
- There are always enough orders to produce at full capacity. While not true in practice, this is the situation we want to analyze as this is the situation during which throughput is below expectations.

4.2.2. The simulation model

For the model, the program Plant Simulation is used. Sundisc Abrasives does not have any software that can be used for discrete event simulation. The University of Twente, however, has a license for Plant Simulation and the program is used in the master program. The program will no longer be available after the project is finished as the license will no longer be accessible. The results, however, are saved and can be accessed at any time. The model of the production line is discussed in Section 4.2.2.1 and the validation and verification of this model is discussed in Section 4.2.2.2

4.2.2.1. The model of the production line

The model (Figure 4.1) starts at the left with the two production machines. The production machine frame (Figure 4.3) consists of a buffer where the trays appear for production and a station where production takes place. After each production machine there is a gluing robot. The gluing robot (Figure 4.2) consists of a buffer where the trays arrive, the station where the trays are glued and a buffer where the trays that have been glued are collected and put on carts. The two streams of movable units (MUs) come together after the gluing robots in one hand gluing station. The hand gluing station (Figure 4.4) is a bit more complex. First there is a buffer where the carts arrive, then the hand gluing station where the hand gluing takes place. Next is a sorter that checks where the cart has to be sent: either the oven or the drain. We then have a separate line for the oven and the buffer for carts after the oven, this buffer feeds back into the actual hand gluing station. The final path is a buffer before the drain that collects the carts that are leaving, and finally a drain where the products exit.

Event control
The event control section of the model in Figure 4.1 consists of elements that are used for reset, initialization and end of a simulation. Furthermore, the event controller is located here, which can be used to speed up, slow down, start and pause the model. As parts enter a processing station, Plant Simulation computes the time it takes until they leave the station and enter that into a list of events. The EventController moves time forward and enacts the events at the appropriate times, based on this list of events. In the case of a part entering a processing station, the event could be that the part leaves the processing station at a scheduled time.

Input data
In the input data section, all the data that is used as input can be found. This includes all the empirical distributions for the processing times and the planning for the order arrivals. The data in this area is not meant to be manually altered; the alterations are done through the experimental factors field.

Experimental factors
The experimental factors section is where the experiments are managed. It contains the elements related to the experiments and a spreadsheet with the experiment settings.

Performance measures
The performance measure section is the last section of the model. This is where the output is shown. The performance measures are stored per individual shift. From the data per individual shift an average per shift is collected in the corresponding spreadsheet. The data per individual shift is not permanently stored, only after an experiment finishes the data of the average per shift is stored.

