# Bachelor thesis

The flow at Van Raam

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# Preface

Dear reader,

You are about to read my bachelor thesis conducted at Van Raam. This is the final assignment of my Bachelor Industrial Engineering and Management at the University of Twente. The thesis aims to reduce the throughput time of the production process at Van Raam.

But before you start with reading the thesis I would like to thank a group of people without whom writing this thesis would have been impossible.

First of all, I would like to thank Van Raam for allowing me to write my thesis at the company. The time at Van Raam was my first internship and it was full of new experiences and lessons that I will remember for the rest of my professional career. Despite the CoViD-19 pandemic, I was welcome to work on-site which allowed me to enjoy the atmosphere at the company. In special I would like to thank Roy Lammers, my internal supervisor. Despite his busy schedule, he would always find a moment to have a discussion and even though he only joined the company recently his insights were of great importance for my understanding of the company. I would also like to thank Jan-Willem Boezel for representing Van Raam during the colloquium.

Second, I would like to thank my UT supervisor Matthieu van der Heijden. I enjoyed all meetings we had during which you provided me with great feedback which helped me taking the thesis to the next level. Despite not having met in real life I still felt like we had a great connection. I would also like to thank my second reader Ipek Seyran Topan, and not just for being my second reader but also for her support and lectures during the introduction of the final modules.

Lastly, I would like to thank my friends and family for supporting me while writing the thesis. In special I would like to thank my buddies Yorick Beekman, Jaap Leuverink, and Jim van Santen for the feedback they provided throughout the process. Last but not least I would like to thank my parents for supporting me wherever possible in the course of this thesis.

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# Management summary

This thesis was written at Van Raam in Varsseveld, a company specialized in the production of adapted bicycles. The mission of Van Raam is to let everybody experience the freedom of cycling. In their high-tech production facility bicycles are produced entirely in-house. Because of the customer segment, Van Raam needs to satisfy customer needs in the short term and since all bicycles are made to customer specification it is not possible to produce bicycles to stock. Meeting these needs in time has however become more and more of a challenge. A cause of not being able to meet these needs is the throughput time of the process where the frames and parts are transformed into fully assembled bicycles. This throughput time is experienced as being too long. The main research question of this thesis is, therefore, formulated as follows:

*How can the throughput time of the paint shop and the assembly process be reduced from six and a half to at most five working days while maintaining the same output?*

The first step in the thesis was to analyse the current situation. This was done by observations on the work floor, conversations with employees, and an analysis of the data generated within the process. This way we learned how a raw frame turns into a fully assembled bicycle. From the analysis, it became clear that relatively high stocks are maintained within the production for which reason an interview regarding the planning and control method was organized. To conclude this phase research was done to identify the bottleneck of the process, this turned out to be the assembly department.

After the analysis, a literature study was performed on planning and control. Of the four activities of planning and control, monitoring and control is the most useful in reducing throughput time. The literature review, therefore, continued by researching the two forms of monitoring and control (push and pull) and methods for applying monitoring and control. The literature review was concluded by a search for methods that could be used to improve monitoring and control at Van Raam. This search resulted in the methods Kanban, POLCA, ConWIP, Bottleneck control, and Workload control.

The methods found in the literature review were scored on throughput improvement, adaptability for fluctuations, applicability at Van Raam, utilization, and sustainability. ConWIP and Bottleneck control scored the best on these criteria. These two methods were selected to be implemented in a simulation of the production process at Van Raam.

In the simulation, the base model (the current way of planning and control) was tested against ConWIP and Bottleneck control (on the assembly department). The methods were compared in terms of KPIs like average weekly output, total output, throughput time, average orders in the process, and utilization. By comparing the KPIs we concluded that both Bottleneck control and ConWIP were able to outperform the base model, in this comparison Bottleneck control attained slightly better KPI values than ConWIP.

After writing the thesis and conducting the experiments the following conclusions could be drawn:

- Of the five researched monitoring and control approaches, Bottleneck control and ConWIP are best applicable at Van Raam.
- By conducting the experiments it became clear that Bottleneck control on the assembly department scores the best on throughput time and WIP level.
- Both Bottleneck control and ConWIP can reduce the WIP level of the process from 300 to at most 180 orders, a reduction of 40%.
- Bottleneck control can reduce the throughput time by 2 days and 10 hours to 3 days and 23 hours, ConWIP performs slightly worse but still attaints a throughput time reduction of 2

days and 8 hours resulting in a throughput time of 4 days and 1 hour. This means that both methods can reduce the throughput time below the required 5 days.
- Both methods can reduce the WIP value by approximately €200.000,-.

Based on these conclusions and findings while conducting the thesis the following recommendations are done:

- Implement Bottleneck control on the assembly department as monitoring and control method. This will lower both the throughput time and the work-in-progress level. To continue the implementation it is advised to attract a student or monitoring and control expert to further guide the process.
- Stockouts and defects in the assembly cause an average waiting time of 1 day and 5 hours for each order. Fixing these problems would help reduce the overall throughput time.
- It is advised to further digitize the paint shop and the assembly department. Within the assembly, the main focus of this should be to decrease (or replace) the order papers and make the process more visible. Within the paint shop, it should be focussed on the stickering process to reduce the number of errors.
- Recalculate the designed throughput times and monitor the time spent at the different stations within the regular assembly.

Implementing these recommendations will improve the throughput time of orders and help Van Raam in its mission to making everyone mobile. Let's all cycle!

# List of acronyms

**BPM** Business process model.

**ConWIP** Constant work-in-progress.

**DBR** Drum, buffer, rope.

**ER** Easy Rider.

**ERP** Enterprise resource planning.

**F2G** Fun 2 Go.

**KPI** Key performance indicator.

**MiMa** Midi Maxi.

**MPSM** Managerial problem-solving method.

**MTO** Make-to-order

**OFAT** One-factor-at-a-time

**POLCA** Paired-cell overlapping loops of cards with authorization.

**QRM** Quick response manufacturing.

**VO** Velo Opair.

**VSM** Value stream map.

**WIP** Work-in-progress.

**WLC** Workload control.

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# 1 Problem identification

The problem identification is the first part of the thesis. We will give a short introduction and context of the company in section 1.1, after which we will define the action problem in section 1.2. In section 1.3 we will arrive at a core problem through the use of MPSM and a problem cluster. The chapter ends with the knowledge questions that will help us solve the core problem, this is part of section 1.4.

## 1.1 Company introduction

Van Raam is a company that in essence produces adapted bicycles for people with disabilities. Its bicycles are sold all over the world with emphasis on Europe and North Amerika. The company was founded almost 110 years ago and currently employs about 230 people. The bicycles are entirely produced in Varsseveld from frame to assembly. This is done in one of the cleanest and smartest factories in the Netherlands where innovative and modern techniques are used. Recently Van Raam has also expanded to Poland to increase capacity to cope with the increase in demand the company is currently experiencing (*Van Raam Expands to Poland*, 2020).

The mission statement of Van Raam is to produce all bicycles in-house using the best quality materials. Combining highly educated personnel, continuous innovation, modern production lines, and market research they produce bicycles that meet the needs of end-users. Among other things, the cooperation with universities and innovation hubs results in a modern designed and technically advanced bicycle. No surprise that Van Raam has recently been announced as one of the most innovative companies of the Netherlands by the Dutch ministry of economics, agriculture, and innovation (*About Van Raam*, 2020).

Van Raam: "Let's all cycle!"

*Figure 1: Assembly department at Van Raam*

## 1.2 The problem

In this part of the project, there will be an elaboration on the problems that are experienced by Van Raam. First, the action problem is identified which is the difficulty that is experienced by the problem owner. For this action problem, a norm and a reality will be established. Then the identification of the core problem will be done. This process is visualized by using a problem cluster. The last part of this chapter will address the selection of the core problem and the motivation for selecting this problem.

### 1.2.1 Action problem

This section will display the different problems that are experienced within the different departments of the process.

**The paint shop**

The paint shop is where the frame is coupled to a specific order, also known as the order decoupling point. The frames are made to forecast and collected from the warehouse, blasted, powder-coated, and inspected. The paint shop workers prefer to paint as many of the same coloured bicycles at once as possible to decrease the number of colour changes. Colour changes are not a hard restriction at the moment but they do take some time. Another problem experienced at the paint shop is that it is experienced as inflexible. Within the current way of working it is difficult to react to orders with a high priority which increases the throughput time.

**The warehouse**

At the warehouse, the parts for the assembly of the bicycles are stored. If frames are ready at the paint shop an order is sent to the warehouse. The employees at the warehouse collect this order and deliver it to the assembly department. There is however no clear structure in which order the parts are picked. The employees at the warehouse prefer to pick as many parts of the same type of bike at once. This prevents them from having to visit the same spot twice. The link between the ERP system and the warehouse also tends to fail. This causes differences in the amount that is expected to be in stock and the true stock.

**The assembly**

In the assembly department, three different types of assembly are performed: Line, cell, and regular assembly. Of these types, the regular and the line assembly line are the largest. In the current situation, there is often a large stock between the paint shop and the assembly department. The supply of frames leads to several problems in the assembly department. In the current configuration, the stocks pile up on the production floor which is experienced as a negative consequence. In the regular assembly, this large stock can also lead to frames that get lost. The mix of frames is also experienced as a problem. Each employee has experience with a limited number of bicycle types. If too many of the same frames are released at the paint shop this can cause the assembly department to clog up.

**The production planners**

The production planners organize the flow of products through the process. They release work orders that arrive from the sales department and monitor the progress of frames through the production process. The production planners experience plenty of problems. First of there is the low visibility of products. Their current ERP system which is based on Exact software has a black box that occurs between the paint shop and the final quality control. This means the production planners have to manually track orders in that part of the process. There is also no clear idea about what quantities of work orders should be released for production and what the optimal mix for the assembly departments is. Lastly, what also occurs within the process is that bicycles that have almost been assembled need to wait on the production floor because some part is missing. It is often known that these parts are out of stock but the work orders of the frames are released at the paint shop anyway.

**Process philosophy**
Currently orders are processed with the “first come, first serve with priority” sequencing method. The process philosophy however states that to achieve an optimal flow and prevent disruptions the process should be “First come, first serve”. To implement this the process should be fast enough to let the product with the shortest required throughput time go through the process without it having to be a priority. This philosophy was inspired form the car industry where the flow of the process should always be maintained.

All of these problems are in some way related to the throughput time of the process which is experienced as being too high. This leads to the main research questions of the thesis which is:

***How can the throughput time at Van Raam be improved?***

Based on this research question the action problem can be stated as follows:

***How can the throughput time of the paint shop and the assembly process be reduced from six and a half to at most five working days while maintaining the same output?***

To reduce the throughput time we can make use of Littles law. In his law Little states that the average work-in-progress is equal to the average arrival rate of work orders times the average time a work order spends in the system (Slack et al., 2016a).

$$L = \lambda * W$$

*Equation 1: Little's law*

By decreasing the stocks within the process we can decrease the average WIP. By maintaining the same arrival rate of products the time in the process has to change. This will result in a decrease in throughput time.

**Norm and reality**
The action problem is based on a norm and a reality. The norm is the situation that is aimed at by implementing the solution, the reality is what the process is actually like. Based on data supplied by Van Raam the throughput time, from the paint shop to final quality control, was on average six and a half working days in the last year. The shortest delivery time for products at Van Raam is however five working days. This time is for example promised for the easy rider 3. Therefore the throughput time of the process should be decreased from six and a half to at most five working days. In a conversation with the CTO, he explained his interest in the minimal throughput time of the process. In this case, there would be no inventories between the different steps of the process.

## 1.3 Identification of the core problem

The action problem is simply too vague and abstract to be answered at once. For this reason, the problems causing the action problem will be identified in this part of the thesis. Out of this selection of subproblems, one will be chosen to become the core problem. As mentioned by (Heerkens & Winden, 2017) it is more effective to solve one problem entirely than to solve many problems partially. This thesis will aim to identify and solve the core problem.
The problem identification can be done with the help of some tools. One of those tools is the problem cluster. This cluster displays the sub-problems of each problem and stops at problems that have multiple causes. These are the potential core problems (Heerkens & Winden, 2017). The

problem cluster can be found in figure 2. The legend implies what the action problem, the core problem, and the potential core problems are.

### 1.3.1 Scope

There will approximately be 10 weeks to work on the project. Therefore it will not be possible to research the entire company. Together with the internal supervisor, we concluded that the scope of the project would be the blasting chamber, paint shop, assembly department, and final quality control. The reason to not reduce the scope even further was that the combination of these departments is important for improving the throughput time. Previous studies have shown that the separate departments run somewhat optimally but the alignment of the process is missing. The result of this is that there is a large stock between the different departments which increases the throughput time of the process. The welding department is excluded from this scope and will be considered as an external supplier. The reasoning behind this is that frames are produced to stock by the forecast. Frames become order-specific after entering the paint shop (only in rare cases a frame is welded to customer specification).

### 1.3.2 Problem cluster

The action problem is something that cannot be answered simply. Many underlying causes will have to be identified. One of these causes will become the core problem which will be solved in this paper. The structure of problems and potential core problems is displayed in figure 2.

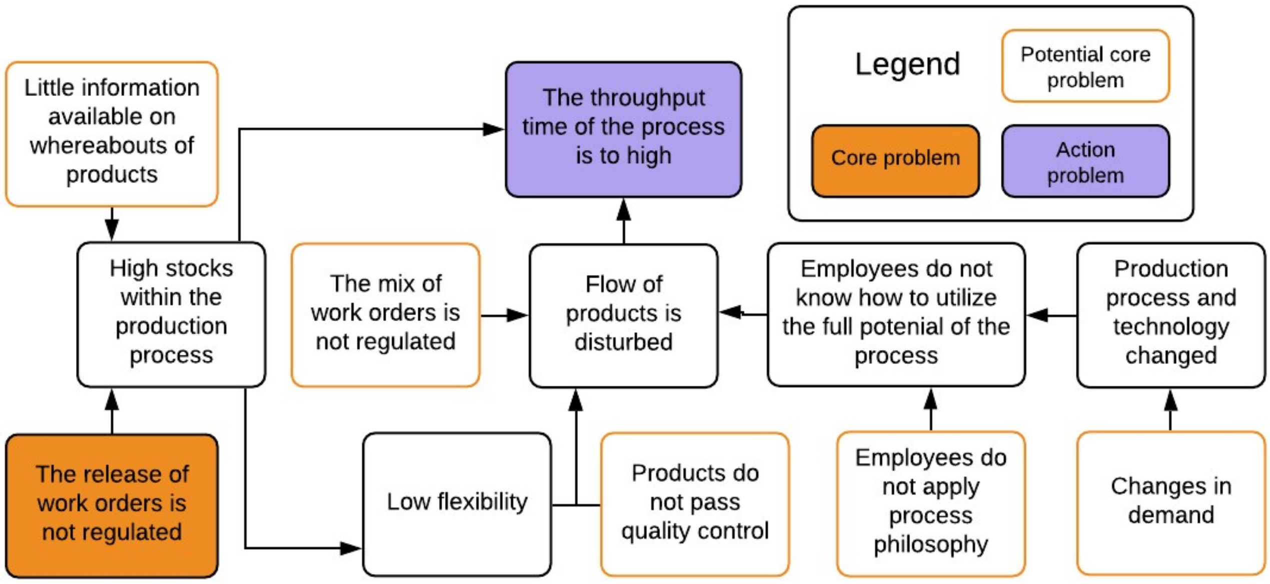


*Figure 2: Problem cluster*

### 1.3.3 Core problem

By doing initial research the problems displayed in figure 2 were discovered. As can be seen, some problems have multiple causes. The problem cluster stops at the problems that have no causes by themselves. These are the problems that can be identified as potential core problems. As explained by (Heerkens & Winden, 2017) there may be multiple potential core problems.
There are four requirements that a problem has to meet to be able to become a core problem.
The first requirement is that the problem is experienced as a problem within the company. If this is not the case then you are spending time and energy on a problem that does not exist.
The second requirement is that the problem does not have a direct cause in itself, there should not be one problem that is the main cause for the chosen core problem.

The third requirement is that the researcher should be able to influence the chosen core problem. If the researcher is not able to change the problem it is not possible to improve the situation.
When the previous requirements rules have been applied often only a few problems remain. The last requirement to arrive at a core problem is to choose the problem that, when solved, generates the highest impact with the lowest costs.