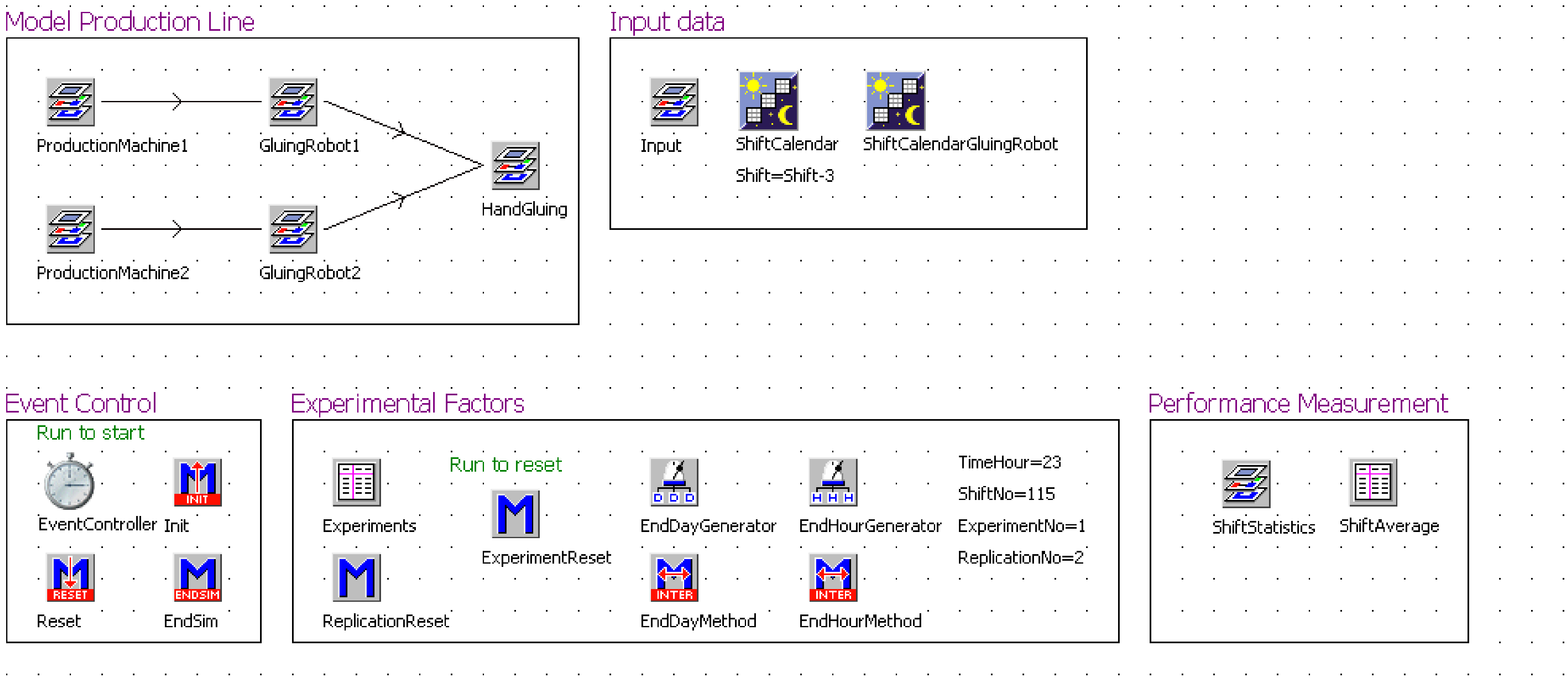

Figure 4.1: Main frame of the simulation model

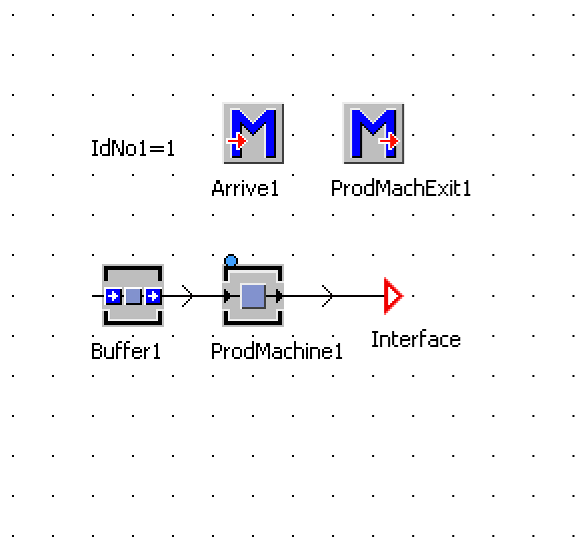

Figure 4.3: Production machine of the simulation model

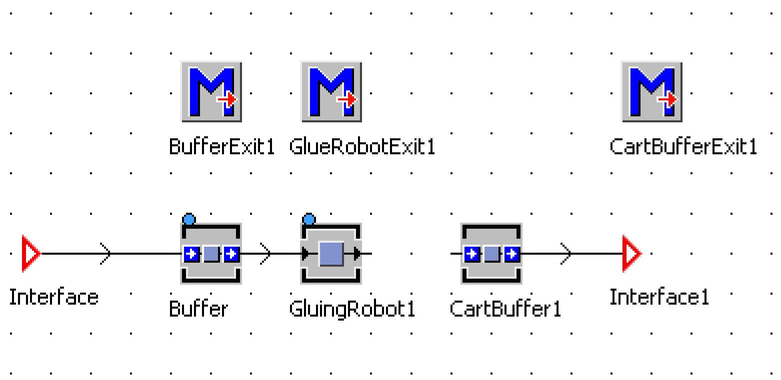

Figure 4.2: Gluing robot of the simulation model

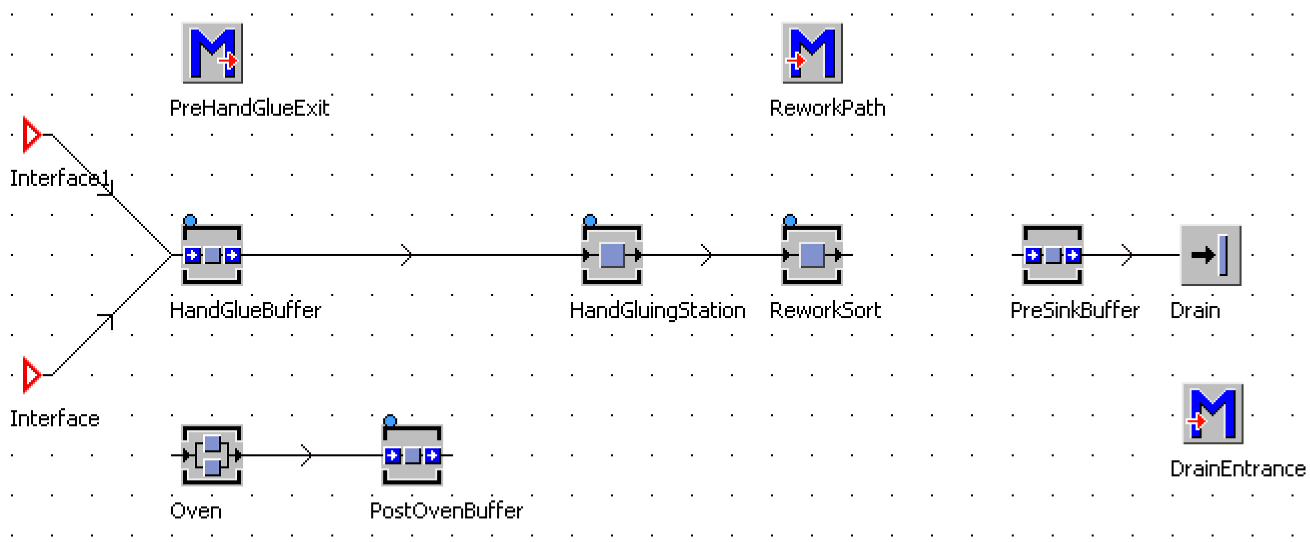

Figure 4.4: Hand gluing of the simulation model

4.2.2.2. Model verification and validation
To verify that the model functions as desired, we analyze if the model is internally coherent. We do this by running the model for 90 days and analyzing the outcomes.

For the production machines, the total time spent producing combined with the total failure time and total set-up time per shift should not exceed 8 hours. While it is possible for failures to occur outside of production time (during breaks), the odds of this occurring should be so small that the total time spent producing should still not exceed 8 hours. For both production machines these times combined indeed do not exceed 8 hours, with 7:50:58 and 7:51:19 for production machine 1 and production machine 2 respectively.

Since the processing times at the gluing robots are deterministic, there is no doubt that these are modelled correctly. The combination of trays on carts, however, is a complicated manner and should therefore be verified. We do this by monitoring the number of trays and carts in the system. The maximum number of trays in the system is 41 and the maximum number of carts is 7. If the carts were not being filled properly they would not have been sent to the next station, this means we would see these two numbers explode. 41 trays and 7 carts is a reasonable amount, most of the time the numbers were far lower.

For the hand gluing station the main issue is the routing of the carts. The correct carts should be reworked and rework should be put in the front of the line when it has to re-enter the hand gluing station compared to new carts. There is no real quantitative way of monitoring this so instead multiple scenarios are monitored. The characteristics of the carts that do not get reworked and the carts that do get reworked are checked. These characteristics matched the desired ones. Scenarios where a cart was waiting to enter the hand gluing station while a cart was also waiting to be reworked are also monitored. In these situations the model also performed as desired.

Before using the model for experimentation we also need to confirm that the model is representative of reality. The junior plant manager and two operators examined the model. They confirmed that the production line was modelled properly despite the assumptions being made.

Based on these observations we conclude that the simulation model indeed represents the situation as desired.

4.2.3. Experimental design
In this section the design of the experiments is discussed. The experiment configuration is discussed in Section 4.2.3.1, the warm up period is discussed in Section 4.2.3.2 and the number of replications is discussed in Section 4.2.3.3.

4.2.3.1. Experiment configuration
As stated in Section 3.4 the main concerns are identifying how much of the production time the production machines are actually running and how much the system produces on average during a shift.

The two main sources of downtime at the production machines have been identified as failures and setups. As such the effects of these two sources of downtime on the throughput are of particular interest. This means that during the experiments, the empirical distributions for the duration of these downtimes are altered. They are reduced, to simulate employees that are better trained at setting up the machines and/or repairing the machines, and increased, to simulate less experienced employees working on the machines. This way the effects of the downtime on the throughput can be shown. Since the production machines are the only stations with significant downtimes, this is only done for the production machines.

To study why the machines are producing less than expected when they are running, the focus is on the effect that the product mix has on the throughput. The production machines are already running at maximum speed so reducing the processing times is not a viable option. The product size, however, seems to have a big impact on the throughput of the machines. The bigger products take a shorter time per tray but have a significantly smaller amount of products on a tray, suggesting that bigger products may be lowering the throughput by a significant amount.

For both the setup times and failure times the following percentages of the empirical data are used for the experiments: 0%, 25%, 50%, 75%, 100%, 125% and 150%. At the 0% experiment, we find the absolute maximum benefit that can be gained from eliminating the setup times. The rest of the experiments are used to identify trends, this means both how much can be gained from improving the times but also how much can be lost due to less experienced operators.

Experiments with the different combinations of these numbers for both the setup times and failure times (for example 50% failure times and 50% setup times) can be found in Appendix B. For the sake of clarity these results have been excluded from the main report.

We also conduct experiments based on the product mix. In these experiments, the extreme product mixes that only contain one type of product from each different bucket are used to find how certain products impact the system. This is done without setup times and these experiments are compared to the experiment where setup times are not present under the current product mix. These experiments allow us to analyze the impact of unknown product mixes on the system by combining the outcomes for the various extreme product mixes. The exact experiment specifications can be found in Table 4.1. In experiment 14 only products of 1 inch in width and 1 inch in height are used. In experiment 15 the used products are 2 inch in width and 1 inch in height. In experiment 16 the used products are 3 inch in width and 1 inch in height. This means there is one experiment for each of the three product buckets established in Section 3.2.1. The 1 by 1 inch products also fall into the category that has to be glued twice at the gluing robots, and twice at the hand gluing station, as mentioned in Section 3.2.2 and Section 3.2.3. This means we can immediately test if these stations can handle the most straining products in this bucket.

Table 4.1: Experiment properties

Experiment number	Setup length	Failure length	Product mix	Experiment number	Setup length	Failure length	Product mix
1	100%	100%	Regular	**9**	100%	25%	Regular
2	0%	100%	Regular	**10**	100%	50%	Regular
3	25%	100%	Regular	**11**	100%	75%	Regular
4	50%	100%	Regular	**12**	100%	125%	Regular
5	75%	100%	Regular	**13**	100%	150%	Regular
6	125%	100%	Regular	**14**	0%	100%	1x1 only
7	150%	100%	Regular	**15**	0%	100%	2x1 only
8	100%	0%	Regular	**16**	0%	100%	3x1 only

4.2.3.2. Warm up period

Because the simulation model aims to collect the steady state performance of the system a warm up period has to be introduced. An empty start of the system is not reflective of the performance of the system after all. Due to the way the system is modelled, the average throughput of the first week is lower than the average throughput of the other weeks. One of the commands that monitor whether there is enough time left to process a tray before the end of the shift starts functioning during the second week. As such the data for the first week of production should not be included in the results. To ensure that the effects on the system do not alter the outcome of the experiments an extra week is added to the warm up period. This leaves enough input data for a total of 100 shifts.

4.2.3.3. Number of replications

To be able to extract reliable results from the simulation, we need to make independent replications (Law, 2006). The most commonly used approach is to determine the amount of replications needed to ensure that the confidence interval of the results, relative to the average, is sufficiently small. To determine the number of replications required, we need the smallest number n for which the following formula holds:

$$\frac{t_{i-1,1-\alpha/2}\sqrt{{S_n}^2/i}}{\overline{X}_n} < \frac{\gamma}{1+\gamma}$$

Here the γ is the relative error which we allow in the results. The relative error we allow here is 0.05. $t_{i-1,1-\alpha/2}$ is the critical value of the student-t distribution with a significance level of α=0.05 and i-1 degrees of freedom. $\overline{X}_n$ and ${S_n}^2$ are the average value and the variance of the performance measure after n replications. The average throughput for the system is used as the performance measure.

As stated, replications have to be independent from each other. Individual shifts are, however, not independent, because an order is continued from one shift to the other. This means that using a shift as a replication is not possible. As such an individual replication consists of 100 shifts, as this is the largest number of shifts that the data allows. Because of this the number of replications for which this formula holds is very small; the performance measure (throughput) requires less than 10 replications. The formula is however recommended to only be used if the number of replications is greater than or equal to 10. As such a number of 10 replications are used for the experiments.

4.3. Conclusion

In order to analyze the throughput and identify options for improving it, a formal model had to be selected. Due to sequence dependent setup times and empirical distributions used for variables in the model we chose a simulation model. The type of simulation chosen is a nonterminating discrete event simulation model. This model aims to measure the steady state performance of the production line. This model was verified by analyzing the performance of the individual stations and validated through expert opinion.

An experiment configuration with different setup times and failure times was chosen based on historical order data, as well as experiments based on extreme product mixes. The goal of these experiments is twofold, first to determine if a reduction of the setup times and failure times is sufficient to reach the objective of this report, and second to identify the impact of product characteristics on the throughput of the system.

We selected a warm up period of 2 weeks, with enough data left to perform 100 shifts per simulation run after those 2 weeks. We selected a total number of simulation runs per experiment of 10.

5. Results and applications

In this chapter we discuss the results from the experiments and how they can be applied to increase the throughput of the system. First we discuss the results of the experiments (Section 5.1) and then apply these results to the current and future situations (Section 5.2).

5.1. Experiment results

In this section we discuss the results of the experiments. In Section 5.1.1 we discuss the results initial experiments as specified in Section 4.2.3.1. In Section 5.1.2 we discuss additional experiments that are conducted based on the results of the initial experiments.

5.1.1. Initial experiments

The first experiment is a representation of the current situation. The results of this experiment can be found in Table 5.1. The table shows the average throughput per shift and the coefficient of variation of the throughput at the stations and the resulting average throughput per shift and coefficient of variation of the throughput at the end of the system.

Table 5.1: Current situation throughput per shift, mean and Coefficient of Variation

Production		Gluing robots		Hand gluing		System	
Average	CV	Average	CV	Average	CV	Average	CV
4624	0.16	4624	0.16	6219	0.33	4624	0.20

Table 5.1 shows a few interesting things; first, the production machines are the bottleneck in the current situation. The average throughput of the system is equal to the amount of throughput at production. Furthermore most of the standard deviation in the system is due to the production machines. The processing times of the gluing robots are deterministic in the model so this is not a surprise. The mean and standard deviation of the throughput at the hand gluing station is much larger but this is to be expected due to the rework at this station. Overall, the hand gluing station does show to have some effect on the standard deviation as this is slightly elevated at the end of the system.

The current situation is compared to the experiments that alter the setup times and failure times: experiments 2-13. This comparison can be found in Table 5.2.

Table 5.2: Results experiment 2-13

	Production		Gluing robots		Handgluing		System	
	Average	CV	Average	CV	Average	CV	Average	CV
Experiment 1	4624	0.16	4624	0.16	6219	0.33	4625	0.20
Experiment 2	5225	0.12	5224	0.12	6933	0.28	5222	0.17
Experiment 3	5046	0.13	5045	0.13	6705	0.29	5037	0.17
Experiment 4	4887	0.14	4892	0.14	6491	0.31	4891	0.17
Experiment 5	4750	0.15	4750	0.15	6347	0.32	4750	0.19
Experiment 6	4512	0.18	4512	0.18	6108	0.34	4513	0.21
Experiment 7	4415	0.19	4415	0.19	5987	0.35	4414	0.22
Experiment 8	4846	0.16	4846	0.16	6451	0.33	4847	0.19
Experiment 9	4786	0.15	4787	0.15	6383	0.33	4786	0.19
Experiment 10	4726	0.16	4730	0.16	6329	0.33	4732	0.19
Experiment 11	4674	0.16	4674	0.16	6269	0.33	4674	0.19
Experiment 12	4583	0.17	4583	0.16	6177	0.33	4583	0.20
Experiment 13	4535	0.17	4535	0.17	6128	0.33	4533	0.21

In Table 5.2, experiment 1 is again the current situation. Experiments 2-7 are related to the setup times and experiments 8-13 are related to the failure times. The fact that the average throughput decreases for experiments 6, 7, 12 and 13 is expected as here the setup times and failure times have been increased, as mentioned in Section 4.2.3.

In Table 5.2 it is shown that only experiment 2, the complete removal of setup times, leads to an average throughput of the system of over 5200, 5222 with a 95%-confidence interval of [5200-5246], while experiment 8 only leads to an average throughput of the system of 4846 with a 95%-confidence interval of [4827-4866]. The complete removal of setup times is of course impossible in practice. A combination of the reduction of setup times and failure times could lead to a higher result, as can be found in Appendix B. This, however, requires a reduction of such a scale that it still would not be a viable solution in practice.

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[redacted]

Figure 5.1: Average throughput

In Figure 5.1 we can see the impact on the throughput of the setup times and failure times reduction. A reduction of the setup times by 25% leads to an increase of 2-3% in throughput while a reduction of the failure times by 25% leads to an increase of approximately 1% in throughput. These trends similarly hold when the times increase instead of decrease. The complete removal of setup times results in an increase of throughput of approximately 13%, compared to the current situation, while the complete removal of failure times results in an increase of throughput of approximately 5%, compared to the current situation.
Another interesting observation is that the bottleneck in all situations still seems to be the production machine. The system throughput does not drop compared to the production throughput at any point in the experiments. This indicates that there is a lot of spare capacity that is unused at later parts of the production process. This explains the linear relation that is found in Figure 5.1 as an increase in throughput at the bottleneck does not shift the bottleneck to another station at any point. While it was known that the production machines are the bottleneck, the extent to which the system is imbalanced was not.
A third observation is that the standard deviation does change a lot due to the setup times, but the failures seem to have no significant impact on it. Still, the main source of the standard deviation seems to be of a different origin as a part of the changes in the CV can be explained by the increase in throughput.

Based on these observations, different experiments become interesting. How does the product mix affect the throughput of machines, what is the bottleneck and the standard deviation at the machines? In order to give an answer to these questions, three more experiments are conducted.

These experiments consist of product mixes that are located solely in one of the three production buckets, the 81 per tray products, the 49 per tray products and the 25 per tray products. The experiments are conducted without setup times because the setup times are sequence dependent and in these experiments there is no sequence of orders. The results of these experiments can be found in Table 5.3.