The first potential core problem is the change in demand. The increased and changed demand had as a consequence that the production process and technology had to change. The tire assembling machine for example had to move to an external location. To cope with these changes the production started optimizing locally. This however led to stocks between the different departments which led to a longer throughput time than required. The change in demand is however something that the company had to cope with to grow and meet customer demand. Therefore it cannot be changed and is not the core problem of this thesis.

The second potential core problem is that employees do not understand the process philosophy. This leads to employees working towards a sub-optimum. This leads to them performing well but the effect on the overall process is negative. This problem is however not believed to be the core problem. It should not be unnecessary to teach each employee the entire process philosophy and the flow of the process should be self-evident and intuitive. During my time at Van Raam, there also was an external party working on the process philosophy and the above-mentioned problems.

The third potential core problem is that too many products do not pass quality control. Doing a small data analysis I found out that of the bikes that have been painted in the last year, approximately 5% was rejected at quality control. For these orders, new frames often have to be painted which increases the throughput time of the order. This problem was however not chosen as the core problem since there are other parties involved in improving the quality. The frames are for example scanned by a 3d sensor to identify mistakes and the stickering process will likely be digitalized.

The fourth potential core problem is that there is little visibility on where products are within the process. Because of this low visibility, it is hard to tell the progression of a bicycle and sometimes causes frames to get lost. This on its turn is bad for the flow of products and has a bad influence on the throughput time. There is however currently a team busy identifying the best points to make the product visible. For this reason, I will not choose this as my core problem.

The fifth potential core problem is the lack of regulation in the release of work orders. In the paint shop, work orders are released in such a way that the number of colour switches is minimal. At the warehouse, orders are processed in such a way that large quantities can be picked. This prevents the employees from having to visit the same storage location twice. These ways of handling the orders can be considered somewhat optimal for the paint shop and the warehouse but lead to a mix that is difficult to cope with at the regular assembly. This possible core problem meets the first three requirements as stated by (Heerkens & Winden, 2017). It however only focuses on the regular assembly which is only a part of the assembly department, therefore it has a moderate influence on the throughput time of the process.

The sixth potential core problem is that there is no clear structure in the way work orders are released. This problem occurs in all departments of the process. Employees are free to handle the flow of orders to their preferences. The production planners release new work orders if they believe it is necessary, it is not based on data and KPI's. Providing a structure for releasing orders in the production process and as a result, decreasing the WIP could for this reason significantly improve the throughput time.
This problem meets the four requirements as stated by (Heerkens & Winden, 2017). It is experienced as a problem, it can be changed, it does not have a direct cause in itself and it can be improved at

similar costs to the previous problem while having a higher impact. For these reasons, the lack of a structured order release has been identified as the core problem. The core problem can be formulated in the following way:

***"The current way of releasing work orders leads to the build-up of stocks within the process which increases the overall throughput time of the process."***

## 1.4 Research design and problem-solving approach

To solve the core problem knowledge questions need to be formulated. Multiple knowledge questions are derived from the core problem. These knowledge questions will piece by piece helps to answer the main research question. The knowledge questions will be formulated with the MPSM method in mind. This method provides a framework that can be used to formulate knowledge questions that cover the entire project from problem identification to evaluation. A Gantt chart of the planning for time spent on the different activities can be found in appendix A.

### 1.4.1 Knowledge questions

1. ***Based on an analysis, what is the current state of the organization concerning production planning and control?***
   The goal of this knowledge problem is to identify the current manner of production management. To answer the question different data gathering methods will be used and data will be presented in multiple ways. First of all, interviews will be conducted with employees to understand their part of the production and attain a broad idea of the production. Van Raam uses the Exact ERP system, from this system information can be retrieved regarding the time frames took to pass the departments of the process. This can help reveal the problem even further. Lastly, an analysis of the structure on which the production is based will also be done. With the information obtained in this research, we will create business process models and a value stream map. This will help to obtain an overview of the current situation.

2. ***Which methods are available within literature to create a structure for production planning and control?***
   This knowledge problem will require extensive literature research. The goal of this research is to identify which optimization methods can provide a structure for the release of work orders and on which KPI's these methods are compared. The characteristics, strengths, and weaknesses of each method will also be identified. In knowledge question three a selection will be made of the methods that suit Van Raam the best and in knowledge question four the methods will be tested in a simulation.

3. ***Which methods can be applied best at Van Raam?***
   This part of the thesis will consist of interviews and a literature study. The interviews will be conducted with people that responsible for the process in which the method will be implemented. The alternative solutions will be graded on criteria like costs, performance, and sustainability. A relative weight will also be assigned to the criteria. The alternatives that receive the highest scores will be subjected to a simulation in the next chapter.

4. **How do the alternative solutions perform in a simulation of the process?**
   In this chapter of the thesis, we will test the methods that were selected in the previous chapter. The test will be done by implementing the methods in a simulation of the production at Van Raam. In this simulation, the effect of the methods on KPI's like throughput time and utilization are measured. Based on this a decision will be made on which method is implemented.

5. ***How can the identified monitoring and control method be implemented at Van Raam?***
   This knowledge problem will be answered by a combination of literature and conversations with employees. A good implementation is important for the success of the chosen method. Through a literature review and conversations with employees, we will create an overview of how implementation can be done and what it should look like.

6. ***What are conclusions and recommendations made for the planning and control system?***
   This question will be answered from a qualitative and a quantitative perspective. The qualitative perspective will be recommendations on which method should be implemented and how this method can be implemented in the process. The quantitative analysis will be conducted through the analysis of data that is obtained in the simulation study. This data can advise on relevant KPIs and what the result of the implementation will be.

### 1.4.2 Restrictions
While working towards a solution there will also be some restrictions in the project. The final solution will have to meet these restrictions otherwise it will not be implemented. The following restrictions have been formed:

- **Business philosophy**: Van Raam has an external company named “Team doet” that has been creating the business process philosophy for them. The contact person at “Team doet” has worked with Van Raam for years and before that was an employee himself. For those reasons, I should not interfere with the current business process philosophy.
- **Warehouse**: While searching for the best way to control the process, the capacity of the warehouse should be taken into account. It also occurs that parts are not in the warehouse when production is started which means the bicycles cannot be assembled. The simulation should take this into account.
- **Time**: To write the thesis approximately 10 weeks are available. Therefore we will not be able to follow all leads.

### 1.4.3 Deliverables
To conclude the problem-solving approach the eventual deliverables are discussed. After finishing the thesis the following deliverables are presented:

1. Literature study on the different methods to apply planning and control.
2. Simulation of the blasting chamber, paint shop, assembly department, and warehouse in which the most suitable production planning and control methods will be tested.
3. Recommendation on the best monitoring and control method, the expected improvements of KPIs, and implementation.

# 2 The current state of the process

In this section we will have a detailed look at the process as it currently is and what shortcomings can be found. In section 2.1 there is an elaborate process description. In section 2.2 we will create a value stream map to identify the value-adding steps in the process. In section 2.3 a study will be done on the current throughput times for the overall production to see if there is a difference between the models. In section 2.4 we will uncover what planning and control method is currently used to steer the process. Section 2.5 will be devoted to identifying the bottleneck of the process. Finally, in section 2.6 we will summarize the findings of chapter 2 and come to conclusions. The knowledge question that will be answered in this chapter is:

***"Based on an analysis, what is the current state of the organization concerning the production management system?"***

## 2.1 Process description

As mentioned in the problem identification the thesis will only focus on the process starting at the blasting chamber and ending at the final quality control. For the completeness of the description, we will however succinctly describe the process that takes place in front of and after the scoped area. Customer orders come in through retailers and are taken in by the sales department. The sales department sends these orders to the production office where the sales orders are translated into production orders. At the production office, backorders are kept and orders that come near the due date are released. If there are orders of a similar colour in the backorder then these are released too if possible.

The welding department, where the frames are assembled, produces to forecast. An estimation is made on the required amount of frames which are then produced and put into storage at the warehouse. This creates a buffer between the welding department and the paint shop. Therefore the welding department can be considered an external supplier.

If a production order is sent to the blasting chamber the employees collect the frames from the warehouse and treat the frames in the blasting chamber. The blasting scrubs and cleans the frame which is necessary for the painting process. Blasted frames are never returned to the warehouse because they risk becoming greasy again. After blasting, the frames are moved to the paint shop where they are immediately processed or wait till there is a free transportation unit.

The paint shop is where the frames become order-specific, known as the order decoupling point. The frames are hung on transport units that move over a rail through the powder coating process. The paint shop works with batches of 10 so-called transport units. The frames move through the paint stations and oven three times. In the first run, the frames receive a primer after which they are heated in the oven. In the second run through the process, the frames are painted in a customer-specific colour after which they enter the oven again. After leaving the oven the frames are stickered and coated with a protective layer. The frames then go through the oven one last time after which they can be taken of the transport units. After being taken off the rail the frames are checked on quality and stored in the paint shop warehouse or, in case of the line assembly, in front of the line. The paint shop prefers to paint as many of the same coloured bicycles as possible at once. The reason for this is that changing colours requires the coating room to be cleaned which costs production time (cleaning the coating chamber takes approximately 3 to 4 minutes). After the process, the frame is checked on quality which is the last point where data is collected in the paint shop. The first point at which the frames, then fully assembled bicycles, are visible again is at the final quality control.

At Van Raam, a bicycle can be assembled in three different ways: regular, cell, and line. The decision of which assembly type will be used to assemble a particular model is based on its yearly demand. It does occur that two models are produced together in a cell or line, this is only possible if the assembly process of the models is rather similar. Currently, this is the case for the Midi and the Maxi that are produced together in a line assembly and for the Opair and the Velo that are produced in the same cells.

Regular assembly is the conventional way of assembling bicycles at Van Raam. The regular assembly exists of three different stations that each have their steps within the process. The module assembly focuses on smaller parts of the bicycle like the steering assembly and the fender assembly. Then there is the pre-assembly that attaches these parts to the frame. Lastly, there is the final assembly where the bicycle is finished. Parts needed for the assembly are collected in the warehouse and moved to the assembly on special trolleys. Each of these trolleys carries the parts needed for the assembly of one bicycle. Once the bicycle is finished the trolley is moved back to the warehouse where it can be used again. Currently, about 15 types of bicycles produced at Van Raam are assembled in the regular assembly. A bicycle is produced in the regular assembly if the demand is not high enough to make a cell or line assembly feasible.

The second way of assembling is cell assembly. In this type of assembly, the frames are fully assembled at one station. Once the frames meant for this type of assembly are painted, they are stored in the paint shop warehouse. If a cell is finished the next frame is collected from the warehouse. The trolleys from the regular assembly are not used in this process. Instead, the parts needed for the assembly are kept in the cell. The parts are supplied through a Kanban system and only special or low-frequency parts are ordered from the main warehouse. The Kanban principle is executed through the use of trays, for each part there are two filled trays with parts at the line. Once a tray is empty it is collected, filled, and returned to the line. This way there are always enough parts in the cell. A product is produced in the cell when there is enough demand, the threshold is about 800 bicycles per year.

The last type of assembly is line assembly of which there are currently 3 at Van Raam. As can be derived from the name the frames move through the assembly line where new parts are assembled at each step. The lines produce bicycles that have a yearly demand of over 1000 units like the Easy Rider and the Fun2Go. If frames have been painted for these lines they are stored at the beginning of the line. At the start of the line, the frames are put onto a special trolley that carries the frame through the line. Similar to the cell assembly, the parts of the bicycle are kept in Kanban-style trains at all stations of the line, only special options need to be ordered at the warehouse.

After a bicycle is assembled at one of the three lines it is moved to the final quality control. Here it is checked on overall built quality, software (in case of an electric bicycle), and options. This is also the point where the frame is visible for the ERP system again. If quality control is passed the bicycle is moved to expedition where it is prepared to be shipped. The business process model (BPM) and a high-level BPM that is based on the described process can be found in appendix B.

What can be concluded from the process description is that the process at Van Raam is a pure flow shop. Pure flow shops can be recognized by only allowing the orders to move in one way and not allowing them to visit the same workstation twice. Based on the order decoupling point we can also conclude that the scoped part of the production at Van Raam is a make-to-order (MTO) process, frames are only painted if a customer order is received.

## 2.2 Value stream map

In the first section of this chapter, the logistical flow of the process has been explained. In this chapter, we will create a value stream map (VSM) to obtain an even better oversight of the process and its steps. A literature study is conducted which can be found in appendix C. The goal of this literature study was to understand the steps necessary to create a VSM. In section 2.2.1 the most important steps within the scope of the thesis will be mapped.

### 2.2.1 Process mapping

In this section, the process will be mapped. The goal of this mapping is to get an overview of the information and material flow within the process. To keep the value stream map concise we only focussed on the key steps within the process. The time that a frame spends at each step within the process as displayed in the BPM is not saved within the system. It was chosen not to execute these measurements because of the limited time available. Based on the primary steps of the process description the following activities will be mapped:

**Warehouse**
Station where the frames are collected for the blasting chamber. The duration of the activities in this station will however not be mapped onto the VSM since it is not part of our scope. It will however be displayed for the completeness of the map.

**Blasting stations**
Frames arrive here from the storage at the warehouse. The frames are blasted after which they are hung on the rails of the paint shop and prepared for the painting process. Preparing the frame for the paint shop consists of covering the parts that do not need to be painted with plugs or tape.

**Paint shop**
The frames wait in front of the paint shop till transportation units are available. The frames then enter the paint shop and make three rounds through the process. The frames then leave the paint shop at the quality control where they are taken off the rail from the rail.

**Assembly department**
The frames are pulled from the storage and go through the assembly process. After the assembly process, the assembled bicycles are moved to the final quality control. A distinction is made between the three types of assembly. The times are based on the designed production time as can be found in appendix I.

**Final quality control**
At the final quality control, the bicycle is inspected for any deficiencies. If the bicycle passes the test it is moved to the expedition department.

**Expedition**
At expedition, the bicycles are prepared for shipping after which they are sent to retailers. It is included in the VSM to provide a clear overview of the process. It is however not part of the scope of this thesis.

Based on these steps and the literature we created a value stream map, the map and its input data can be found in appendix C. By summing up the time spent on value-adding activities we were able to calculate that the total value-adding time of the process is 19 hours and 4 minutes which is slightly more than two working days. With the knowledge that we merged some steps with intermediate storage, we can conclude that the true time in which value is added is approximately two days.

## 2.3 Data analysis

To calculate the current throughput times data of the process was acquired from the ERP system. The retrieved data was limited since Van Raam moved into a new facility in 2019, the warmup period that resulted from this relocation would provide unreliable data. The data contains information covering the period from 12-3-2020 till 11-5-2021. Together with the company supervisor, it was decided that this data would be representative of the production process. The information was presented to me using two sheets, more information regarding the data can be found in appendix D. Using the data we were able to create table 1 in which the mean throughput time, the standard deviation, and the total production of the different models is displayed as well as the type of assembly.

| Assembly type | Model | Mean throughput time (days:hours) | St. deviation (days:hours) | Total production (orders) |
|---|---|---|---|---|
| Line | Easy Rider 2 | 06:06 | 03:22 | 2868 |
| Line | Fun 2 Go | 06:02 | 03:09 | 1932 |
| Line | Midi Maxi | 05:19 | 04:07 | 1236 |
| Cell | Velo Opair | 06:18 | 03:02 | 1080 |
| Regular | Other | 06:11 | 03:14 | 2974 |
| Line | Easy Rider 3 | 07:21 | 04:13 | 680 |
| Total | All | 06:09 | 03:19 | 10770 |

*Table 1: Throughput times*

Most noticeable about table 1 is that the mean average throughput time of all bicycles at Van Raam is approximately six and a half working days. What can be seen is that there is a clear difference in the throughput time of the different models. The Easy Rider 3 has the longest throughput time and standard deviation, this can be explained by the fact that it has only been in production since the end of 2020. The Easy Rider 3 line experienced some start-up problems which caused the throughput time to be longer and resulted in a higher deviation. It should also be noted that the assemblies cannot be compared directly since the assembly methods have different assembly times. The higher deviation in the production of the Midi Maxi line can be explained by the fact that the last orders for the Easy Rider 2, which will soon be out of production, are produced in the Midi Maxi line. The original line which was used for the Easy Rider 2 production was replaced by the Easy Rider 3.

In figure 3 we displayed the distribution of the throughput time. This provides the insight that the most occurring throughput time is 5 working days.