Table 5.3: Results experiment 14-16

	Production		**Gluing robots**		**Hand gluing**		**System**	
	Average	CV	Average	CV	Average	CV	Average	CV
Experiment 1	4624	0.16	4624	0.16	6219	0.33	4624	0.20
Experiment 14	6334	0.05	6334	0.05	12496	0.08	6247	0.11
Experiment 15	4610	0.05	4610	0.05	4610	0.10	4610	0.10
Experiment 16	3778	0.06	3778	0.06	3773	0.07	3773	0.07

Here we find that the bottleneck of the system does not shift for experiment 15 and 16. There does seem to be a slightly lower system throughput than production throughput in experiment 14. CV of the production machine and the subsequent system is, however, greatly reduced compared to experiment 2, which also had no setup times in the experiment. This indicates that the product mix has a large impact on the standard deviation of the throughput.

From these experiments we can also clearly see that the throughput of the production machine, and therefore the system, changes due to the product mix. A shift where solely products from the 49 products per tray or 25 products per tray buckets are produced is simply incapable of reaching the goal of 5200 products per shift, even when the setup times are completely removed. The maximum throughput they could achieve would be 4610 with a 95%-confidence interval of [4590-4629] and 3778 with a 95%-confidence interval of [3758-3797] respectively. Only the 81 products per tray bucket is capable of reaching an average of over 5200 products per shift, namely 6335 with a 95%-confidence interval of [6309-6326]. Still this number is only reached when there are no setups at all.

5.1.2. Additional experiments

The previous experiments that the only meaningful way to improve the throughput is to expand the amount of machines in the production line. However the fact that the production machine is the bottleneck in almost all of the experiments means that the capacity of the gluing robots and the hand gluing station is masked. Because of this it is interesting to analyze the characteristics of the individual stations and what their maximum average throughput is.

To this end the simulation model is slightly altered. Instead of the products arriving at the production machine, the model now has them arrive at the gluing robot. This circumvents the previous bottleneck. This way the full capacity of the gluing robots is shown and so is the full capacity of the hand gluing, provided that this station is the new bottleneck. For the product buckets where this was not the case a separate experiment was done to increase the throughput of the gluing robot, thus making the hand gluing station the new bottleneck. The results of these experiments can be found in Table 5.4. The table shows the full capacity of each part of the system as if they were an individual system. “Production” shows the maximum average throughput for the combined production machines. “Gluing robot” shows the maximum average throughput for the combined gluing robots. “Hand gluing” shows the maximum average throughput for the hand gluing station and “System” shows how the throughput for hand gluing translates into products leaving the system. For these experiments the buckets identified for the gluing robots in Section 3.2.2 are used. The product mixes for the experiments are as follows:

- Normal product mix: historical data
- Bucket 81 2x: 1 inch by 1 inch (1x1)
- Bucket 81 1x: 1 inch by 0.765 inch (1x¾)
- Bucket 36&49: 2 inch by 1 inch (2x1)
- Bucket 25: 3 inch by 1 inch (3x1)

Table 5.4: Maximum average throughput per bucket

	Production		Gluing robots		Hand gluing		System	
	Average	CV	Average	CV	Average	CV	Average	CV
Normal product mix	5225	0.12	8458	0.10	8614	0.25	6808	0.22
Bucket 81 2x	6335	0.05	7346	0.01	12654	0.07	6328	0.07
Bucket 81 1x	6335	0.05	9663	0.02	12628	0.05	12628	0.05
Bucket 36&49	4610	0.05	10487	0.01	7639	0.05	7639	0.05
Bucket 25	3778	0.06	7589	0.02	3897	0.05	3897	0.05

Table 5.4 clearly shows how imbalanced the system is and how the product mix plays a role in this imbalance. For example for the Bucket 81 2x the gluing robots have the highest maximum throughput in the system while for bucket 81 1x this is the case for the hand gluing station (notice that while the average for the hand gluing station is higher, it results in fewer products leaving the system, this can be explained by rework). The most noteworthy thing is the CV at the gluing robots. The processing time of the gluing robots in the model is deterministic, closely resembling reality. This means that when the product mix consists of one type of product only, the CV is very small. It can be in its entirety attributed to the fact that the last shift of every day ends production earlier than the

first shift. This leads to the CV found in the buckets. However for the normal product mix the CV is even comparable to the CV for the production machines. This further shows the impact the product mix has on the standard deviation of the throughput.

In the current product mix the average maximum throughput for the production machines is far lower than that of the gluing robots and the hand gluing station. Keeping in mind that the data is without setup times, this difference becomes even larger when we do include them.

With this information it becomes clear that the main problem at a required higher will be balancing which machines to add to which stations to most efficiently increase the throughput of the system.

5.2. Application of the results in the current and future situations

In this section we first discuss the future situations and then the current situation. While this approach may seem counter intuitive discussing, the future situation first allows us to lay down some general rules that can be used to transform everything that is applied to the current situation into something that can be used in the future.

Future situations

Since the production line is relatively new and the product mix has not been established yet, it would be of great help to have the possibility to generalize the results from the experiments to different product mixes. It should be possible to construct the maximum average throughput for each station with different product mixes based on the outcomes shown in Table 5.4.

As it is clear that the properties of the product have a big impact on the speed of production it is not possible to simply multiply the product mix with the average maximum throughput. The amount of production time used to produce products is the measure that is needed to determine the expected average maximum throughput for different product mixes.

In order to find the amount of production time used for a certain bucket we start with the product mix and divide this by the average maximum throughput. The total of the outcomes for all buckets is then used as the benchmark for the 100% of the production time. The outcome for each individual bucket is then divided by the sum of all buckets and thus the percentage of production time dedicated to the individual bucket is found. This percentage is then multiplied by the average maximum throughput to construct the maximum average throughput for that product mix. An illustration of this process can be found in Appendix C.

We can apply the process shown in Appendix C to different product mixes. The expansion of the production line has not been gradual; contracts that are agreed upon are long term and concern large increases in production volume. This means that the results need to remain usable in cases of extreme changes to the product mix. As an illustration we show the outcome of the process that can be found in Appendix C for the following product mix:

- Bucket 81 2x: 20%
- Bucket 81 1x: 20%
- Bucket 36&49: 20%
- Bucket 25: 40%

This is very different from the product mix in the current situation. When we calculate the new maximum average throughput per station we get the outcomes shown in Table 5.5.

Table 5.5: Maximum average throughput per shift in the hypothetical situation

	Production	Gluing robots	Hand gluing	System
Current situation	5225	8457	8619	6808
Hypothetical situation	4707	8354	6187	5673

When we compare the current situation to the hypothetical situation we see that the maximum average throughput at the production machines has been slightly reduced, from 5225 to 4707, the maximum average throughput at the gluing robots has remained nearly the same, 8457 in the current situation and 8354 in the hypothetical situation, the maximum average throughput at the hand gluing station has been significantly reduced, from 8619 to 6187, and the maximum average throughput for the whole system was also lowered from 6808 to 5673. The production machines still remain the bottleneck but the maximum average throughput at the hand gluing station has become much closer to the maximum average throughput at the production machines than before.

This generalization means that the outcomes of the project will remain relevant and usable even if the product mix changes.

Current situation
The goal of the project is to increase the throughput of the production line to over 5200 per shift. It has already been established that this is not possible through any other means than expanding the amount of machines in the system. The application of the results to the current situation therefore consists of analyses that determine at which station the addition of a machine increases the throughput the most.

Most of the standard deviation can be attributed to different times at which the shift ends and the product mix. The only station where the standard deviation remains high is the hand gluing station. This is however the last station in the system and because of that the standard deviation at the hand gluing station is not a concern for the rest of the system. As a result, making calculations simply based on the averages is a good indicator of the results that adding a machine to the system would have. This can be done for the current product mix and for the extreme product mixes to identify in which situations potential problems could occur without having to test a large amount of hypothetical product mixes.