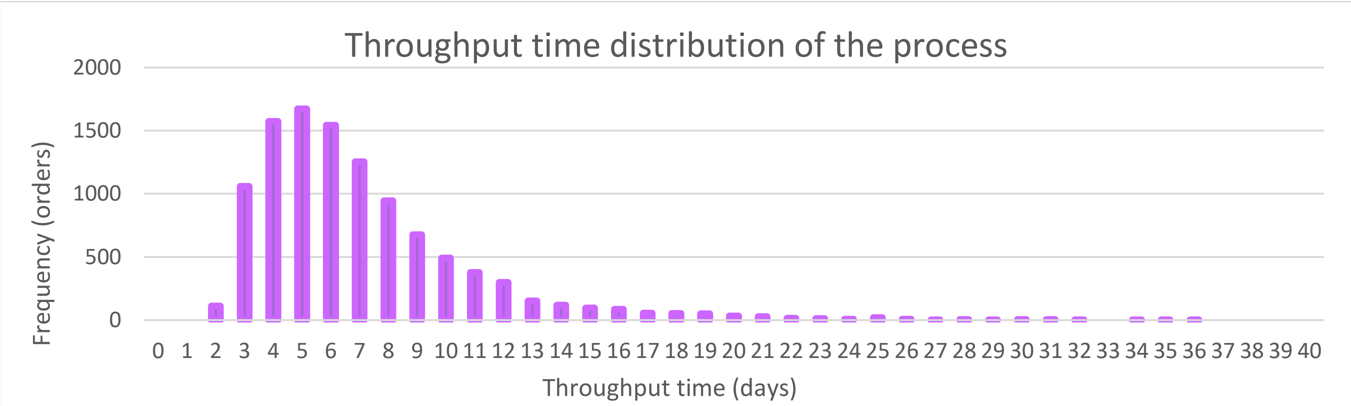


*Figure 3: Distribution of throughput time*

With the available data, we are also able to display the number of orders within the system at any given moment, the graph can be seen in figure 4. What can also be seen is that the amount of orders stabilizes at the end of 2020, this is caused by the Christmas break when production was halted for two weeks. We can however conclude from the graph that the number of work orders within the system is stable at approximately 290. This means that at any given moment there are about 290 orders between the paint shop intake and the final quality control.

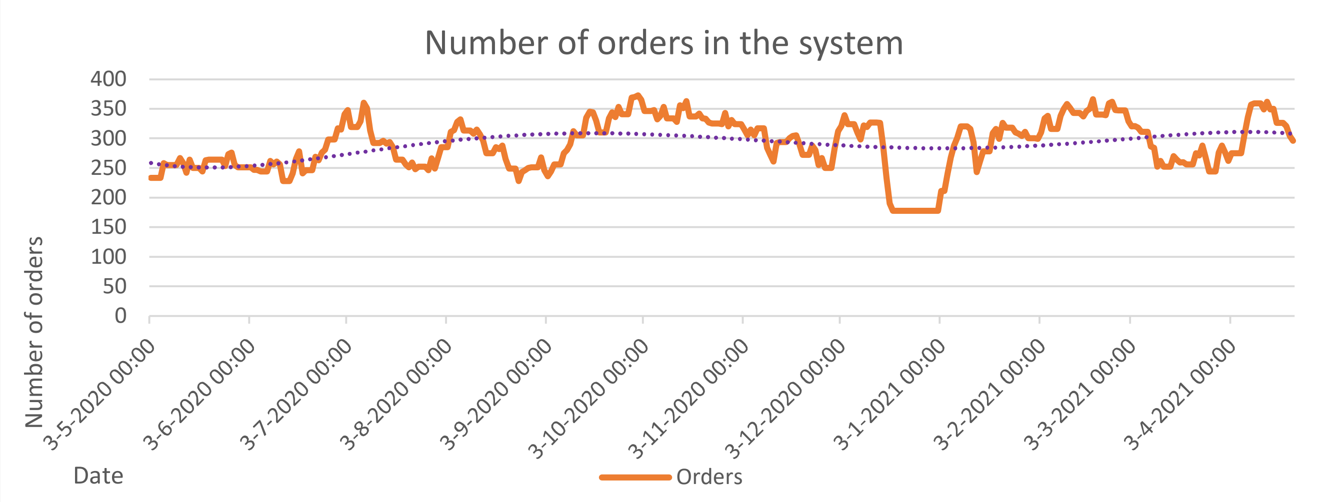


*Figure 4: number of orders in the process*

What we know is that a significant portion of these 290 orders is waiting to be processed within the system.

We can now also verify if the throughput rate and the average amount of orders in the process are correct. Using Little's law we know that the WIP is equal to the release rate multiplied by the throughput time. From this we obtain:

$$290 = release\ rate * 6{,}4 \ \rightarrow \ release\ rate = \frac{290}{6{,}4} \approx 45$$

Since we know that there are 244 production days per year we can calculate that the yearly production:

$$45 * 244 = \ 10.980\ Produced\ orders\ per\ year$$

From the available data, we know that the total production in a year is 10.387. We can conclude that the calculations of the average WIP and throughput time are acceptable.

## 2.4 Planning and control method

To understand the current way of planning and control I interviewed the employee responsible for organizing the flow of products through the process. The interview was conducted in a semi-structured way. The advantage of this interviewing structure is that it allows for the respondents to be understood with their world perspective in mind. The predetermined structure, on the other hand, allows for specific topics to be discussed with complex interpersonal talk (Sandy & Dumay, 2011). In the interview, I asked a series of questions to understand the current way of planning and control. The way this is done could be a likely cause for the stock between the paint shop and the assembly department. The interviewee aims to plan the release of work orders at the paint shop in such a way that there are always enough work orders in the system for the assembly station to continue work. The number of work orders required to achieve this is however not clear. The interviewee counts the frames each morning after which it is decided how many work orders are released to be painted. From this, it can be concluded that there is an overview of the stock in the process, through a lot of physical labour, but that there is no guideline on the ideal level. Based on the average number of frames that is used daily interviewee tries to maintain the stock at about 2,5 to 3,5 days. The high stock has as a consequence that there are always frames available for the process. The downside however is that the large WIP increases the throughput time of the process, frames have to wait longer before they can be assembled. The current way in which monitoring and control are performed could considered to be a type of Bottleneck control in which the bottleneck is the assembly department and the WIP is controlled at an unclear level. The WIP is somewhat monitored but since it is not limited to a particular quantity it is not possible to calculate a service level.

## 2.5 The bottleneck of the process

Important for the decision of what monitoring and control method would be most suitable for the process at Van Raam is what the bottleneck of the process is and the utilization level of the other departments. At the moment the assembly process can be considered to be the bottleneck, its capacity decides how many bicycles are assembled at the end of the day and the main focus of the current monitoring and control method is to always have enough frames available at the assembly department. The paint shop and blasting stations are not bottlenecks, at the moment these departments only produce 4 days per week. The warehouse is not believed to be the bottleneck, there is enough capacity to process all orders placed by the assembly department. Lastly, the final quality control is also not considered to be the bottleneck of the process. Frames can usually directly be inspected once completed in the assembly department.

## 2.6 Conclusion

As mentioned in the introduction of this chapter we can now answer the knowledge question of this chapter:

***"Based on an analysis, what is the current state of the organization concerning the production management system?"***

With the information found in the research, we can conclude that the current throughput time of the process is approximately six and a half working days while the value-adding time is less than two days. We also learned that at any given moment there will approximately be 300 bicycles within the process. Concerning the current method of planning and control, it became clear that some form of Bottleneck control is used. Work orders are released if the current stock is lower than 3 days of production. The aim is to always have enough frames in stock to let the assembly department continue with production. In the next chapter, we will do a literature search into what activity of planning and control can help us maintain the stock within the process at a minimum.

# 3 Planning and control: literature study

In this chapter, we will conduct a literature search on the different planning and control methods that are known in literature. We will start in section 3.1 with the different activities that belong to planning and control. In section 3.2 we will describe the different methods available within literature to apply monitoring and control. A conclusion will be drawn from the findings in section 3.3. Using this literature and information found in this chapter we hope to answer the following knowledge question:

***"Which methods are available within literature to create a structure for production planning and control?"***

## 3.1 Planning and control activities

In this section, we will dive into the activities of planning and control. As mentioned by (Slack et al., 2016b) there are four main activities of operations management. These activities are loading, sequencing, scheduling, and monitoring and control. The activities meant by these terms however go under many names, but the idea remains the same.

The first activity is loading. With loading we mean the amount of work that is allowed to enter the system based on the capacity of machines, work centres, departments, and factories. A system can either have a finite or infinite loading policy. At Van Raam orders are released according to finite loading, this way the work-in-progress can be kept at the required level. Whether a decision should be made for either finite or infinite loading depends on the KPIs of your process. Examples of these KPIs are the likelihood of drastic changes in product specification, errors in data, and rush orders (Matsuura et al., 1995).

The second activity of planning and control is sequencing. Loading provides information about when orders are allowed to enter the system, with sequencing the order in which the orders are released into the system is determined (Slack et al., 2016b). There are many sequencing methods of which a selection is displayed in appendix E in table 12. At Van Raam, the orders enter the system based on the earliest due date (EDD), within the process the "first in, first"(FIFO) is performed. It does however occur that an order is released with priority, the sequencing method can therefore be considered a "first in, first out with priority" (FIFO-WP). This is however not the preferred method by the company since it takes the flow out of the process.

The third activity is scheduling. Scheduling concerns the point in time at which operations are on an order are started. Within scheduling, there are two main categories: forward and backward scheduling. At Van Raam backward scheduling is performed, the order should be finished just before the due date.  Per extra operation the number of possible schedules grows enormous, it is therefore almost impossible to find the best schedule. Heuristics are then used to arrive at an acceptably good schedule.

The fourth and last activity of planning and control is monitoring and control, as mentioned by (Stevenson et al., 2005) improving the monitoring and control method can be useful in reducing the throughput time. This activity executes the plan that is created by the previously mentioned activities. There are many ways in which monitoring and control can be performed. For a more elaborate description of these forms, we refer to appendix E. An important element of monitoring and control is how the intervention into the activities of the process takes place. A key distinction within this field is the difference between push and pull systems. When performing push control the orders are "pushed" through the process. The push process is characterized by high internal stocks, high utilization, and long throughput times. The pull system on the other hand is characterized by a low WIP level, a fast throughput time, and a steady utilization. As you might have noticed the characteristics of pull control are what we hope to achieve in the Process at Van Raam, we therefore will focus on methods to apply pull control. As mentioned earlier the current process philosophy is also aimed at achieving pull control. We will, therefore, in *section 3.2* elaborate on the different methods to apply pull control in a production process. In appendix F a literature study can be found on push and pull control. A more elaborate literature review of the different planning and control activities can be found in appendix E.

## 3.2 Monitoring and control methods

In this chapter, we will elaborate on the different monitoring and control methods that can be found within literature that are applicable in a pull-controlled environment. There are numerous variants and hybrids but we will focus on the classical approaches as specified by (Stevenson et al., 2005). These are Kanban, POLCA, ConWIP, Bottleneck control, and WLC. To keep the thesis concise we will only elaborate on the methods that were later found to be best applicable at Van Raam. The description of the other methods can be found in appendix E.

### 3.2.1 ConWIP

ConWIP is an abbreviation of “constant work in progress” and strives to maintain a constant WIP (Bonvik et al., 1997). It is a closed production management system in which a fixed number of cards travel through a circuit that includes the entire production line. At the end of the line, the cards are detached from the products and allow new orders to enter the process (Halevi, 2001). Since the request of demand is immediately sent to the first workstation, ConWIP is also known as single-stage Kanban (Huang et al., 1998). As explained by (Huang et al., 1998) ConWIP can be considered to be some sort of hybrid between push and pull. It offers substantial pull system advantages by controlling WIP but can be applied to a wide variety of manufacturing environments like most push systems (Darlington et al., 2015). The most important parameters for setting ConWIP are the number of cards that control the WIP and the order throughput times. In addition, the length of the advance release window has to be set. It determines the point in time at which an order is allowed to be released for production. Before this time the order has to stay on the backlog list (Lödding, 2013). The challenge of ConWIP is that there must be enough work orders within the system to not let the bottleneck starve but at the same time prevent work orders from waiting within the system, which increases the throughput time (SPEARMAN et al., 1990).

ConWIP is a closed manufacturing system like Kanban and has some advantages over open systems: Closed systems are generally easier to control, the variances are smaller, and a smaller average WIP for the same throughput which results in a shorter flow time (Halevi, 2001). ConWIP is also simpler to operate since the only variable that has to be determined is the work-in-progress for the entire line. In a Kanban system, for example, the number of cards (and so the WIP) has to be specified for each working station (Darlington et al., 2015; Spearman & Zazanis, 1992). Because of the constant work-in-progress, the throughput time of the orders in the production can be predicted well and are easy to plan (Lödding, 2013). Another advantage of ConWIP over Kanban is that there are plenty of queueing models available to test the performance of ConWIP systems. Modelling stochastic Kanban systems is however rather difficult (Spearman & Zazanis, 1992). ConWIP can be applied in production processes where Kanban is impractical because of too many part numbers or significant setup times. By allowing WIP to collect in front of the bottleneck, ConWIP can function with lower WIP than Kanban (SPEARMAN et al., 1990). It also does not cause any blocked WIP in the throughput of orders in the production unlike other monitoring and control methods (Lödding, 2013).

With ConWIP it is clear how many work orders are within the process, the distribution of these work orders across the different workstations is however not known. Some production processes have a complex flow of materials in which orders flow through different workstations. WIP and throughput fluctuations on the workstations, therefore, do not inevitably compensate for one another. Accordingly, the variance of the throughput time increases (Lödding, 2013). (Gaury et al., 2000) state that a disadvantage of ConWIP is that the inventory level of the individual workstations within the system is not controlled. Uncontrolled high inventories might occur in front of slow or broken-down machines (Bonvik et al., 1997). ConWIP also does not take into consideration the bottleneck principle which states that the bottleneck should be monitored to determine the best WIP level. (Hopp & Spearman, 2008) argue that this is not necessary since WIP will automatically build up in front of the bottleneck resulting in high utilization. However, if there is a clear bottleneck, it seems obvious that WIP should only be controlled up to that bottleneck. The resulting method is described in professional literature under various names (Lödding, 2013). In this thesis, we will call it bottleneck control and it is described in *section 3.2.2*.

### 3.2.2 Bottleneck control

As might be expected the Bottleneck control method is the simplest way of converting the bottleneck principle into a monitoring and control method. The basic idea of this method is that each time the bottleneck finishes a work order, a new work order is released at the beginning of the process. Under this monitoring and control method, the line is subdivided into two parts. The first part up until the bottleneck is WIP controlled and the second part is not WIP controlled. Bottleneck control is rather similar to ConWIP with the difference being that ConWIP controls the WIP of the entire process (Lödding, 2013). In literature, Bottleneck control is described under many names. (Slack et al., 2016b) calls it Drum, buffer, rope (DBR), and (Stevenson et al., 2005) names it Theory of constraints. Top apply Bottleneck control two parameters have to be set: The number of bottleneck cards within the process and the advance release window within which orders are allowed to be released early.

Due to constant WIP, the order throughput times can be predicted well up to the production's bottleneck. When the WIP levels and throughput times for the production line following the bottleneck workstation are rather constant, this also applies to the throughput time of the entire process. In this case, Bottleneck control can provide high delivery reliability. The fact that the method is so focussed on the utilization of the bottleneck leads to the prevention of bottleneck starvation, the bottleneck can therefore almost always continue with production. Another advantage of the method is that it cannot cause blockages within the production, similar to ConWIP and the later explained Workload control. A great advantage of this system is then that it can outperform even ConWIP if there is a clear identifiable bottleneck station within the process (Lödding, 2013). In a case study performed by (Darlington et al., 2015) a reduction of throughput time by 57% and a reduction of WIP by 60% was achieved.

Bottleneck control is good at reducing WIP fluctuations up until the bottleneck. After the bottleneck, the WIP is not controlled anymore as mentioned before. Workstations after the targeted bottleneck might become temporary bottlenecks, this could result in large WIP fluctuations (Lödding, 2013). In some processes, the bottleneck can even move from one station to another. The method struggles with this so-called 'wandering bottleneck' phenomenon. Despite attempts to accommodate for this there is still doubt about the applicability of the method in complex flow environments where more routing variations can occur and the bottleneck can move regularly (Stevenson et al., 2005). Whereas the ability to directly control the overall WIP is a strength of Bottleneck control, it cannot regulate WIP at the workstation level. This is the same struggle as experienced by ConWIP (Lödding, 2013). High utilization of the bottleneck is also important. If the utilization is low the need to release new orders if a card has become available can lead to orders that are started early, this increases the overall WIP level. Lastly, the technique has received a lot of criticism in literature. Early criticisms focus on a lack of disclosure about the full details of the method and later on the claim of optimality while this was rather doubtful. Eventually, it has been shown that it is not an optimal approach. The method has also been associated with a poor start-up rate and continual rescheduling (Stevenson et al., 2005).