To find the best ways to increase throughput, an incremental addition approach is used. Every time one machine is added to the production line, this can be a production machine, a gluing robot or a hand gluing machine. Then for each of these options, calculations are made to determine how this would improve the maximum average throughput of the system as a whole, if at all. The option that increases the maximum average throughput for the current product mix is selected but it is also shown for which buckets the addition of a different machine would be beneficial. This allows us to see where small improvements to a machine in the future could be beneficial and to what extent. This makes sure that the results remain useful after this project.

At each time there is only one option that increases the maximum average throughput for the current product mix since there is only one bottleneck, this means that the one machine that increases the maximum average throughput for the current product mix is selected.

If the product mix changes in the future, the process mentioned earlier in this section can be used to construct new throughputs and repeat the same process. An illustration of this process can be found in Appendix C.

In order to make the process more realistic, the outcomes from Table 5.4 for the production machines are altered to incorporate the setup times as they are currently (See Section 3.5). The average maximum throughput for the production machine with setups was 4624 and without the setups was 5225 (see Table 5.2). The throughput with setups relative to the throughput without setups is 4624/5225=0,885. For the extreme product mixes we assume that the production time lost due to setups remains the same. Thus the maximum average throughput of the production machines, for all product mixes, from Table 5.4 are multiplied by 0,885 to better reflect the current situation.

The outcome for the current product mix can be found in Table 5.6. In Table 5.6 a configuration has the following format: number of production machines- number of gluing robots – number of hand gluing machines. For example, the current situation is: 2-2-1.

Table 5.6: Incremental machine addition summary

Machines added	Configuration	Throughput	Throughput increase
0	2-2-1	4624	x
1	3-2-1	6808	2184
2	3-2-2	6936	127
3	4-2-2	8456	1521
4	4-3-2	9248	790
5	5-3-2	11478	2311
6	6-3-2	12685	1126
7	6-4-2	13615	930
8	6-4-3	13871	256
9	7-4-3	16184	2311
10	8-4-3	16914	730

With Table 5.6 the benefits gained from incrementally adding a machine can be found. Appendix A shows the full incremental additions with the extreme product mixes and can be used to find the bottlenecks for certain product types in certain configurations. This would help identify where small improvements to machines, such as setup and failure time reduction, would be beneficial to the throughput of the system as a whole. This allows for more targeted improvements in the future, even after expansions have been made.

The first three iterations of the process can be found in Table 5.7. This table is used to explain the process and how to identify the bottlenecks. The full table can be found in Appendix D.

Table 5.7: Incremental machine addition 3 iterations

Machine added:	Product mix	1	2	3
Production machine	Current situation	6808	6808	8457
	Bucket 81 x2	6328	6328	7346
	Bucket 81 x1	8410	9662	9662
	Bucket 49&36	6120	7639	8160
	Bucket 25	3897	3897	6686
Gluing robot	Current situation	4624	6808	6936
	Bucket 81 x2	5607	6328	8410
	Bucket 81 x1	5607	8410	8410
	Bucket 49&36	4080	6120	6120
	Bucket 25	3343	3897	5015
Hand gluing machine	Current situation	4624	6936	6936
	Bucket 81 x2	5607	7346	7346
	Bucket 81 x1	5607	8410	8410
	Bucket 49&36	4080	6120	6120
	Bucket 25	3343	5015	5015

In Table 5.7 the impact of the incremental addition of machines on the maximum average throughput is shown. There are three possible machines to be added, a production machine, a gluing robot or a hand gluing machine, as shown in the table. In the columns the maximum average throughput of the system is shown if this option was taken. For example: if we add one production machine the maximum average throughput of the system would increase to 5237. The addition of a gluing robot or hand gluing machine would leave the maximum average throughput at 3557, there is no improvement there. Then for the second iteration we would add the hand gluing machine as this increases the maximum average throughput to 5335, while adding a gluing robot or production machine would keep the maximum average throughput at 5237. For the third iteration a production machine is added, increasing the maximum average throughput to 6506, while adding one of the other machines would keep the maximum average throughput at 5335.

The maximum average throughput for each option is taken by looking at all the individual machines and selecting the one with the lowest maximum average throughput. This machine is considered to be the bottleneck machine. The machine that was selected to be added is shown by the green cell color in the cell with the maximum average throughput for the current situation. The color yellow is used to show which machine addition would have been selected if only products within that bucket were made. For example, while the machine selected to be added as the second machine is the hand gluing machine, the production machine would have been added based on a product mix of only products in bucket 81 x1 and bucket 49&36. However since these do not make up a big enough portion of the product mix, the hand gluing machine was added. Therefore, it is possible that a machine is selected based on the current product mix but that it is not the best option for one of the extreme product mixes. It is highly unlikely that the product mix will change so dramatically that this results in a shift from a strong benefit from adding one kind of machine to a strong benefit from adding another kind of machine. Generally these differences matter when the benefit of adding just one machine is already relatively low. Still it is important to note just how much of an impact a radical change in the product mix can have and keeping this in mind would help to anticipate the needed alterations to accommodate such radical changes.

With this table it is also possible to identify the bottlenecks for certain types of products. In each column it is shown where the bottleneck used to be in the system, since the addition of a new machine increases the capacity of this bottleneck. For example, if one machine has been added, the bottleneck for the products in bucket 81 x1 and bucket 49&36 is the production machine while the bottleneck for the bucket 81 x2 and bucket 25 is located at the hand gluing station. This is found by finding the yellow cells in the column of adding the second machine. This will help identify when improvements to which machines are a good option for improving total throughput of the whole system. For example bucket 49&36 seem to always keep having the production machine as the bottleneck while the bucket 81 x2 almost always has the gluing robot as the bottleneck.

5.3. Conclusion

Based on the first round of experiments, the following results were found. For the setup times a reduction of 25% lead to an increase in throughput of 2-3% while a reduction of the failure times of 25% lead to an increase in throughput of about 1%. This linear relationship can be explained by the fact that the production machines are the bottleneck, and even stay the bottleneck after the changes in setup time and failure time. Based on this, we concluded that reducing the setup times and failure times is not enough to reach the required improvement in throughput.

This shifted the focus of the experiments to adding additional machines. In these experiments, each individual machine was treated as the bottleneck to find its individual characteristics. Based on these characteristics, an incremental addition approach was used to add machines to the system. This approach led to a final solution of 8 production machines, 4 gluing robots and 3 hand gluing machines, with a throughput of 13011 products per shift.

All of these outcomes can be used to extrapolate the throughput for future product mixes. This ensures that the outcomes stay relevant even when changes to the product mix occur.

6. Conclusion & recommendations

In this chapter we draw the conclusions of this research (Section 6.1), provide a discussion on the limitations of the research in Section 6.2, provide recommendations for Sundisc Abrasives in Section 6.3, and give suggestions for future research in Section 6.4.

6.1. Conclusion

The main research question of this project is:

How can Sundisc improve the average throughput of their flap wheel production line to at least 5200 flap wheels per shift?

This question was answered through three sub-questions, which are discussed in Section 6.1.1, the answer to the main research question will be given in Section 6.1.2.

6.1.1. Summary of answering the sub-questions

The first sub-question is: *What is the current situation at the production plant?*

In answering this sub-question we give a structured view of the production. This resulted in an overview of the system as can be seen in Figure 2.22. The system has two separate production lines with a production machine and a gluing robot, which then come together at a single hand gluing machine. Here products can be glued once, sent to the oven and then be finished, or they can be glued once, sent to the oven for 15 minutes, glued again and then sent to the oven again, for the final time.

The second sub-question is: *How can the data be used to construct a conceptual model?*

In answering this sub-question we translate the view of the production process from the first sub question into a conceptual model, based on the data. The characteristics of the machines are explored in terms of the data. The result of this sub question are summarized in Table 3.6. The gluing robots are represented by a deterministic processing time; the processing time of the hand gluing station is represented by an empirical distribution. The processing time of the production machines are also represented by an empirical distribution, as is the time to repair and the set-up time. The time to failure for the production machine is represented by a Weibull distribution.

Another result of this sub question is that the products are put in different buckets. This is largely done across the lines of the amount of products per tray, as can be seen in Table 3.4. The exceptions being that the products of the 49 per tray and 36 per tray are put in the same bucket and that the 81 products per tray bucket is split by how many times they have to be glued in the gluing machine, once or twice. The products in the buckets are treated as if they are one and the same product.

The third sub-question is: *How can the current situation be modelled in a formal model?*

In answering this sub-question we first determined what type formal model to use. The formal model used is a nonterminating discrete-event simulation model. The production line was modelled using Plant Simulation. This model was verified and validated by expert knowledge and analyzing the data related to parts of the simulation and analyzing the product flow in the simulation. Multiple experiments were conducted to find a solution to the main research question. The first experiments focused on the setup times and failure times, later settling on the characteristics of individual machines to find the impact of adding more machines to the system.

6.1.2. Answer to the main research question

The main research question is:

How can Sundisc improve the average throughput of their flap wheel production line to at least 5200 flap wheels per shift?

From the results of the experiments we found that a 25% decrease in the setup times results in a 2-3% increase in throughput and that a 25% decrease in failure times results in an approximate increase in throughput of 1% for a maximum total increase of 5%. A complete removal of setup times would lead to an increase in throughput of 13% and a completel removal of failures would lead to an increase in throughput of 5%. While the complete removal of setup times would lead to a throughput of 5222 with a 95%-confidence interval of [5200-5246], changes of that magnitude are not viable in practice. This means that there was no practical solution that would result in the required increase in throughput.

The focus shifted to the addition of new machines in order to increase throughput. An incremental addition approach was used to add up to 10 machines to the system based on the current product mix, the result of which can be found in Table 5.6. We found that the addition of one production machine increased the maximum average throughput of the system to 6808, well over 5200. To aid in future decision making the result of adding more machines was included in this report, as well as a way of generalizing these results to a changing product mix, to ensure that the outcomes remain useful in the future.

Thus, based on the research conducted in this report, the average throughput of the flap wheel production of Sundisc can be increased to 5200 flap wheels per shift by adding an additional production machine.

6.2. Discussion

Here we discuss the limitations of this research.

First we discuss the limitations due to assumptions made about the production line. The first limitation here is that we assumed that there are always enough raw materials on stock to produce all the orders. This means that the throughput may be slightly overestimated compared to the real situation. Another assumption is that certain types of products are always hand glued once or always hand glued twice. This is not true in practice, there is, however, no telling what the impact was. A third limitation is due to the creation of the buckets. Multiple products were lumped together based on the characteristics that had the most impact on processing times. Naturally this means that some characteristics which also impact processing times were omitted in the model. More complete data would have allowed us to forego the creation of these buckets and allowed for a more detailed view of the impact of certain more extreme products within the buckets on the production line.

There are also limitations due to assumptions made about the data. First of all a lot of empirical distributions were used, instead of theoretical distributions. Empirical distributions have some limitations, for example, extreme cases are likely to be excluded in them while a theoretical distribution would have allowed for a small chance for these to happen in the model too. This therefore reduces the variability in the model while this variability does exist in the actual production line. Another limitation is due to the lack of data for the hand gluing machine and the setup times. The amount of data for these two instances was so limited that no statistical analysis could be performed. This does put some limitations on the research but not too many, the hand gluing machine is at the end of the production process and therefore does not have a significant impact on the rest of the system, and the setup times were part of the experiment parameters. We therefore know what the impact would be on the throughput if the setup times turn out to be different from the model.

Another part of the limitations of this study is the fact that only one performance measure for the system is collected at this time: the throughput at the production machines. No other performance measures are collected at any time during the production. While this is not an issue right now, since the production machines are the clear bottleneck, this does mean that there was no way to verify a large part of the model by comparing it to the current situation. We were able to confirm from the machine operators that it reflects the current situation, but this does not carry the same amount of weight as comparing it to current performance measures.

6.3. Recommendations

The research shows that the best way to increase throughput at this moment for Sundisc is to add another production machine to the production line. After that adding another hand gluing machine and another production machine will lead to the second spike on throughput for the system. Such changes, however, bring different problems and opportunities with it.

While at this moment the production machines are by far the main bottleneck of the production system, this will change in certain configurations with additional machines, for certain product types. At the moment, only the throughput at the production machines is collected as a performance measure. We would recommend expanding this to certain other performance measures and to slightly alter the way the current performance measure of throughput at the production machine is used.

One of the important things about a Performance Indicator, as stated by Fortuin (1988), is that it can be influenced or controlled by the user. The issue with the throughput of the production machines is that the product mix causes a lot of variability in the throughput at the production machines. In other words, the product mix determines the throughput at the production machine to a large extent. The operators have no control over the product mix; as such the performance measure fails in this regard. This can be fixed by selecting a bottom line product, for example the 1 inch by 1 inch product, and determining how many other products can be made in the time that this product can be made. For example, during the research we found that in the same time it takes 4873 products of 81 products per tray, one could make 3546 products of 36 & 49 products per tray. As such a product of 39 & 49 products per tray should count 1.37 times as much as a product of 81 products per tray. While this does raise the complexity of the performance indicator somewhat, it greatly enhances the amount of influence an operator has on the performance indicator.

Even then, however, the performance indicator is not without problems. Another aspect that impacts the throughput of the production machine is the setup times. While the operators have some influence on how long a setup takes, they have no influence on the amount of setups that occur; this is decided at the planning stage. We also found that the amount of setups does impact the throughput to a significant degree. This means that the amount of setups is a very interesting performance measure. Reducing this performance measure could result in significant increases in throughput after all. Adding this performance measure would greatly help in deciding if the amount of setups warrants changes to the production process in order to try to reduce them. It can also be used to determine if a drop in throughput is the result of increased setups. This performance measure is easy to collect; there is already a record of the sequence in which production occurred. We also know between which type of product a setup occurs, and which type of setup occurs. Because of this, the performance measure can easily be gathered from the data already available.

As mentioned in Section 5.2, a change in the location of the bottleneck would also reduce the throughput at the production machine as a reliable indicator of the throughput of the system as a whole. Therefore we also recommend adding a performance measure for the throughput at the hand gluing station. This station is clearly variable and has processing times that are very different from the production machines. The gluing robots are not variable at all, meaning they will require less monitoring. Again, as mentioned above, the different aspects of the products at the hand gluing station, resulting in different processing times should be included. An additional measure to keep track of how many of the trays require rework would further increase the ability to track improvements at the hand gluing station and to predict the routing of a product through the system. At this point, nobody, aside from the operator that is working on a specific tray, can make a reliable prediction about the odds of that tray having to be reworked. A performance measure that tracks which tray is reworked and which tray is not would therefore offer valuable insights. A simple tracking of how many times a cart has entered the hand gluing station, once or twice, and how many trays were on that cart, with which products, would possibly suffice. If it turns out that it is regularly the case that not all trays on a cart have to be reworked, but some do, it may be required to reduce this to a tray level instead of the cart level.

Other performance measures that were mentioned in Kenny & Dunk (1989) are more related to the overall performance of the line when it comes to interactions with customers. For example, a performance measure for the rate at which delivery schedules are met is very high on the list of performance measures that are considered to be important by production managers. No such performance measure is in place in Sundisc yet, making it hard to compare changes in the system to the performance that is seen by the customers. Another performance measure that is very high up the list is the difference between planned output and actual output. This is a measure for how reliable the planning system is.

Further collection of data would be useful for discovering less obvious characteristics that impact the throughput. In this research the most used characteristic is the number of products per tray. This does, however, mean that differences within these buckets are largely ignored. As an example, for some products in the 81 products per tray bucket, the average processing time at the gluing robot is longer than the average processing time at the production machines, while for other products in the same bucket it is the other way around. The aggregation to the same bucket results in a situation where just one of these scenarios is modelled. Improved data on the processing times at the different stations would allow for lower aggregation levels. Higher accuracy of data could also be used to improve a planning system in the future due to superior predictions.