Since Bottleneck control is so similar to ConWIP organizations often find it hard to choose between the two. As described by (Lödding, 2013) two main criteria can help make this decision. The first criterium is the position of the bottleneck. The further upstream the bottleneck is, the greater the advantage of Bottleneck control. If the bottleneck is the last station of the process then ConWIP and Bottleneck control are identical. The second criterium is the utilization of non-bottleneck stations. If the non-bottleneck workstations of a production process are also highly utilized then the advantage of Bottleneck control might disappear. ConWIP may then even achieve higher output rates. This can be explained through the fact that a station that is highly utilized has a higher chance of becoming a bottleneck.

## 3.3 Conclusion

The goal of this chapter was to answer the second knowledge question which was formulated in the following way:

***Which methods are available within literature to create a structure for production planning and control?***

To answer it, we did a literature search into planning and control. We identified the four activities of planning and control (loading, sequencing, scheduling, and monitoring and control) and their roles within a process. The identified methods are Kanban, POLCA, ConWIP, Bottleneck control, and Workload control. For each of these methods strengths and weaknesses that are known in literature were summarized. A table that provides an overview of these strengths and weaknesses can be found in appendix G. In the next chapter, we will review we will try to find the best applicable method for Van Raam.

# 4 Method selection

In this chapter, we will investigate which monitoring and control method is the best fit for Van Raam. We will do this by establishing criteria on which the methods can be graded in section 4.1. In section 4.2 we will give the criteria a ranking that will be used while grading the methods in section 4.3. Lastly, in section 4.4 we discuss  the conclusion that can be drawn and answer the knowledge question belonging to chapter 4:

***"Which methods can be applied best at Van Raam?"***

## 4.1 Grading criteria

In the previous chapter, we arrived at a selection of monitoring and control methods, to compare the methods we already conducted a literature review on their characteristics, advantages, and disadvantages in *chapter 3*. The methods can now be scored on different criteria, to arrive at these criteria we looked at what criteria were used in similar studies. The created criteria were discussed with the stakeholders like the operations manager, production manager, and quality manager. After these discussions, the final selection of grading criteria was established.

**Throughput time improvement**

The first and most obvious criteria for the method is that it should improve the throughput time of orders at Van Raam as stated in the description of the assignment. The throughput time is the amount of time a work order spends within the process, the throughput time of an order is calculated in working days. The throughput time can be improved by changing the monitoring and control method of the process as mentioned by (Stevenson et al., 2005).

**Adaptability for fluctuations**

With this criteria, we refer to two types of fluctuations. The first type is the fluctuations caused by the change in demand, the company has been growing hard in recent years which created a large variance in the yearly demand. With the second type of fluctuations, we refer to the demand per model. This demand varies over time which requires the process, and so the monitoring and control method to be flexible.

**Applicability and implementation at Van Raam**

The chosen method should be applicable to the production process at Van Raam. This is important since the type of process influences the performance of the monitoring and control method. The methods will perform best if they can be fully implemented in the process.

**Utilization**

The fourth criterion on which the methods will be assessed is the utilization of workstations within the process. Utilization is measured in terms of the time that a machine is producing within the available production time, usually expressed in a ratio. Utilization levels are commonly high, if the utilization of a machine is low it indicates idle time in which the machine is not creating value.

**Sustainability**

The last criteria on which the methods will be graded is sustainability. Sustainability has always been an important factor for Van Raam. In the comparison, we will focus on the improvement of quality and the reduction of waste.

## 4.2 Weights

Initially, all stakeholders were interviewed separately to establish the criteria. In these sessions, a selection of criteria found in literature was shown after which the stakeholders were asked if they could add criteria. The respondents were asked to scale the criteria from most important to least important, this already indicated the ranking that could be given to the criteria. In a second session, the respondents came together and were asked to grade the criteria on a scale from 0 to 3 (low to high respectively). Based on these sessions table 2 was created.

| Criteria | Ranking |
|---|---|
| Throughput improvement | 1 |
| Adaptability for fluctuations | 2 |
| Applicability | 3 |
| Utilization | 4 |
| Sustainability | 5 |

*Table 2: Ranking of the criteria*

## 4.3 Scoring the methods on different criteria

In the previous sections, we have described the criteria on which the methods can be evaluated. In this section we will score each method on the criteria, this will allow us to find the best applicable solutions for Van Raam.

### 4.3.1 Scoring Kanban

Since Kanban is the basic form of applying pull control it has similar advantages. The method is known for reducing throughput time and inventories. It is also a visual system that makes it easier to reduce the WIP which will, following Little's law, indirectly decrease the throughput time of the process (Lödding, 2013). The main characteristics of Kanban are its operating simplicity and ability to reduce WIP (Halevi, 2001). The method, therefore, scores well on throughput improvement.

Kanban is not the most flexible system, it often needs another system to provide the necessary flexibility and since cards are appointed to specific workstations it takes time to adapt to fluctuations. Another disadvantage is that it does not consider the varying processing times of orders which occur at Van Raam (Lödding, 2013). Bikes with more options require more processing time. (Halevi, 2001) also states that even if the system is fully implemented it still occurs that it cannot cope with fluctuations in demand. Kanban scores moderate on the ability to cope with fluctuations in demand.

At Van Raam, about 21 models are produced which indicates a high product variety. Kanban is known for having difficulty coping with a high product variety (Halevi, 2001). This is elaborated on by (Lödding, 2013) who explains that with each new product variant, a Kanban card for that variant needs to be added, the increased number of different Kanban cards increases safety. It must however be said that the supply of components to the production lines is already organized using a Kanban system. This means Van Raam already has some experience with the method which makes implementing it easier. This is especially important since literature suggests that Kanban is hard to implement (Stevenson et al., 2005). The method, therefore, scores modestly on applicability.

Kanban controls the process by limiting the WIP per workstation which means it can attain a high overall utilization. Within the Kanban method, it is however possible that work orders are blocked if there is no capacity at the next station.  It does also needs other systems to determine the workload per workstation. The visibility for which the system is known does however help in determining the optimal number of cards per workstation (Lödding, 2013). Kanban scores satisfactory on utilization.

Kanban is one of the most basic methods to perform monitoring and control at workstation level, therefore it has the same advantages as pull control over push control. Since the system manages the system at workstation level it is possible to maintain short queues. These short queues minimize the time between the creation and detection of a defect which in turn reduces waste in the form of rejects. (Ou & Jiang, 1997) even suggest that the improved quality is the most prized achievement of pull control systems. For these reasons, the method scores well on sustainability.

### 4.3.2 Scoring POLCA

POLCA was created as part of Quick Response Manufacturing (QRM). QRM, and so POLCA, focuses on the reduction of throughput times. In case studies, companies were able to shrunk inventories 30, 60, or even 90% and reduce the throughput time by 22 up to 68% (Krishnamurthy & Suri, 2009). The method, therefore, scores well on throughput time improvement.

Concerning the capability of handling fluctuations in demand, POLCA is rather similar to Kanban. It lags the capability to be flexible without the aid of other systems and does not consider the time variability of order processing (Stevenson et al., 2005). The system will also become less flexible as the number of cells increases (Lödding, 2013). However, (Suri, 1999) mentions that the method is somewhat better capable at handling fluctuations than Kanban due to the cell structure which provides flexibility for variations. POLCA scores fair in terms of adaptability for fluctuations.

The process at Van Raam deals with a relatively high number of variants, an advantage of POLCA is that it can cope with highly engineered production, small batches, and high product variety (Krishnamurthy & Suri, 2009). (Stevenson et al., 2005) however states that the method, though applicable in the MTO industry,  is best suitable for a general flow shop or a job shop. It works well for highly engineered products that can have different routes through the process. At Van Raam, there is however only one possible route which means the ability to specify the different routes does not create an advantage. For these reasons the method scores low on applicability.

Following the QRM mindset, the POLCA attains to operate at 70 to 80% of capacity (Krishnamurthy & Suri, 2009). Higher utilization could lead to a false sense of security and increased lead times as warned by (Suri, 1999). As mentioned, however, the process at Van Raam is focussed on achieving a high utilization at the assembly department. The method, therefore, scores modestly on utilization.

The POLCA process helps create a better visual control which can help surface problems with quality control and machine downtime. Since the higher quality output of the workstations leads to less rejected products it can help the process decrease its environmental footprint (Krishnamurthy & Suri, 2009). The method also limits the inventory of workstations which means problems will surface earlier. For these reasons POLCA scores, similar to Kanban, well on sustainability.

### 4.3.3 Scoring ConWIP

ConWIP is another form of applying pull control in a process and is associated with reduced inventories and shorter throughput times (Hopp & Spearman, 2004). The method is believed to have a higher throughput rate than Kanban with the same WIP level since it does not cause any blocked WIP in the throughput of orders in the production (Lödding, 2013) (Halevi, 2001). For these reasons, ConWIP scores good on throughput time improvement.

Since the method does not regulate inventory at station level it can easier react to changes in demand. Where other systems need to specify the WIP  per workstation ConWIP only has to increase or decrease the number of cards in the process. (Halevi, 2001) reported that ConWIP can easily handle the introduction of new products and changes in the product mix. It is also robust regarding changes in the production environment and is easy to forecast. Like the already scored methods, ConWIP does not entail a system that can cope with backlogs, it will need an additional system to handle these (Lödding, 2013). ConWIP, therefore, scores satisfactory on adaptability on fluctuations.

The implementation of ConWIP is relatively easy. The only variable that has to be specified for the method to work within a process is the number of cards, and so the WIP (Spearman & Zazanis, 1992). Since the cards of the system are not model specific it would be a convenient method to use, especially at the regular assembly where 14 models are assembled. The disadvantage for the system at Van Raam would however be that orders are not regulated at workstation level. (Stevenson et al., 2005) concluded that ConWIP is of great applicability to the MTO industry, the question remains however if it can provide the necessary control at job entry and job release stages. The method is best suitable for the pure- or general flow shop which matches with the process at Van Raam. For these reasons, the method is scored satisfactory on applicability.

ConWIP does not regulate the workload at workstation level. Solely the WIP that can be within the system is limited. Therefore workstations within this system might be idle quite often which leads to a lowered utilization. Not being able to control the inventory level at workstation level is a clear disadvantage of ConWIP as stated by (Gaury et al., 2000). (Hopp & Spearman, 2008) however argue that orders will gather in front of the bottleneck which ensures that the utilization of the bottleneck is high. ConWIP does however score moderate on utilization.

The previously scored methods had the advantage that the time between creation and detection of a defect is limited by the inventory size of the workstations. ConWIP does however not specify a buffer size per workstation which causes defects to be detected later. This would increase waste since the number of rejected products is higher. The WIP level in a ConWIP system will however be significantly lower than in a standard push system which means defects will be detected earlier. The method still scores low on sustainability.

### 4.3.4 Scoring Bottleneck control

Bottleneck control is rather similar to ConWIP, arguments for choosing either of them can be found at the end of *section* 3.2.2. The assembly department is considered to be the bottleneck at Van Raam which means Bottleneck control is well applicable. The method could therefore be a good option for the process and scores well on throughput improvement.

Bottleneck control does not include a component that can regulate backlog in case of schedule or demand deviations. The method needs to be combined with another system to cope with this (Lödding, 2013). An advantage the method does have is that cards are not assigned to specific stations, in productions like Van Raam where the demand of models varies a lot this is an advantage since methods with station-specific cards would lead to high inventories. This allows it to quickly adapt to fluctuations for which reasons it scores well on adaptability.

According to (Stevenson et al., 2005) the method is well applicable in the MTO industry. Furthermore, it works better in a pure- or general flow shop than a job shop since the bottleneck is less likely to wander. The production at Van Raam is a MTO pure flow shop which indicates that Bottleneck control could be well applicable to the process. The process also has a rather stable bottleneck. Bottleneck control is also simple to implement, procedural rules can easily be communicated and the method has only two parameters that need to be set: the advance release window and the number of bottleneck cards. The method, therefore, scores good on applicability.

Bottleneck control is focused on maximizing the utilization of the bottleneck, the utilization of the other workstations is however not regulated. Furthermore, the method even works best if the utilization of other workstations is lower since they can then not become momentarily bottlenecks (Lödding, 2013). Since the overall utilization of the process will be low the method scores moderate on utilization.

Similar to ConWIP, Bottleneck control does not limit the inventory size between workstations and so does not provide a better overview of the process. The lack of a limited inventory per workstation increases the time between creation and detection of a defect and so the number of defects. It must however be said that Bottleneck control does limit the WIP up until the bottleneck, defects will therefore be detected earlier than in a push system. The method still scores low on sustainability.

### 4.3.5 Scoring Workload control

Although (Bertrand & van Ooijen, 2002) were able to improve the throughput time of order by 40 up to 50% in their empirical research, theoretical researches however report reductions of only a few percent or even an increase in total order throughput time. This phenomenon is also known as the WLC paradox where there is a discrepancy between theory and practice. In addition, wrong estimates of the parameters can heavily influence the output of the system (Bertrand & van Ooijen, 2002) and the parameters of WLC are hard to estimate. Guidance for estimation is scarce (Stevenson et al., 2005). A reduction in throughput time is therefore hard to guarantee which is why this method scores low on throughput time improvement.

A pool in front of the process is part of the WLC methodology, this allows it to reduce congestion on the work floor. This stabilizes the performance of the process and makes it independent of variations of the incoming demand (Stevenson et al., 2005). Adapting to these changes does however require extensive calculations. An explicit backlog control is however not part of the method, it thus would be useful if the method is combined with a system that can help to ensure delivery reliability in case of demand deviations (Lödding, 2013). Workload control, therefore, scores well on adaptability.

WLC is a sophisticated monitoring and control method specifically designed for the MTO industry. It is however best suitable for a general flow shop or job shop while the process at Van Raam is a pure flow shop (Stevenson et al., 2005). To implement the system its parameters have to be set, estimating these parameters can be difficult and incorrect values have serious consequences (Stevenson et al., 2005). Then there is the already mentioned WLC paradox, this is the name for the phenomenon that theory and practice often differ in the application of WLC. Based on these arguments the method scores modestly on applicability.

As explained by (Stevenson et al., 2005), a steady utilization is the aim of Workload control. Aligning load to the capacities is even called a fundamental characteristic of WLC by (Lödding, 2013). The method, therefore, scores high on utilization.

The stock at the different stations within a process is somewhat regulated by the WLC method. The relatively low inventories allow defect products to be detected early on, however not as early as when the stock of processes would have been directly limited by the monitoring and control method. Therefore the sustainability of WLC is somewhat less than those of methods that control the process at workstation level. For these reasons WLC scores decent on sustainability.

## 4.4 Conclusion

We can now answer knowledge question three which stated:

***Which methods can be applied best at Van Raam?***

Based on the scores of the methods it appears that ConWIP and Bottleneck control are the methods that are most likely to allow for the highest improvement. Kanban is in third place, its main drawback is that it has difficulty handling changes in demand. WLC and POLCA come in last. Both methods are aimed at a highly engineered process which the production at Van Raam is not. Answering the knowledge question, ConWIP and Bottleneck control are the methods that seem most reasonable to implement in the simulation.

# 5 Simulation

In this chapter, we will do a simulation of ConWIP and Bottleneck control to find the method that leads to the largest improvement of the throughput time of the process. This will help us answer the question:

***"How do the alternative solutions perform in a simulation of the process?"***

In section 5.1 we will explain why we chose to create a simulation instead of the other modelling techniques. After this explanation, we will create a conceptual model in section 5.2. Then, in section 5.3 we will create a simulation model based on this conceptual model. In sections 5.4 and 5.5, the verification and validation of the simulation model will be performed after which the two monitoring and control methods will be implemented in sections 5.6 and 5.7. In section 5.8 we will perform a costs analysis after which we will draw conclusions in section 5.9.

## 5.1 Simulation

The decision to create a simulation model was based on the characteristics of the process at Van Raam. It is a stochastic production process and so contains a lot of variabilities. (Robinson, 2014) state that simulation is the modelling technique that is best capable of including variability and its effects. Other modelling methods like linear programming and simulated annealing are deterministic and can include little to no variability. These other modelling methods will also become rather complex after implementing variability. The second advantage of simulation is the transparency, while trying to convince stakeholders of the model it helps that simulation is such an intuitive and visual method. This can help create an understanding of, and confidence in, the model (Robinson, 2014). (Banks, 1999) also suggests that manufacturing systems can most often be modelled well. Simulations also proved the possibility of performing a "What-If" analysis. This will be useful in the study for testing the monitoring and control methods and the effect of different configurations.

## 5.2 Conceptual model

In this section, we will describe the conceptual model that will be the backbone of our simulation. Using this conceptual model the monitoring and control methods described in the previous chapters will be tested on multiple KPIs. The conceptual model will be built according to the principles described by (Robinson, 2014). This framework to create a conceptual model exists of five stages: developing problem situation, determining project objectives, identifying model inputs, identifying model outputs, and finally determining the model content. In developing the simulation model we will stick to these steps.

**Problem situation**

In this first stage of the conceptual model, the goal is to obtain a good understanding of the problem situation. In this thesis, we have already done this in *chapter 1* in which we identified the action problem, created a problem cluster of the core problem, and selected a core problem. Therefore, we have a clear idea of what the problem is. In *chapter 2* we analysed the process, the result of this analysis was a  process description, BPM, and VSM. The BPM and VSM can be found in appendix B and C respectively. The process description in *section 2.1* in which the characteristics of the process have been described will be the input for the model. Figure 5 displays a flowchart of the simulation, more detailed flowcharts of processes within the simulation can be found in appendix J.

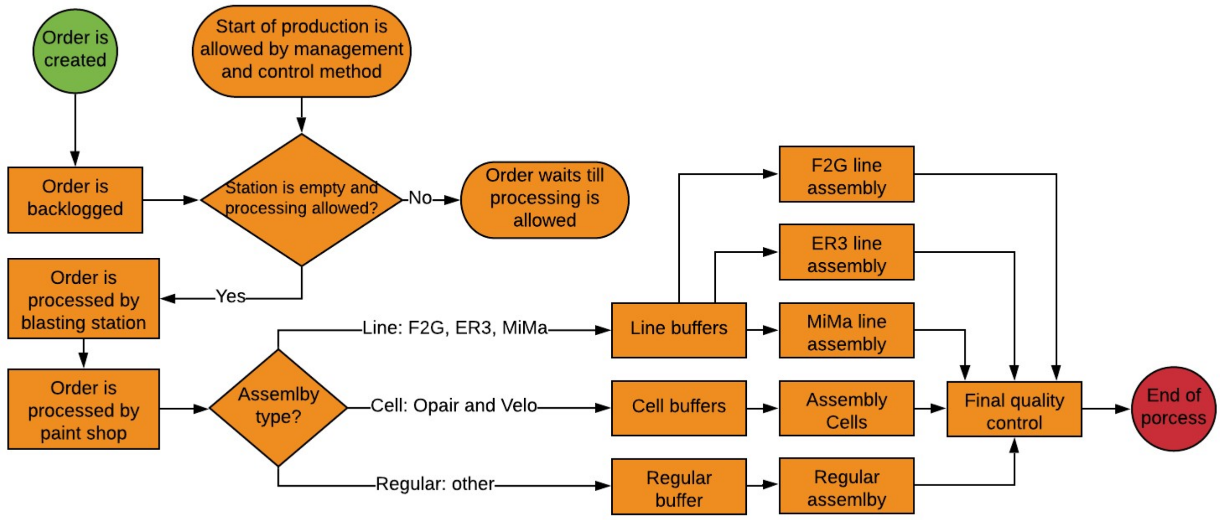


*Figure 5: Flowchart of the simulation model*

**Project objectives**

The next stage of the conceptual model is determining the modelling and general project objectives. This stage exists of three aspects: The client's wish, the required level of performance, and the constraints of the model. The client's wishes and required level of performance has been discussed in *chapter 1*. As can be read in the chapter the identified action problem is the throughput time of the process. Currently, this throughput time is six and a half working days where a throughput time of 5 working days is required. The constraints of the model are discussed later in this section. Within the project objectives there are also some restrictions:

- The run speed of the simulation should not be too long. With the large number of inputs and the high number of experiments, the runs should not take too long.
- The model should be easy to understand.
- The flow of the process should be optimized. Therefore, orders within the process can only proceed to the next station using the first-in-first-out sequencing rule.

**Experimental factors**

The model inputs are how the modelling objectives are to be achieved. For this simulation, the main inputs are the monitoring and control methods as described in *chapter 3*. Furthermore, we will also include some other inputs like influences of delivery reliability of suppliers, increasing the capacity of departments within the scope, and growth in demand. All factors will be tested using the one-factor-at-a-time (OFAT) method. This means that we will only vary the value of one variable within a run. This will however have its influence on the result because variables tend to interact with each other, the so-called "interaction effect", the results will, therefore, not be completely reliable. In this simulation we will assume that the interaction between the variables is minimal, but as mentioned interaction does occur. The simulation contains the following experimental factors:

- Monitoring and control methods
    - Current planning and control method
        - Inventory per model
    - ConWIP
        - ConWIP cards per model
    - Bottleneck control
        - Bottleneck station
        - Bottleneck cards per model

**Responses**
The output of the simulation is the value of the KPIs. The output of a simulation can have two purposes. The first purpose is to identify if the objectives of the simulation have been achieved. The second purpose is to help identify why objectives were not met. In this simulation we will retrieve the following outputs:

- **Throughput time**: The average, standard deviation, and confidence interval of the time a work order spends in the system. These KPIs are calculated for the models that pass through the different assembly methods and all orders combined.
- **Waiting time**: The time work order spends waiting in the system, specified per department and assembly station.
- **WIP level**: The average, standard deviation, and confidence interval of the number of orders in the system.
- **Yearly output**: Total amount of finished orders in a year of production.

**Modelling content**
This is the fifth and last part of the conceptual model. In this section, the scope and level of detail of the simulation will be determined. Most important is that the simulation can provide the required outputs by the given inputs. For the scope, the main question is what will be modelled and for the level of detail, the question is how it will be modelled. As mentioned in *section 1.3.1* the scope of the thesis is the process that starts at the blasting chamber and ends at the final quality control. The data available does however not include the blasting chamber, we will for the completeness of the model include the blasting chamber in the simulation but the processing time that will be used for validation and verification only consists of the process that starts at the paint shop and ends at the final quality control.

**Simplifications**

- **Assembly times**: The assembly department of the process is a black-box. As explained in *chapter 1* the orders are visible when leaving the paint shop and when leaving the final quality control. There is however no data retrieved within the assembly, therefore we will calculate the processing time of the departments based on the real output and available production time per year. The company that designed the assembly process provided an overview of the designed throughput times, in practice the throughput times were however significantly higher than the designed values. Deriving the throughput times from the actual output is, therefore, more reliable.
- **Aggregation of components**: In the model, the bicycle only exists of one part that has to be painted. In reality, most models have a front fork and some have a swingarm that can have a different colour. In literature, this is known as the aggregation of model components as described by (Robinson, 2014).
- **Paint shop process times**: As explained in the process description the paint shop works with batches that are powder coated at once. In the simulation, we based the stochastic processing time on the available data. The orders are subjected to different processes within the paint shop, in agreement with the company supervisor we decided to see the paint shop as a single process. Within the paint shop, there are also set-up times between batches if consecutive batches require a different colour, this is included in the model since we based the throughput time in the simulation on the entire throughput time of the paint shop. As can be seen in table 11 in appendix D, 4,9% of the orders do not pass the quality control after the paint shop, this causes a delay that is included in the processing time as calculated for the paint shop.

- **Line assembly**: In reality, the time spent at each station of the line fluctuates with the number of options fitted to a bicycle. In the simulation, we took the average throughput time which means that the fluctuations are incorporated in this throughput time. The throughput time, therefore, does not fluctuate in the simulation.
- **Regular assembly**: In reality, the regular assembly department exists of three different steps. As mentioned before the modular, pre and final assembly. There are 14 bicycle models assembled in the regular assembly which each spend a different amount of time at the stations. There is unfortunately no data available on the time spent at these separate stations. Therefore we calculated how many stations would be necessary to create the same throughput as the real assembly. As can be found in appendix K the number of required working stations was determined to be 10.
- **Easy Rider**: The provided data contained the models Easy Rider 2 (ER2) and Easy Rider 3 (ER3). The ER3 will however replace the ER2 in the coming months. In consultation with the company supervisor, we decided to consider all demand for the ER2 as demand for the ER3 since the demand for ER2 will be replaced by the ER3. This will also make the model more realistic for future use.
- **Holidays**: In the model, each week is a working week, there are no holidays included in the planning of the simulation. The decision was made to not include holidays since this would create an unrealistic throughput time for orders that would be waiting during the holidays. In reality, production is halted for two holiday weeks per year.
- **Working hours**: The production process at Van Raam has a slightly longer than normal work shift from 07:00 till 16:30 on Monday till Thursday, Friday the process is only producing from 07:00 till 12:00. On Monday till Thursday, there are the regular breaks: 10:00-10:15, 12:30-13:00, and 15:00-15:15. On Friday there is only the early break (10:00-10:15). This means the active production time is 38,75 hours per week. The paint shop is usually not scheduled to paint new frames on Friday, the employees are however at work and perform other tasks related to the painting processes. We, therefore, decided to let the paint shop be active all week.
- **Due date**: The orders in the simulation do not have due dates, orders are released based on de demand of the monitoring and control method in a first come first serve sequence.

**Assumptions**

- In the simulation, all orders are released and processed using the FIFO (first in, first out) method. This means that once released, the sequence of the orders following the same route will not change. In reality, it does however occur every once in a while that an order receives priority, for example, to make the due date. Doing this however disturbs the flow of the process and it is preferred by the company not to do this. Having to apply priority to orders is partially caused by slow throughput time, if the throughput time would be shorter the orders would be able to go through the process as a regular order while still making the due date.
- For the simulation, it is assumed that there will always be enough orders such that new orders can be released once allowed by the monitoring and control method. In reality, the demand for a model might be lower than expected, it could then occur that there are no orders of that model in the backorder list. This is however most likely to occur in the regular assembly where other models can also be assembled. The fact that the business is growing fast also makes the occurrence of this situation less likely.
- In the model, we assume that there are always enough parts available to complete an order as it enters the process. In reality, it however occurs that frames cannot be assembled since there either was a late delivery of components or the order was released while the parts

were not in stock. Together with orders that do not pass quality control and have to visit the internal service station this phenomenon causes the right-hand tail that can be seen in figure 3 in *section 2.3*. To include this time in the simulation we added a waiting time of 1 day and 5 hours to all orders that moved through the process between the assembly department and the final quality control.

## 5.3 Creating the simulation model

To create the simulation I used Tecnomatix Plant Simulation, a programming software developed by Siemens. The software was used since it is available for all UT students and I have experience using it from previous courses. Plant simulation is a discrete-event simulation software that is characterized by the fact that it jumps from one event to the next. Discrete event simulations are especially applicable in modelling queueing systems, and since many systems can be interpreted as queueing systems it is widely used across a whole range of organizations (Robinson, 2014). The fact that it is well applicable in simulating queueing systems makes it useful to simulate the process at Van Raam. The model built in plant simulation was based on the flowchart visible in figure 5 in *section 5.2*.

As can be seen in figure 5 the process consists of five major processes: the backorder, the blasting station, the paint shop, the assembly department, and the final quality control. The created flowchart can be seen as a schematic version of the BPM created in *section 2.2*. For further clarification, more specific flowcharts of the individual processes were created. These can be found in appendix J. A screenshot of the model in plant simulation can be found in appendix M.

## 5.4 Verification

The main focus of verification is a correct translation of the conceptual model into the simulation model. While creating the simulation model the three methods of verification were used. The first method is checking the code. This was done after each alteration of the code to ensure the data was saved correctly and that the material units flowed through the process correctly. The logic and data generated by the model were also discussed with non-experts. In practice the code was most often first written down after which the simulation was tested, this would sometimes result in an error after which the code was debugged. If the code worked some debuggers were entered to ensure that the material units took the right path and that the values were calculated correctly. Debuggers were also installed such that the simulation would stop if strange values appeared (for example if the processing time of a station was lower than 0).

The second method of verification is visual checks. Throughout the creation of the model visual checks were performed. This was done by letting the simulation run for some time and then slow it down to check if the material units moved in the correct direction. This manner of verification was especially useful when checking if the buffers in front of the line were sufficient. If the buffer would run out often it became clear that the level of stock was too low.

The third and final method of verification was through inspecting the output reports. Some KPIs and tables were implemented in the model to verify that the simulation was correct. Some errors in the calculation of the throughput time were for example discovered by examining the output reports.

## 5.5 Validation

To validate the model we will make use of the framework as described by (Robinson, 2014). In his book, he describes a framework that can be used to validate your simulation model. The framework consists of 6 parts: Conceptual model validation, data validation, white-box validation, black-box validation, experimental validation, and solution validation.

Conceptual model validation aims to validate the simplifications and assumptions that have been made while creating the model. A model cannot include all factors that influence the outcome in the real world, it would simply become too complicated. We, therefore, made assumptions and simplifications while creating the simulation model. To validate these simplifications and assumptions a session was organized with the company supervisor. Based on this session the assumptions and simplifications were adjusted where necessary. I, therefore, consider the conceptual model validated.

Data validation has been applied throughout the thesis. During the meetings with the supervisor, the outcomes of the data were discussed and validated. The information obtained from the data was presented to the supervisor and if there was doubt about the validity of the data extra analysis was done. As described in the analysis phase of the thesis the data was cleaned from any inconsistencies to make sure the data was as accurate as possible.

Although white-box validation is conceptually different from verification they are rather similar in practice. Therefore we refer to the verification part of the conceptual model in section 5.4 for the white-box validation.

When performing black-box validation the behaviour of the model is considered. The behaviour can be validated with two approaches. The first approach is through comparing the system with the real world. If the inputs for the simulation are the same as the real world the output of the system should be comparable. The second approach is through validating the model with other models. In this thesis, we will only apply black-box validation by comparing the simulation to real-world data. To do the black-box validation the simulation was run for 4000 days including the warm-up period, the results of this experiment can be found in appendix L. In the simulation, the throughput time is 6 days, 9 hours, and 38 minutes. As has been found in the data the actual time the orders on average spend in the process is 6 days, 9 hours, and 35 minutes. In the simulation, the orders spend on average 805 minutes being processed and 1137 minutes waiting in the paint shop. Adding this up results in a total processing time of 1 day, 8 hours, and 42 minutes. In the data, it can be found that the true throughput time of the paint shop is approximately 1 day, 7 hours, and 58 minutes. This difference is possible since the simulation is based on a random distribution and not on fixed values, statistical fluctuations are inherent to simulation models. In the simulation the average processing time at the assembly stations is 430 minutes, the average time spent waiting in the assembly department is 6785 minutes. Adding these times results in a throughput time of 5 days and 15 minutes. From the data, it can be retrieved that the real throughput time of the assembly department is on average 5 days, 1 hour, and 36 minutes. This difference is likely to be caused by the fact that the simulation cannot capture all variability of reality. If the simulation model is run for 415 days (one year and the warm-up period) the output is 10983 orders, this is almost equal to the in *section 2.3* calculated 10.980 orders. This difference is caused by two factors, the first is the fact that the simulation does not include holidays and the second is that the simulation is based on random distributions which can cause a deviation. In the simulation, the average amount of orders in the system is approximately 297 while there are in reality 290 orders in the system on average. The reason for this discrepancy is that in the simulation cell frames are produced all year while in the data the cell was created after some months. The cell has its own stock which increases the average number of orders in the process.

Experimental validation concerns the attention to issues of initial transient effects. We will cope with these issues by determining a proper warm-up period, run-length, and number of replications. First, it is however important to decide on a simulation type. The simulation is continuous since it does not have an endpoint. The simulation is therefore non-terminating. As we will later see the outputs of the simulation reach a steady state after some time. The time from the start of the simulation to the point in time where the output reaches a steady-state is initialization bias. This phenomenon is caused by the fact that the system starts empty which is not realistic in the real process. To overcome the initialization bias we determined a proper warm-up period, number of replications, and run length. The calculations, which can be found in appendix H, let to the values displayed in table 3.

| | |
|---|---|
| Run-length | 2000 days |
| Number of replications | 10 replications |
| Warm-up period | 50 days |

*Table 3: Simulation settings*

The last method of validating the model is solution validation. This form of validation is performed by comparing the performance of the solution in the simulation to the performance of the solution to the real-world implementation. The time for writing this thesis is however limited and the implementation is not part of the thesis. We will therefore also not be able to perform solution validation.