Similarly, the hand gluing station suffered from a severe lack of data. Improvements in the amount of data available could prove very helpful in identifying possible improvements for the throughput times at this labor intensive station.

6.4. Future research

In this research the focus shifted from reducing the setup and failure times to increasing the amount of machines in the system. For the current scale of production this indeed has a bigger impact on the throughput. However if the scale of production increases through the addition of machines, then the reduction of particularly the setup times could have a big impact. Methodologies such as the Single-Minute exchange of Die could prove useful; Cakmakci (2009) reports setup time reductions of up to 90% in the automotive industry using this methodology. Future research into the possibilities might prove worthwhile. Méndez & Rodríguez (2015) present a more in-depth example of how Single-Minute exchange of Die was applied to reduce the setup times at a production line of interconnection axle's.

Another option that is of interest is a possible change from the current Make To Order system to a Make To Stock system for the more regular products. This would allow for greater control over the setups. This is interesting because there are three different types of setups with different average setup times. Not only would this be helpful with the setups, it would also allow for a planning that takes into account that as the system grows, the bottlenecks will switch from the production machines to other machines for certain types of products. In a Make To Stock system the location of the bottleneck in the system at a certain point in time would be easier to control. Rajagopalan (2002) offers a heuristic that allows for decisions regarding which products to make to stock and which products to make to order. In this heuristic the products selected for Make To Stock always have a reduction in the number of setups of over 50% compared to if these products were produced according to Make To Stock, showing the possibility for improvements in setups. Federgruen & Katalan (1999) offer different strategies for implementing a hybrid Make To Order and Make To Stop system. As an alternative to the addition of Make To Stock to the system, or as a complementary measure, improvements to the planning system are also interesting. As stated in Section 6.3 the addition of machines will shift the bottleneck for certain product types, thus reducing the throughput at the production machines as a reliable measure for the performance of the system. This has the added consequence that a planning based on the reduction of the setup times at the production machines may not always be optimal. Due to the nature of the system a resource driven planning that takes setup times into account would be worth investigating.

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Appendix A: Distribution fitting

For some of the random variables we conducted goodness-of-fit tests to assess the quality of the fitted theoretical distributions as based on the variable data. The random variables for which this was done were the production times at the production machine, for the bucket of 81 products per tray, the time to repai,r and the time between failures at the production machines. As explained in Chapter 3, there are more random variables but we did not perform goodness-of-fit tests on these for varying reasons.

As the goodness-of-fit test, the chi-squared test (χ^2-test) is used. The chi-squared test splits a distribution into multiple bins. Each bin contains the same amount of expected observations. For example, if you have 100 data points, the chi-squared test will make bins where if one draws 100 random data points from the distribution, the same amount of points would be found in each of the bins. Then the amount of data points per bin is counted. If this number differs too much from the expected number of observations then the distribution does not fit with the data. The equation for the chi-squared test can be written as follows:

$$\chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i}$$

Where n is the number of bins, O_i is the frequency of empirical data in the bin and E_i is the expected frequency of the theoretical distribution. This shows that the χ^2 measure is meant to show the difference between the data and the expected distribution.

The probability of obtaining a test result at least as extreme as the one found is shown as the p-value. If the p-value is smaller than 0.05 the theoretical distribution is rejected.

The chi-squared test outcomes for the processing times can be found in Table A.1, the test outcomes for the time to repair can be found in Table A.2 and the test outcomes for the time between failures can be found in Table A.3.

Table A.1: Chi-squared test for processing times

Distribution	Beta	Normal	Erlang	Exponential	Gamma	Lognormal	Weibull
p-value	$1.27*10^{-10}$	$7.01*10^{-9}$	0.0033	0	0.0056	$7,39*10^{-4}$	$8.26*10^{-10}$

Table A.2: Chi-squared test for time to repair

Distribution	Beta	Normal	Erlang	Exponential	Gamma	Lognormal	Weibull
p-value	$5.31*10^{-13}$	0	0	$2.52*10^{-12}$	$4.42*10^{-13}$	$8.66*10^{-13}$	$1.24*10^{-12}$

Table A.3: Chi-squared test for time to failure

Distribution	Beta	Normal	Erlang	Exponential	Gamma	Lognormal	Weibull
p-value	0.17	0.26	x	0.81	0.82	0.40	0.82

For both the processing times and the time to repair all theoretical distribution are rejected. For the time to failure multiple distributions can be fitted, with the exception of the Erlang distribution. The Weibull distribution has the highest p-value.

Appendix B: Combining setup times and failure times reduction

In combining the setup times and failure times reduction we conducted 36 more experiments. These experiments consist of all the additional configurations that were not covered in Table 5.2. The outcomes for these experiments can be found in Table B.1. The layout of this table is slightly different from Table 5.2. We have already established the broad causes for the variability in the processes so adding a measure for the standard deviation in this table is not interesting. Therefor the table will only concern the average throughputs. The percentage of change compared to the current situation will also be shown, to make it easier to interpret the orders of magnitude of changes. The numbers in the configuration columns present the multiplier for the random variable. For example, a 0.25 in the Setup times column means a 75% reduction in setup times, so only 25% remains.

Table B.1: Outcomes additional experiments

			Production		Gluing robots		Handgluing		System	
	Setup times	Failure times	Average	Percentage	Average	Percentage	Average	Percentage	Average	Percentage
Current situation	1	1	4624	1.00	4624	1.00	6219	1.00	4625	1.00
Experiment 1	0	0	5500	1.19	5500	1.19	7311	1.18	5500	1.19
Experiment 2	0.25	0	5320	1.15	5320	1.15	7069	1.14	5319	1.15
Experiment 3	0.5	0	5146	1.11	5146	1.11	6857	1.10	5142	1.11
Experiment 4	0.75	0	4996	1.08	4995	1.08	6652	1.07	4988	1.08
Experiment 5	1.25	0	4724	1.02	4724	1.02	6323	1.02	4726	1.02
Experiment 6	1.5	0	4605	1.00	4604	1.00	6199	1.00	4604	1.00
Experiment 7	0	0.25	5423	1.17	5423	1.17	7186	1.16	5417	1.17
Experiment 8	0.25	0.25	5242	1.13	5241	1.13	6983	1.12	5241	1.13
Experiment 9	0.5	0.25	5077	1.10	5077	1.10	6776	1.09	5075	1.10
Experiment 10	0.75	0.25	4921	1.06	4921	1.06	6534	1.05	4916	1.06
Experiment 11	1.25	0.25	4661	1.01	4661	1.01	6262	1.01	4666	1.01
Experiment 12	1.5	0.25	4547	0.98	4546	0.98	6143	0.99	4549	0.98
Experiment 13	0	0.5	5354	1.16	5354	1.16	7101	1.14	5353	1.16
Experiment 14	0.25	0.5	5168	1.12	5173	1.12	6882	1.11	5170	1.12
Experiment 15	0.5	0.5	5010	1.08	5009	1.08	6658	1.07	5000	1.08
Experiment 16	0.75	0.5	4861	1.05	4861	1.05	6458	1.04	4859	1.05
Experiment 17	1.25	0.5	4608	1.00	4608	1.00	6206	1.00	4611	1.00
Experiment 18	1.5	0.5	4503	0.97	4503	0.97	6098	0.98	4504	0.97
Experiment 19	0	0.75	5290	1.14	5289	1.14	7028	1.13	5286	1.14
Experiment 20	0.25	0.75	5110	1.11	5110	1.11	6810	1.10	5110	1.10
Experiment 21	0.5	0.75	4948	1.07	4948	1.07	6560	1.05	4943	1.07
Experiment 22	0.75	0.75	4804	1.04	4803	1.04	6403	1.03	4805	1.04
Experiment 23	1.25	0.75	4560	0.99	4560	0.99	6153	0.99	4559	0.99
Experiment 24	1.5	0.75	4456	0.96	4456	0.96	6047	0.97	4457	0.96