## 5.6 Simulating ConWIP

To implement the ConWIP monitoring and control system we will first have to calculate the number of ConWIP cards. The assembly can be divided into 5 types: there are the three line assemblies, the cell assembly, and the regular assembly. To ensure the utilization of all assembly types the ConWIP cards will be divided among them which means a card can only carry orders that are meant for a specific assembly type. The division of cards over the different assemblies can be found in figure 6. It will therefore be important to monitor the output per assembly type, this should not differ from the base model. The experiments that were conducted to determine the amount of ConWIP cards per station can be found in appendix L. This resulted in 29 cards for the Fun 2 Go line, 46 cards for the Easy Rider 3 line, 18 cards for the Midi Maxi line, 22 cards for the cell assembly, and 50 cards for the regular assembly. Using these inputs the output visible in table 4 was created, these output values can be compared to the output of the base mode. The output per week of the different assembly types can also be found in appendix L.

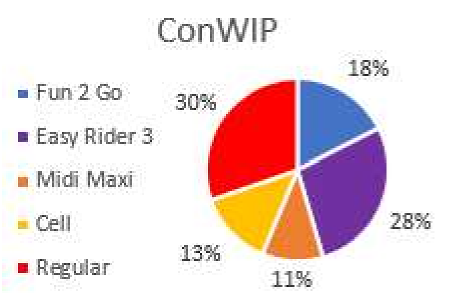


*Figure 6: Bottleneck cards per production type*

| | Throughput time | Average orders in the system | Total output | Average weekly output |
|---|---|---|---|---|
| Mean | 4:01:13:12.1286 | 178,92 | 58.860 | 210,5 |
| Standard deviation | 05:13 | 0,5020 | 44,9489 | 0,1605 |
| 95% confidence interval | (4:01:09:28; 4:01:16:56) | (178,56; 179,28) | (58827; 58891) | (210,4; 210,6) |

*Table 4: ConWIP model KPIs*

## 5.7 Simulating Bottleneck control

To implement Bottleneck control a bottleneck has to be identified and the number of capacity cards has to be determined. Setting an advance release window is usually also part of setting up bottleneck control. We, however, do not use due dates as mentioned in the simplifications for which reason we will not create an advance release window.

In search of the bottleneck, we will not consider the final quality control since it is the last station of the process. Bottleneck control and ConWIP function the same if we chose the last station of the process as our bottleneck as described by (Lödding, 2013). This leaves the blasting station, the paint shop, and the assembly department as potential bottlenecks. The bottleneck is usually the station with the highest constant utilization. This leads us to believe that the assembly department will be the bottleneck since it has the highest utilization in the base model. As discussed in *section 2.5* the analysis also indicated that the assembly department is the bottleneck. We will however consider all three as potential bottlenecks, the best of these three will be compared to ConWIP and the base model. The results of these tests can be found in appendix L. What can be concluded from the tests is that the assembly department is the clear bottleneck of the process.

Using the assembly department as bottleneck we conducted the same tests as with the ConWIP method. The cards were similarly to ConWIP divided among the five assembly methods. Doing the OFAT tests it was found that 29 cards for the F2G line, 46 cards for the ER3 line, 18 cards for the MiMa line, 21 cards for the cell assembly, and 48 cards for the regular assembly achieve the shortest throughput time while providing similar output to the base model. The division of cards among the assembly types can be seen in figure 7. This setup resulted in the KPIs visible in table 5. The output per assembly type can be found in appendix L.

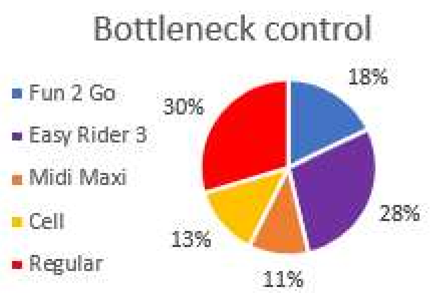


*Figure 7: ConWIP cards per production type*

| | Throughput time | Average orders in the system | Total output | Average weekly output |
|---|---|---|---|---|
| Mean | 3:23:34:52 | 174,34 | 58.866 | 210,5 |
| Standard deviation | 06:14 | 0,4875 | 44,9376 | 0,1644 |
| 95% confidence interval | (3:23:30:24; 3:23:39:20) | 173,99; 174,69) | (58833; 58898) | (210,4; 210,6) |

*Table 5: Bottleneck control model KPIs*

## 5.8 Costs analysis

Based on the reduction in WIP we can also calculate the reduction in WIP value. We decided to do this by requesting information on the costs price of the parts used in the standard configuration of all models and creating an average of this based on the production in the last year. The data used can be found in appendix N. The average cost of the parts of an order turned out to be approximately €1715,-. Using this information we were able to create table 6.

| Model | Average reduction in throughput time | Difference in average WIP | Difference in average WIP value |
|---|---|---|---|
| Base model | 0 | 0 | € - |
| ConWIP | 2:08:23:14 | 118 | € 202.379,68 |
| Bottleneck | 2:10:01:34 | 121 | € 207.524,92 |

*Table 6: WIP value reduction*

## 5.9 Conclusion

After performing the simulations of the different monitoring and control methods we can answer the main question of this chapter which stated:

***How do the alternative solutions perform in a simulation of the process?***

Answering this question one could argue that Bottleneck control was found to provide the largest improvement in throughput time while having the lowest number of orders in the system. Compared to the base model the throughput time was lowered by 2 days, 10 hours, and 1 minute. Simultaneously, the average number of orders within the process was lowered by 121. These improvements were achieved while maintaining the weekly output of 210,5 orders. The weekly per model also remained the same as can be found in appendix L.

ConWIP attained slightly higher values for throughput time and average orders in the system. The method was able to reduce the throughput time by 2 days, 8 hours, and 23 minutes which left a gap of 1 hour and 39 minutes with the improvement made by bottleneck control. Also, the average number of orders within the system was slightly higher compared to bottleneck control, 179 compared to 176.

The reduction of WIP also led to a lower WIP value. Using the weighted average costs of a painted frame we were able to calculate that applying Bottleneck control on the assembly department would reduce the WIP value by €207.524,- and that applying ConWIP control can reduce the WIP value by €202.379,-.

What we can conclude is that both Bottleneck control on the assembly and ConWIP would be useful systems to improve the throughput time and reduce the average number of orders in the system. On all KPIs Bottleneck control scores slightly better than ConWIP but the difference is too small to exclude ConWIP. An overview of the KPIs of the different methods can be found in table 7.

| Method | Average throughput time | Output | Weekly output | Average orders in the system |
|---|---|---|---|---|
| Base model | 6:09:36:26 | 58.872 | 210,5 | 297 |
| ConWIP | 4:01:13:12 | 58.860 | 210,5 | 179 |
| Bottleneck | 3:23:34:52 | 58.866 | 210,5 | 176 |

*Table 7: Comparison of management and control methods*

# 6 Implementation at Van Raam

This chapter considers the implementation of the selected method at Van Raam. In section 6.1 we hope to find the best way of implementing the monitoring and control method by a combination of literature and conversations with employees. From the findings in section 6.1, we will then draw conclusions in section 6.2. The research question that is answered in the chapter is formulated in the following way:

***"How can the identified monitoring and control method be implemented at Van Raam?"***

## 6.1 Implementation

The simulation showed us that Bottleneck control slightly outperformed ConWIP. The decision to implement Bottleneck control instead of ConWIP was however based on the point at which orders are detached. In the real process, batches of bicycles arrive from Poland which in the case of ConWIP would hold up the flow of cards and so the process. With Bottleneck control, this is however not a problem since the cards are released after the last workstation of the assembly department which ensures the continuation of the process flow.

To implement Bottleneck control, (Lödding, 2013) identified some important factors. First off, there should be an identifiable bottleneck within the scoped production process. In the simulation, this was identified to be the assembly department. The overall utilization of the process should not be too low, if that is the case other methods might perform better. At Van Raam the overall utilization is however rather high, the utilization at the assembly department even approaches 100%. Lastly, in processes in which the material flow is complex other monitoring and control methods that release orders with a workstation-specific load balance can attain a higher output. In the production process at Van Raam, the materials however follow one direction, only exceptions visit the same station twice. By meeting these requirements Bottleneck control seems, as expected, well applicable.

Implemented at Van Raam the method would function as follows. Cards are gathered at the production planning, if a new order can enter the blasting chamber the order with the earliest due date of a model type for which a card is available is selected. The card is then attached to the order and enters the process. The order and the card stay attach throughout the blasting chamber, paint shop, and assembly department. Only after being fully assembled at the assembly department card can be detached from the now assembled bicycle. If for some reason an order has to be taken out of the assembly department because of missing parts or defects the card stays attached. The order will then be moved to the internal service department where it will later be finished. After being finished at the internal service department the card can be detached from the bicycle. In other words, we could state that a card can only be detached if the bicycle is ready to enter the final quality control.

To implement the method the amount of cards is usually set at a comfortable level to get used to the system. The number of cards can then be reduced over time until loss of utilization is experienced. At Van Raam, this will be characterized by empty storage in front of the assembly stations. (Framinan et al., 2003) referred to this method as "card setting" and "card reducing". The number of cards that are maintained will usually result in a small stock in front of the bottleneck to prevent it from becoming idle. It should be noted that the number of cards in the process is a dynamic process and moves following the in- or decrease in production. A comfortable level for "card setting" at Van Raam is 250, the division of the cards between the different assembly types can be based on the percentages in figure 7 in *section 5.7*. In the future, Van Raam might want to add new line assemblies to their production. If a new assembly type is added to the production process a new type of card should also be added. The number of cards can again start at a comfortable level and be reduced over time.

Over time the system can also be digitized. Instead of attaching physical cards to the orders, which will in some process be hard to do, the cards can also become digital. The production system can keep track of the number of orders within the Bottleneck control system and inform the production planner what orders can or should be released. Before this can be arranged the number of data points within the process should however be increased.

For facilitating the implementation it is advised to let either a student or an implementation expert continue with further development of the implementation plan. Some employees will also require some additional training to use the system to its full potential.

## 6.2 Conclusions

After doing a literature study and having conversations with employees involved in the process we were able to sketch an overview of how the plan could be implemented. First off, it became clear that bottleneck control is the monitoring and control method that can be implemented best. For that reason, we continued the implementation without considering ConWIP. By looking at literature we were able to conclude that the process at Van Raam has characteristics that make a successful implementation of Bottleneck control possible. Concerning the specific application at Van Raam the method should start with approximately 250 capacity cards, these can be reduced over time. The planned further digitization of the process can also be combined with the monitoring and control method, this could replace the physical cards with digital signals. Lastly, we recommend continuing the implementation with a student or expert in the area of monitoring and control to further guide the implementation.

# 7 Conclusion and recommendation

Chapter 7 starts by addressing the conclusions and recommendations that can be drawn from the research. This can be found in sections 7.1 and 7.2 respectively. In section 7.3 the contribution to practice is discussed. Lastly, ideas for future research are discussed in section 7.4.

## 7.1 Conclusions

Through a literature research and assessing articles, we were able to determine that Bottleneck control and ConWIP are the most suitable monitoring and control methods for the process at Van Raam. Though the production process is hard to simulate we achieved it doing reasonable assumptions. Following the literature research and the simulation we can draw the following conclusions:

- Applying Bottleneck control on the assembly department is the best performing monitoring and control method and is suitable for implementation at Van Raam.
- Bottleneck control (on the assembly department) and ConWIP are both able to outperform the current planning and control method. Both methods improve the throughput time by at least 2 days or 31% while reducing the WIP by more than 100 orders or 33%. The KPI values of Bottleneck control are slightly better than ConWIP.
- On average an order waits one day and five hours because of stockouts and defects that withhold it from passing the final quality control.
- Of the five researched monitoring and control methods (Kanban, POLCA, ConWIP, Bottleneck control, and Workload control), Bottleneck control and ConWIP are most suitable for the process at Van Raam.

## 7.2 Recommendations

Based on the conclusion drawn in the thesis we can do the following recommendations:

- Apply Bottleneck control on the assembly department as monitoring and control method is advised. This will reduce the throughput time of the production process by at least two days. Another effect of implementing this monitoring and control method is a reduction in WIP of at least 100 orders. This decreases the WIP value of the orders in the process by approximately €200.000,-. To continue the implementation it is advised to let a student or monitoring and control expert further guide the process.
- During my period at the company, problems occurred with the stock level of components in the warehouse. The amount expected to be in stock and the actual amount in stock differed from each other which led to half-assembled bicycles that had to wait for missing parts. From the simulation, we learned that this distortion in combination with bicycles that do not pass quality control leads to an average delay of 1 day and 5 hours per order. Solving these issues would already lead to a large improvement in throughput time.
- Further digitization of the process is advised. At some places, this digitization could even be useful in improving the throughput rate. At the blasting chamber for example employees have to remember or write down which parts are required and where to find them. Providing the employees with information about which parts to collect and where to collect them can significantly shorten the time required to pick orders. Further digitization also includes installing more measuring points within the line, this creates visibility.
- As part of this further digitization, it is also advised to increase the number of points where the order is visible for the ERP system. In the current process, there is a large black-box between the paint shop and the final quality control. Monitoring the orders within this black-

box by, for example, making them visible once the assembly process is started would make monitoring and so improving the process a lot easier.
- While creating the simulation it became clear that the designed throughput time and the true throughput time differ quite substantially. We, therefore, recommend reassessing the throughput time of the assemblies. In this assessment, it is advised to monitor the time spent at each of the three stages of the regular assembly for each model, in the simulation we had to simplify this to a set amount of stations. Knowing these times would also be convenient for determining the optimal product mix for the regular assembly.
- Improving the quality of the painting process is also advised, currently one in twenty paint shop orders does not pass the paint shop quality control. The order has to go through the paint shop again which increases throughput time.

## 7.3 Discussion

The research has its limitations. The amount of data provided by the company was large but contained some errors, these were removed during visual inspections. Outliers could however have been skipped and using a statistical method could prove more valid. Some assumptions also had to be made while creating the simulation. Though validated by the company removing these assumptions would improve the accuracy of the simulation.

## 7.4 Contribution

**Theoretical**

While writing the thesis a literature study has been conducted focussed on the different monitoring and control methods. The contribution of this research lies in the application of monitoring and control methods. As described by (Stevenson et al., 2005) both ConWIP and Bottleneck control are believed to be applicable in a pure-flow environment. By implementing the methods in our simulation of the process we have proven that this is indeed possible. (Stevenson et al., 2005) also described that the throughput time of a process can be improved by changing the monitoring and control method. In this thesis, we have proven this by improving the throughput time of the process by altering the monitoring and control method.

**Practical**

The thesis has been written at Van Raam. The simulation created in *chapter 5* can be used to test different monitoring and control methods and varying configurations which makes it useful as a decision support tool. In *chapter 6* the implementation of the monitoring and control methods is discussed, this can be used by the company to apply either Bottleneck control or ConWIP. These insights are considered to be a practical contribution to the company.

## 7.5 Future research directions

**Monitoring and control methods**

In this research, we have only focussed on the primary methods of applying monitoring and control. These have however been established years, even decades ago and in the meantime hybrid systems have been created. Potential future research could be to continue the research but expand the planning and control methods with these hybrids.

**Product mix at the regular assembly**

Within the process, there are no rules on the product mix that arrives at the assembly department. At the regular department, this leads to problems since the division of work between the different departments is skewed and changes over time. Determining the optimal product mix for the assemblies has potential for future research.

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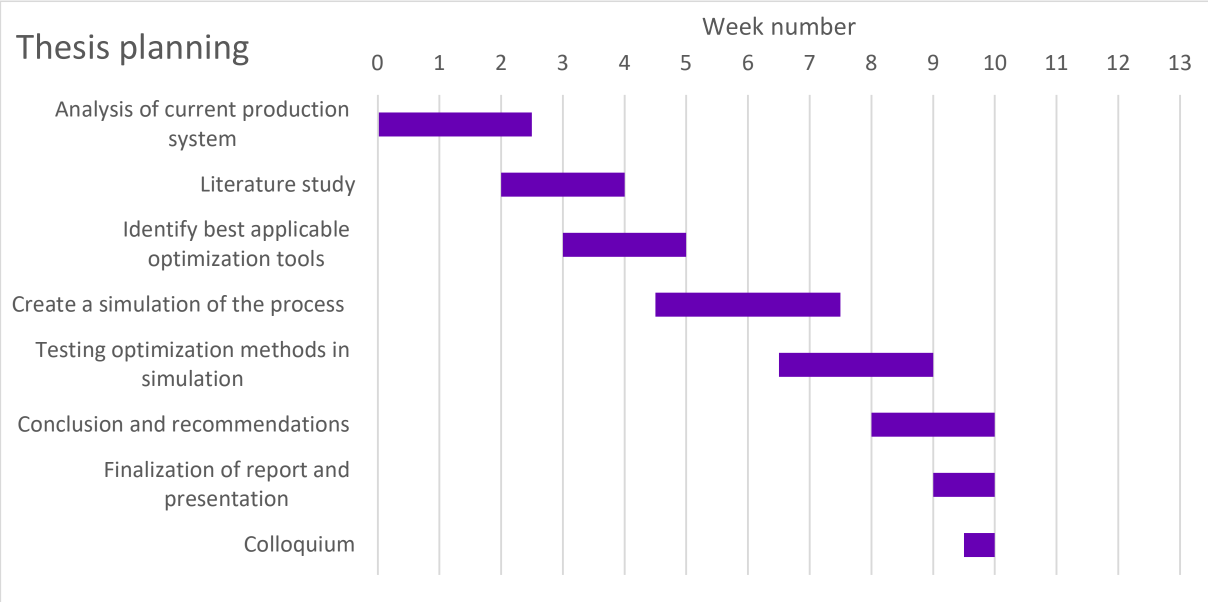
# 9 Appendices

## Appendix A



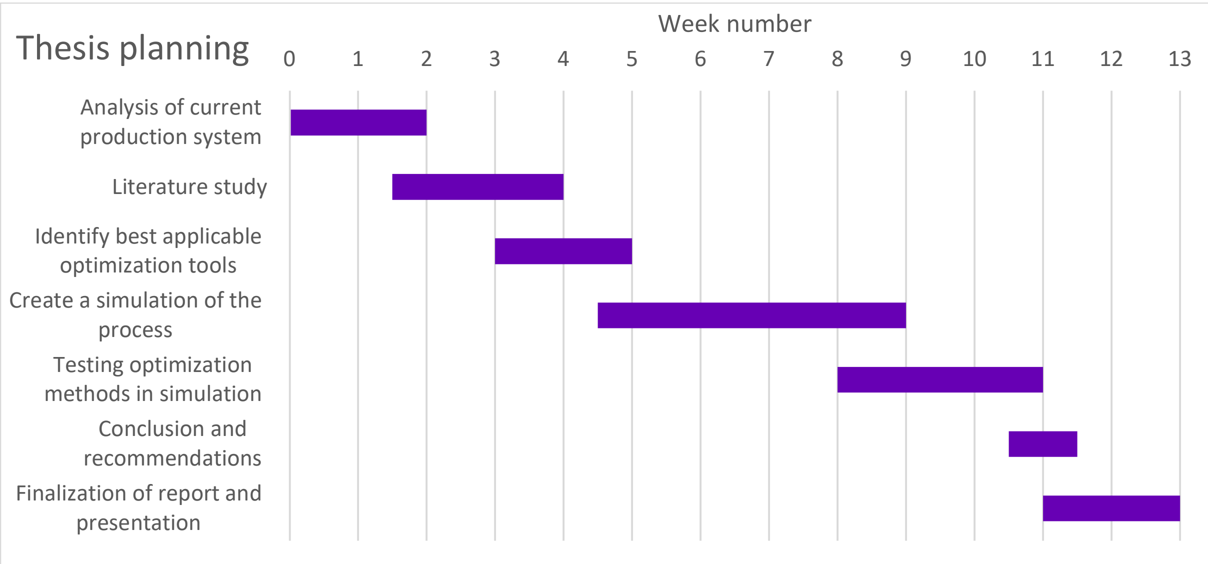




*Figure 8: Gantt chart of thesis planning*

| Task | Starting week | Weeks to complete |
|---|---|---|
| Analysis of current production system | 0 | 2 |
| Literature study | 1,5 | 2,5 |
| Identify best applicable optimization tools | 3 | 2 |
| Create a simulation of the process | 4,5 | 4,5 |
| Testing optimization methods in simulation | 8 | 3 |
| Conclusion and recommendations | 10,5 | 1 |
| Finalization of report and presentation | 11 | 2 |

*Table 8: Thesis planning in numbers*

**Reflection**

As can be seen in the planning, writing the thesis took some longer than expected. The foremost reason writing the thesis took longer than expected was that simulating the process at the company was more difficult than expected. The data available was extensive but needed some cleaning. Data about some important parts of the assembly department was also not being collected. Obtaining results from the simulation also took quite some time, the settings of the simulation caused the running time to be quite long. Since OFAT tests were performed on all 5 different product types it also took a lot of time before all tests were done. The other activities however went according to plan. Within the first few weeks the analysis of the company was finished, some details were added later. The same was true for the literature review, in slightly more than two and a half weeks the search was conducted. The part after the simulation which consisted of conclusions, recommendations, and finalization went according to plan. The green light meeting took place on the 12th of July and the thesis was finished on the 15th. In consultation with the supervisor, we however decided to move the colloquium to the end of the summer break, august 23rd to be exact. Overall I must say that writing the thesis took quite longer than I initially expected, this however did not bother me since I liked working on the thesis and enjoyed my time at Van Raam.

# Appendix B

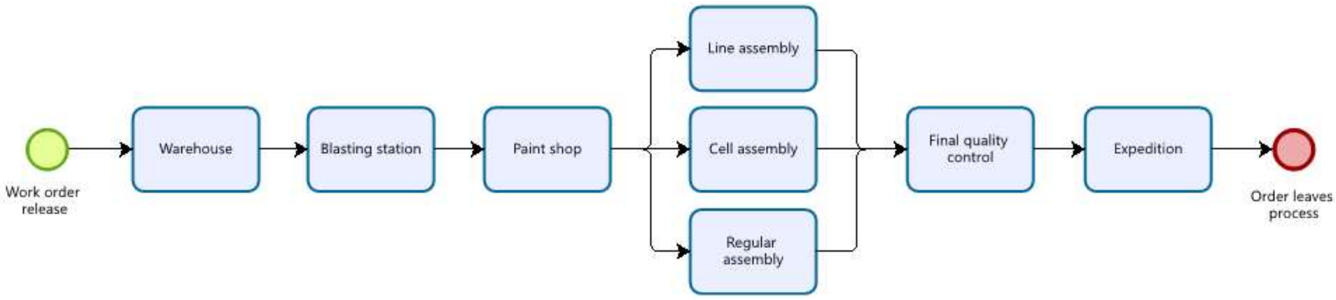



*Figure 9: Concise overview of the process*

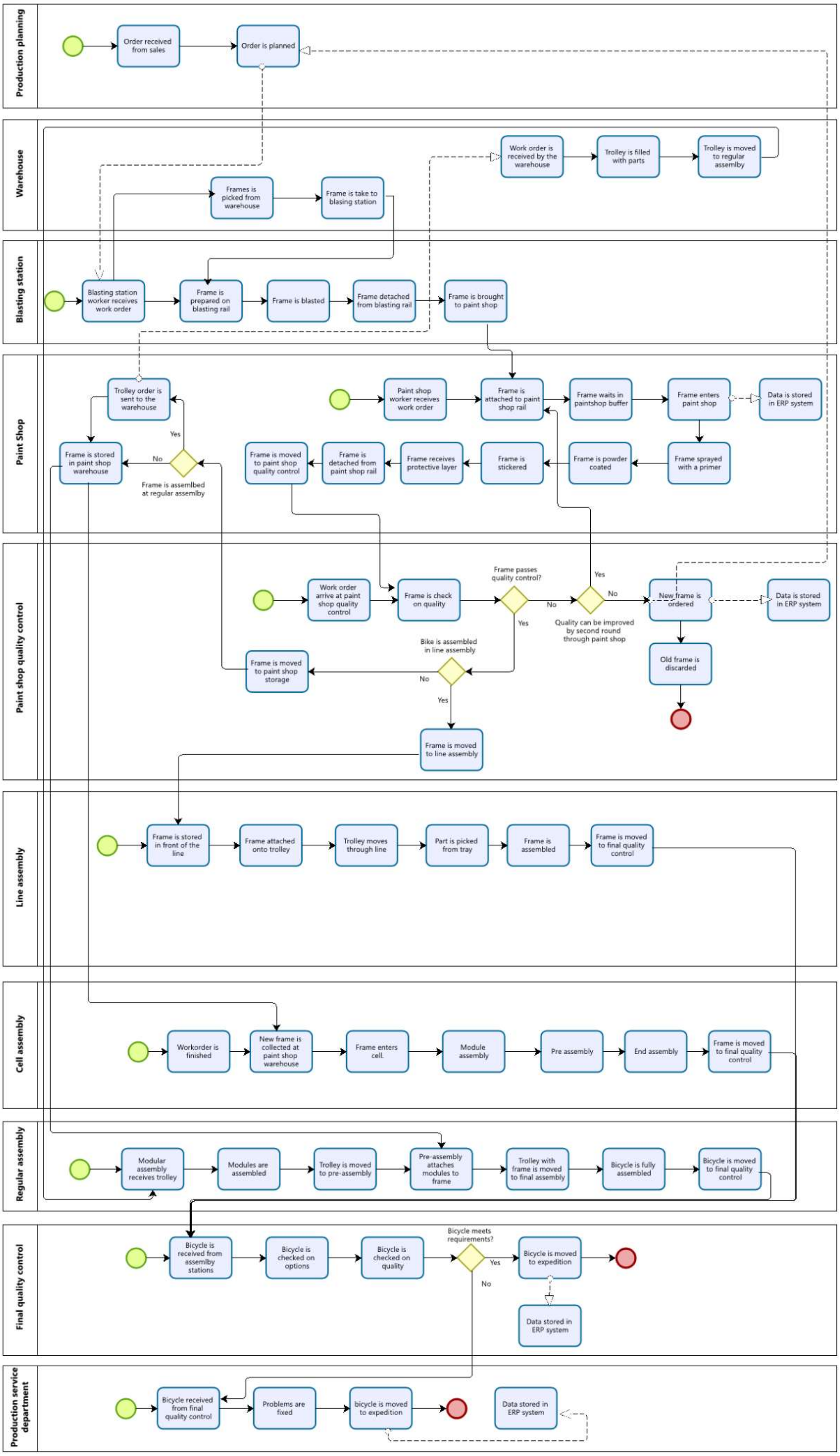



*Figure 10: BPM of the scoped process*

# Appendix C

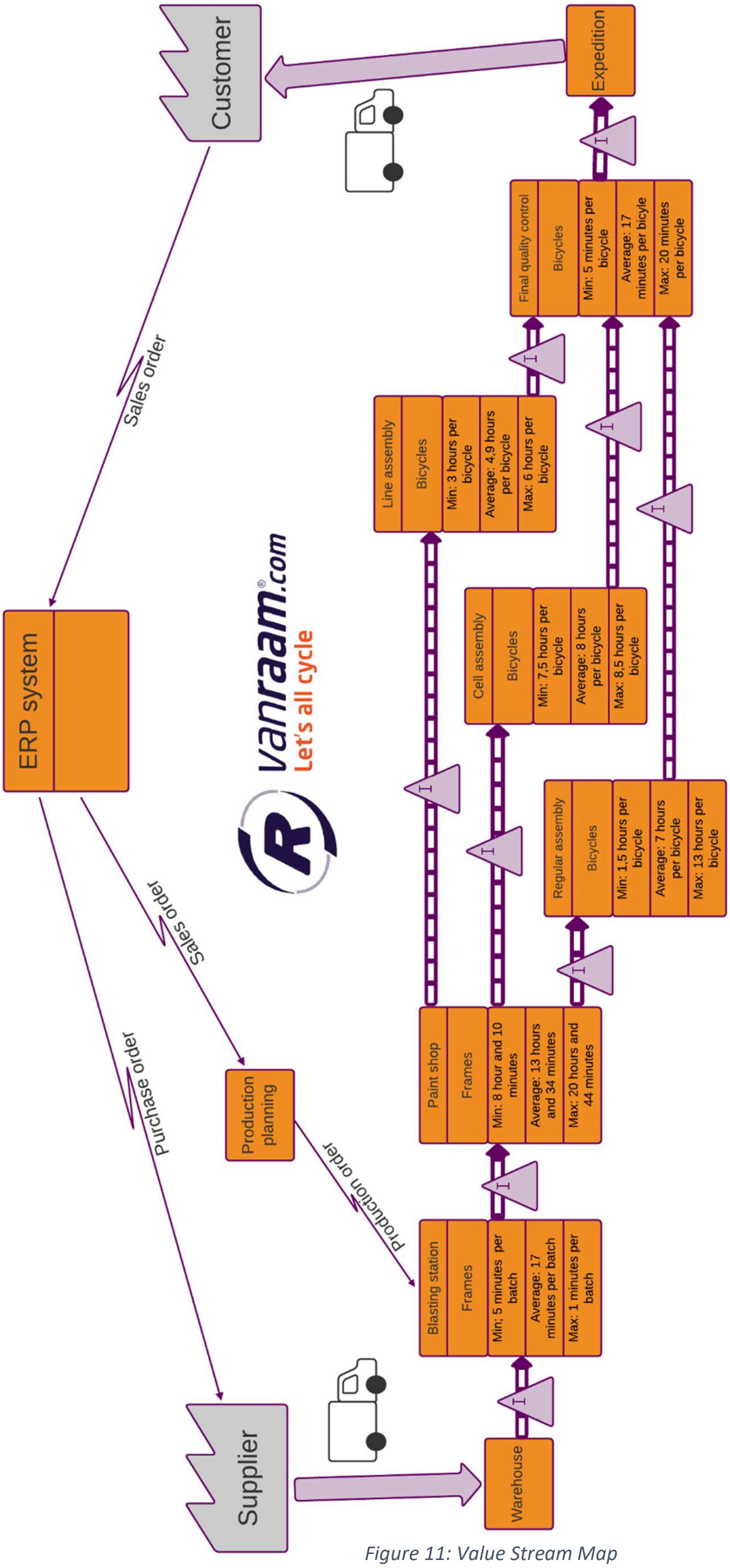



Figure 11: Value Stream Map

| Activity | Description | Minimum time | Average time | Maximum time | Variable | KPI |
|---|---|---|---|---|---|---|
| **Frame blasting** | The frames are blasted in the blasting cabin | 5 minutes | 17 minutes | 17 minutes | Batches existing from 2 to 10 frames | Time to blast a batch |
| **Powder coating** | The frames are painted, stickered, and coated | 8 hour and 10 minutes | 13 hours and 34 minutes | 20 hours and 44 minutes | Batches of 10 rail carts | Time to paint a frame |
| **Line assembly** | The frames are assembled in the line | 3 hours | 4,9 hours | 6 hours | Frame/half-assembled bicycle | Time to assemble a bicycle |
| **Cell assembly** | The frames are assembled in the cell | 7,5 hours | 8 hours | 8,5 hours | Frame / half assembled bicycle | Time to assemble a bicycle |
| **Regular assembly** | The frames are assembled in the regular assembly station in a conventional way | 1,5 hours | 7 hours | 13 hours | Frame/half-assembled bicycle | Time to assemble a bicycle |
| **Quality control** | The frames go through the final quality control | 5 minutes | 17 minutes | 20 minutes | Fully assembled bicycles | Time to check a bike |

*Table 9: Input for VSM*

**VSM literature study**

Value stream mapping is a tool of lean manufacturing and is helpful to get an overview of the flow of the process. VSM was chosen since it is specifically designed for processes with flow, this is what Van Raam hopes to achieve by improving the planning and control mechanism. Value stream mapping is a process improvement technique populated by Rother and Shook (1999). It is typically developed to understand the value-adding and non-value-adding activities from both information and material flow in a value stream (Mudgal et al., 2020; Shou et al., 2017). In this thesis, we will use it to obtain an overview of the steps taken in the production and the time these steps take. The VSM is based on the guidelines established by (Rother & Shook, 1999). The technique is known for its ability to display relevant flows, link manufacturing processes with supply chain activities, and relate production planning and demand forecast with the production schedule. It can even provide information on inventory levels in different phases of the production schedule (Jasti et al., 2019). The advantages are nicely enumerated by (Rother & Shook, 1999):

- Visualizes more than single-process level, the flow is visible.
- Does not only show the waste but also the sources of waste in your value stream
- Helps to make decisions about flow apparent so they can be discussed.
- Forms the basis for an implementation plan by offering a blueprint for how the door-to-door flow should operate.
- The method shows the linkage between information flow and material flow.