Experiment 25	0	1.25	5160	1.12	5159	1.12	6852	1.10	5155	1.11
Experiment 26	0.25	1.25	4984	1.08	4984	1.08	6614	1.06	4978	1.08
Experiment 27	0.5	1.25	4836	1.05	4835	1.05	6433	1.03	4835	1.05
Experiment 28	0.75	1.25	4695	1.02	4695	1.02	6292	1.01	4697	1.02
Experiment 29	1.25	1.25	4472	0.97	4472	0.97	6061	0.97	4471	0.97
Experiment 30	1.5	1.25	4365	0.94	4365	0.94	5899	0.95	4361	0.94
Experiment 31	0	1.5	5090	1.10	5089	1.10	6744	1.08	5083	1.10
Experiment 32	0.25	1.5	4930	1.07	4930	1.07	6542	1.05	4930	1.07
Experiment 33	0.5	1.5	4779	1.03	4779	1.03	6375	1.03	4778	1.03
Experiment 34	0.75	1.5	4648	1.01	4648	1.01	6246	1.00	4651	1.01
Experiment 35	1.25	1.5	4424	0.96	4423	0.96	5987	0.96	4421	0.96
Experiment 36	1.5	1.5	4325	0.94	4325	0.94	5841	0.94	4324	0.93

Appendix C: Changing the product mix

In Section 5.2 we mentioned that there is a process by which we can use the outcomes of the experiments with the extreme product mixes to construct any potential product mix that may occur in the future. Here we illustrate how this is possible. For our example we use the current situation, after this we discuss how this approach can be applied to all product mixes. The data used will be from Table 5.4. This means that in our example we will use the data from the individual machines to construct their individual maximum average throughput

From the experiments we have the following data:

- Total amount of products produced
- Total amount of products produced per bucket
- Average throughput of products
- Average throughput of products per bucket

From these the averages of these indicators we construct the throughput for the product mixes.

Table C.1: Total amount of products produced under the normal production schedule

Production machines	**Bucket 81 2x**	**Bucket 81 1x**	**Bucket 36&49**	**Bucket 25**	**Total**
Total amount of products produced	244686	37276	181673	58812	522446
Percentage of product mix	0.47	0.07	0.35	0.11	1.00
Gluing robots	Bucket 81 2x	Bucket 81 1x	Bucket 36&49	Bucket 25	Total
Total amount of products produced	362969	61390	312927	108225	845511
Percentage of product mix	0.43	0.07	0.37	0.13	1.00
Hand gluing machine	Bucket 81 2x	Bucket 81 1x	Bucket 36&49	Bucket 25	Total
Total amount of products produced	439206	45879	279388	96519	860992
Percentage of product mix	0.51	0.05	0.32	0.11	1.00
System	Bucket 81 2x	Bucket 81 1x	Bucket 36&49	Bucket 25	Total
Total amount of products produced	270210	45405	268851	57025	680777
Percentage of product mix	0.40	0.07	0.39	0.08	1.00

In Table C.1 we can see the total amounts of products produced per station and how much of the product mix consists of products from the different buckets. Due to different total amounts the product mixes differ slightly. This is expected in this situation. If a normal production run was used, these numbers would be more the same, except for the hand gluing machine due to rework.

Table C.2: Total amount of products produced under extreme production schedule

Production machines	Bucket 81 2x	Bucket 81 1x	Bucket 36&49	Bucket 25
Average amount of products produced	633516	633516	460978	377757
Gluing robots				
Average amount of products produced	734362	966022	1048629	758875
Hand gluing machine				
Average amount of products produced	1262821	1262821	763929	389740
System				
Average amount of products produced	776918	1262821	763929	389740

In Table C.2 we can see the total amounts of products produced per station for the extreme product mixes. For example a production machine is able to product 633516 products if it is only making products of the size 1 inch by 1 inch.

With these two tables we can now formulate how much of the production time is spent on making different products. For example: 47% of the product mix consists of products form the bucket 81 2x at the production machine. This amounts to the total number of 244686 products. The amount of production time spent on making these products is 244686/633516 = 39%. As we can see, while the product accounts for 47% of the product mix it is only being produced 39% of the time. Table C.3 shows these calculations being applied to all the other stations and buckets as well.

Table C.3: Average time spent on production

Production machines	Bucket 81 2x	Bucket 81 1x	Bucket 36&49	Bucket 25
Average time spent on production	0.39	0.06	0.39	0.16
Gluing robots				
Average time spent on production	0.49	0.06	0.30	0.14
Hand gluing machine				
Average time spent on production	0.35	0.04	0.37	0.25
System				
Average time spent on production	0.34	0.04	0.35	0.15

With these percentages we now know how much time is spent on each bucket for each individual station. The next step is to multiply these percentages with the throughputs found under the extreme product mixes. The idea behind this is that 39% of the time the production machine is running at the throughput found for bucket 81 2x, 6% of the time it is running at the throughput found for bucket 81 1x, 39% of the time it is running at the throughput found for bucket 36&49 and 16% of the time it is running at the throughput found for bucket 25. The results of multiplying these numbers with the throughputs from Table 5.4 can be found in Table C.4

Table C.4: Average constructed throughputs

Production machines	**Bucket 81 2x**	**Bucket 81 1x**	**Bucket 36&49**	**Bucket 25**	**Total**
Average throughput	2447	373	1817	588	**5225**
Gluing robots					
Average throughput	3631	614	3130	1082	**8457**
Hand gluing machine					
Average throughput	4401	459	2794	965	**8619**
System					
Average throughput	2702	454	2689	963	**6808**

If we compare the throughputs from Table 5.4 with the throughputs from Table C.4 we find that the outcomes are indeed close to each other. 5225 compared to 5223 for the production machines, 8457 compared to 8458 for the gluing robots, 8619 compared to 8614 for the hand gluing station, and 6808 compared to 6808 for the system as a whole.

Using the same approach, the average throughput for any other product mix can be constructed, both for the characteristics of individual machines, as shown here, and for the system as a whole, such as the results found in Table 5.3.

Appendix D: Incremental machine addition

Table D.1: Incremental addition approach full results

Machine added:	Product mix	1	2	3	4	5	6	7	8	9	10
Production machine	Current situation	6808	6808	8457	8457	11560	12686	12686	13616	16183	16914
	Bucket 81 x2	6328	6328	7346	7346	11019	11019	11019	12656	14691	14691
	Bucket 81 x1	8410	9662	9662	9662	14017	14493	14493	19325	19325	19325
	Bucket 49&36	6120	7639	8160	10200	10200	12239	14279	14279	14279	16319
	Bucket 25	3897	3897	6686	7589	7795	7795	7795	7795	11692	11692
Gluing robot	Current situation	4624	6808	6936	9248	9248	11560	13616	13616	13871	16183
	Bucket 81 x2	5607	6328	8410	11019	11213	12656	12656	12656	16820	18364
	Bucket 81 x1	5607	8410	8410	11213	11213	14017	16820	16820	16820	19623
	Bucket 49&36	4080	6120	6120	8160	8160	10200	12239	12239	12239	14279
	Bucket 25	3343	3897	5015	6686	6686	7795	7795	7795	10030	11692
Hand gluing machine	Current situation	4624	6936	6936	8457	9248	11560	12686	13871	13871	16183
	Bucket 81 x2	5607	7346	7346	7346	11019	11019	11019	14691	14691	14691
	Bucket 81 x1	5607	8410	8410	9662	11213	14017	14493	16820	16820	19325
	Bucket 49&36	4080	6120	6120	8160	8160	10200	12239	12239	12239	14279
	Bucket 25	3343	5015	5015	6686	6686	8358	10030	10030	10030	11701