Value stream mapping does however have its limitations, the technique remains a pencil to paper-based technique resulting in limited accuracy. Processes with high variety and low volume are hard to implement. The product variety is however limited at Van Raam which makes the process easier to implement. (Rother & Shook, 1999).

## Appendix D

The first sheet contained the following information:

- The order number
- The article code
- Data about in which type of assembly the bicycle had been assembled.
- A description of the bicycle type and options.
- The date on which the order was released.
- The date on which the frame was planned for the paint shop
- The date that the first part of the frame entered the paint shop
- The date that the last part of the frame entered the paint shop
- The date that the frame arrived at quality control
- The planned delivery date of the order

The second sheet contained more specific data about the paint shop. This sheet contained the following information:

- The order number
- The article code
- Description of the article
- Name of the paint
- The point in time at which the first part of the frame entered the paint shop
- The point in time at which the last part of the frame entered the paint shop
- Whether the frame was rejected at the paint shop quality control
- The reason why the frame was rejected at the paint shop quality control

The first sheet was useful for calculating the throughput rate of the combined paint shop and assembly department. The sheet however also contained some incomplete information. This incomplete information was mostly caused because the orders had not passed quality control yet. The rows that contained incomplete information were deleted. Some orders had an incomplete packing list, these frames did however pass all steps of the process which meant they could be included in the research. This meant we had to delete 367 orders or 3% of the 11217 orders.

A second more serious type of noise was discovered in the data. While digging through the data it was discovered that employees would sometimes switch the frames of orders. If the frame of an order did not pass quality control it would happen that the frame of another order was used. For the data, this meant that the order whose frame was used to complete the order that it would take longer while the order that received the frame was processed a lot quicker. The data in these cases would show that a bicycle passed quality control before all parts were painted. This noise could be uncovered by looking at the throughput time of orders, this rate would in those cases be negative. The cases that could be identified in the data were deleted from the sheet. The orders with a throughput time of 0 and 1 day were also deleted from the data since the time needed to make the bicycle is at least more than one working day, as we learned from the VSM. In total 766 orders had to be deleted from the data or about 7%.

Using the remaining data of the first sheet, the combined throughput time of the paint shop and the assembly department could be calculated. A decision had to be made at what moment the frame could be seen as work-in-progress. This could either be when the first part of the frame entered the paint shop, or when the last part enters the paint shop. The decision was made to choose the first moment a frame part enters the paint shop as the moment the order enters the system. At that moment the work order is in production and so it can be considered WIP.

Using the information of the second sheet we were able to calculate the rejects for different reasons and an overall reject rate. The information is displayed in table 10.

| Reason | Frequency |
|---|---|
| 1.1 - Damaged | 337 |
| 1.2 - Welding mistake | 217 |
| 1.3 - Welding spatter | 12 |
| 2.1 - Paint drops | 38 |
| 2.2 - Pollution | 169 |
| 2.3 - Coating not covering | 104 |
| 2.4 - Nebulization | 7 |
| 2.5 - Pits | 39 |
| 2.6 - Rough frame visible | 4 |
| 3.1 - Transfer damaged | 20 |
| 3.2 - Air bubbles | 40 |
| 3.3 - Stickered incorrect | 90 |
| 4.1 - Frame lost | 15 |

*Table 10: Reasons for rejects*

With the information on the second sheet, we were also able to calculate the total rejection rate of the quality control at the paint shop. We concluded that almost 5% of the frames are rejected which translated to 1 in 20 frames being rejected(!). The information is displayed in table 11.

| | |
|---|---|
| Total | 22271 |
| Rejects | 1092 |
| Percentage rejects | 4,9% |

*Table 11: Reject percentage*

## Appendix E

**Loading**
With loading we mean the amount of work that is allowed to enter the system based on the capacity of machines, work centres, departments, and factories. A system can either have a finite or infinite loading policy. In a finite loading system, the orders are released when the shop or machine has fewer jobs remaining than a predetermined minimum. The machine then receives work up to a maximum. In the case of infinite loading, the jobs are released anyway. Instead of looking at how many jobs remain in the system the jobs are released at a predetermined release date for time (Wisner, 1995). At Van Raam orders are released according to finite loading, this way the work-in-progress can be kept at the required level. Whether a decision should be made for either finite or infinite loading depends on the KPIs of your process. Examples of these KPIs are the likelihood of drastic changes in product specification, errors in data, and rush orders (Matsuura et al., 1995). To arrive at an optimal loading policy the valuable operating time also has to be taken into account. There are 168 hours in a week which is the maximum available time. Machines will however not run constantly. Time for example needs to be reserved for breakdowns, set-ups, changeovers, quality loss, and some other time-consuming activities during which the machine or process is not able to produce. The total amount of time a machine could produce is called the available operating time, the time the machine was available for productive working is called the valuable operating time (Slack et al., 2016b).

**Sequencing**
Once the loading system has been established it is clear when orders enter the system. It has however not yet been decided which order will be processed first and which will be processed last. This is where the sequencing activity of planning and control is performed. The sequencing method will use predefined criteria to arrange the order in which the different jobs enter the process (Slack et al., 2016b). In table 12 some commonly used sequencing methods are listed and explained. At Van Raam, the production philosophy indicates that the process should strive towards a FIFO flow. The master production schedule releases the order based on the due date. At the moment it however functions more like a FIFO with priority, also known as a FIFO-WP. The research into sequencing at Van Raam will remain shallow, the reason for this is that one of the restrictions is that we cannot change the business process philosophy. We do however provide a recommendation on what sequencing method could improve the process at the company.

Priority rules can also be combined, as concluded by (Sels et al., 2012) these combined priority rules as found in literature always outperform separate priority rules on objective functions. As described by (Leu, 1999) it is also possible to apply two-stage heuristics (group scheduling) while sequencing orders. In the research in the assemble-to-order environment, it was concluded that two-stage heuristics always outperformed single-stage heuristics.

Researching which sequencing method suits your process best can be rewarding. As mentioned by (Stevenson et al., 2005) releasing mechanisms have a significant effect on the performance of the production system, being able to reduce WIP and lead times.

| Abbreviation | Name | Explanation |
|---|---|---|
| CP | Customer priority | Customers receive a priority score based on a predetermined scale. Orders with high customer priority are processed first (Slack et al., 2016b). |
| (E)DD | (Earliest) Due date | Gives priority to the job whose due date is earliest (Kiran, 2019). |
| LIFO | Last in first out | The order that arrives last is processed first, often used for practical reasons (Slack et al., 2016b). |
| FIFO / FCFS | First in first out / First come first serve | The order that arrived the earliest in the queue of the machine is processed first. (Doh) |
| LOT / LPT | Longest operation time / Longest processing time | The order with the longest required operating time is processed the first (Slack et al., 2016b). |
| SOT / SPT | Shortest operation time / Shortest processing time | The order that has the shortest operating time receives the highest priority. Useful in situations in which many jobs need to be finished (Slack et al., 2016b). |
| SLK | Least slack | Slack is the number of days an order would be completed before its due date if processing started now. The order that would be finished the least days before its due date is chosen(Kiran, 2019). |
| COVERT | costs over time | The order is selected that has the highest cost over time, costs can for example be a penalty due to delay (Doh et al., 2013). |

*Table 12: Sequencing methods*

**Scheduling**

The sequence in which orders will be processed has now been established. The next activity of planning and control is scheduling. This is an important activity since it has a major impact on the productivity of a process (Kiran, 2019). Processes often require detailed planning in which the starting time of different operations is scheduled. Making this schedule can however be rather hard because of the number of options available. If the number of orders and machines increases the number of possible schedule options increases factorial and exponential respectively as displayed in the next formula (Slack et al., 2016b).

$$\text{Number of possible schedules} = \left( (Number\ of\ jobs)!\ \right)^{(Number\ of\ machines)}$$

*Equation 2: Calculating the number of possible schedules*

Despite the advances made in computational power only small to medium-sized problems can be solved within a reasonable time due to the enormous amount of alternatives (Lohmer & Lasch, 2021). Within the activity of scheduling, two main principles are forward and backward scheduling. With forward scheduling, the orders are scheduled from the day they are released to a finite capacity. It aims to complete jobs as early as possible. Backward scheduling, on the other hand, will schedule all operations of an order starting from its due date and working backward. Here the objective is to finish a job as close as possible to or on the due date of the order (Lalas et al., 2006). Because of the large number of possible schedules, it is often not the goal to find the optimal schedule but an acceptably feasible one. Heuristics are used to arrive at this acceptably feasible solution (Slack et al., 2016b). Well-known examples of backward scheduling are master requirements planning (MRP) and Just-in-time (JIT) manufacturing (Kiran, 2019; Slack et al., 2016b). Lastly, we would like to mention that scheduling might seem rather similar to loading, there is however a clear difference. Where loading, as mentioned earlier, focusses on machines, work centres, departments, and factories. Scheduling concentrates on products, parts, and operations (Kiran, 2019).

**Monitoring and control**

Through loading, sequencing, and scheduling a plan can be created. This plan is however useless if the real process does not execute it properly, the fact that our world is stochastic will also create deviations from the original plan. Therefore monitoring and control are necessary. Any deviation of the plan should be rectified through some intervention which might require some replanning.

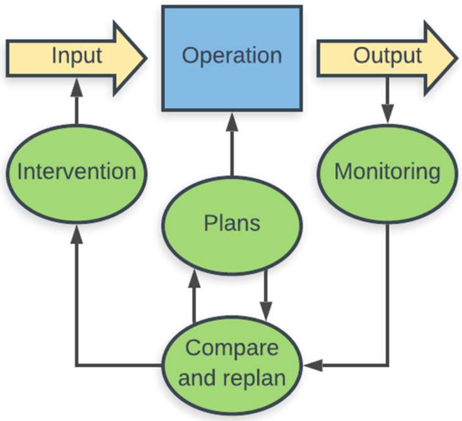



*Figure 12: Monitoring and control of an operation*

With the means of interventions, the input of the process is regulated. Through monitoring, the output that is associated with some input is measured. This is then compared with the plans which can be altered if deemed necessary (Slack et al., 2016b).

Many types of control are applicable in different situations. As (Slack et al., 2016b) stated there are different questions that you need to ask before the right type of control can be identified. The first question you should ask is if the situation is unambiguous or not. If the objectives are not unambiguous and this cannot be resolved then “negotiated control” or “political control should be applied. The next question that should be asked is if the process knowledge is complete. If this is true and the process is repetitive then routine control should be applied. If it is not routine then expert control should be applied. If there is a lack of knowledge of the process and it is a repetitive activity, the decision should be made to apply trial-and-error control. If the activity is not repetitive there should be chosen for intuitive control. (Hofstede, 1981) mentioned another type of control named judgemental control. This type of control should be applied if the objectives are unambiguous but there are no measurable outputs. Figure 12 displays the decision three that can be used to determine which type of control should be used.

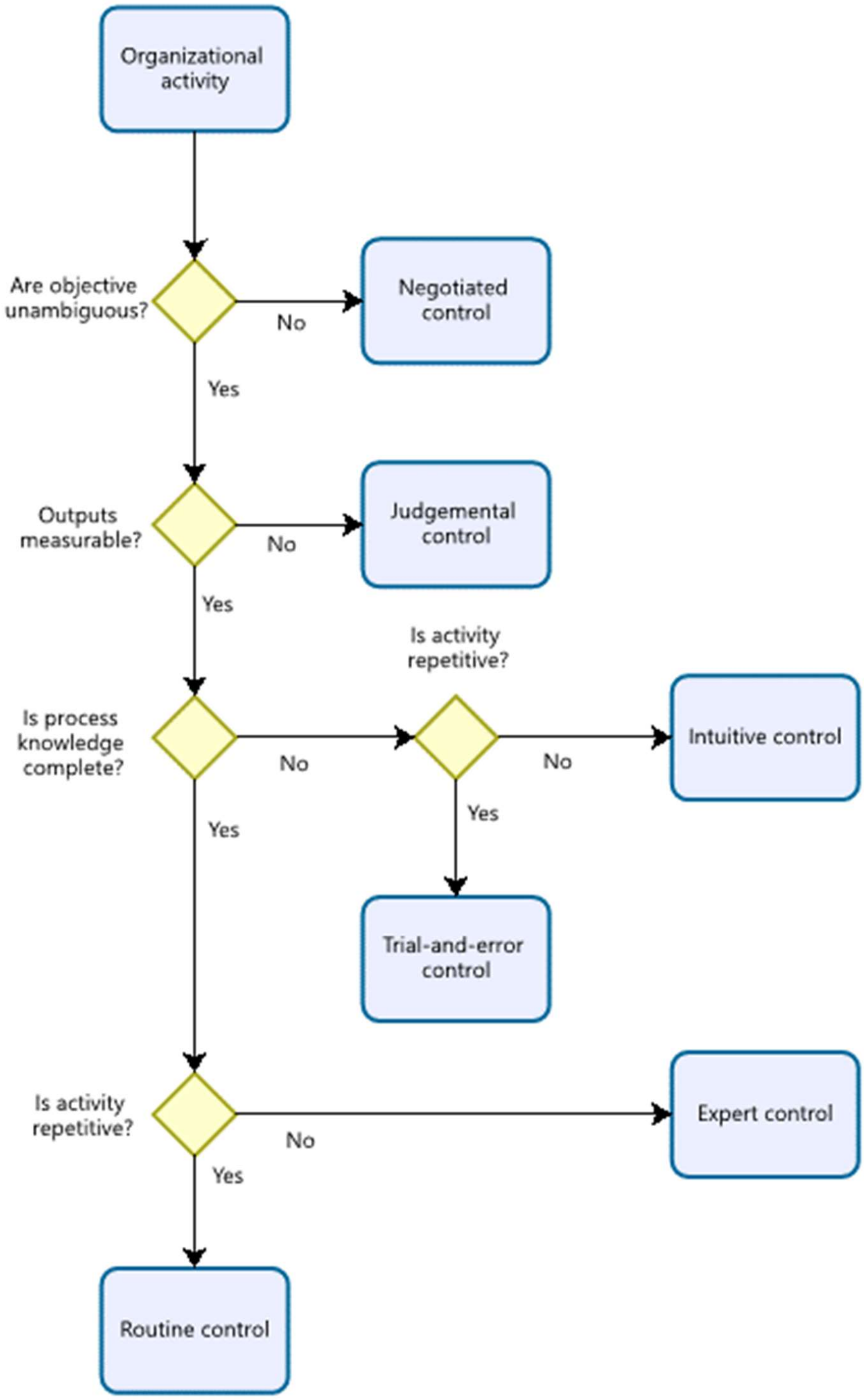



*Figure 13: Decision tree for monitoring and control type*

## Appendix F

As mentioned there are two key elements for interventions in a process which are push and pull. In this part of the thesis, we will elaborate on the functions and differences of push, pull, and push-pull systems.

The terms push and pull refer to the means for releasing jobs into and within the production facility. When using a push system the order is released on a starting date that is calculated by subtracting the lead time from the date that the order is due. An application form of a pull system is a Master requirements planning (MRP). In a pull system, the downstream work centres pull stock from the previous stages. All workstations then perform tasks only to replenish the outgoing stock. In a pull system, the workload can be coordinated through some sort of signal in the form of a card like in the Kanban or POLCA method (Spearman & Zazanis, 1992). Historically, the push system is more used. This can be explained by the fact that the pull system was invented later. Studies in the late 1990s have however revealed the superiority of the pull over the push system which caused it to be widely adopted in the production and manufacturing industry (Prakash & Feng, 2011).

**Pull control**

A pull production system can be recognized through the explicit limitation of the amount of work that can be in the system (Hopp & Spearman, 2004). Using work-in-progress (WIP) the system adjusts throughput to meet the required demand (Ou & Jiang, 1997). The most important decision that has to be made is the maximum allowed WIP for the entire process or the different workstations (Spearman & Zazanis, 1992). For a system to be pull-controlled, all workstations within the systems should perform pull control. If one of the working stations does not have a finite buffer the system is called a push-pull hybrid (Grosfeld-Nir et al., 2000). This system is graphically displayed in figure 14 in which the black arrows represent the flow of materials and the striped arrows represent the flow of information.

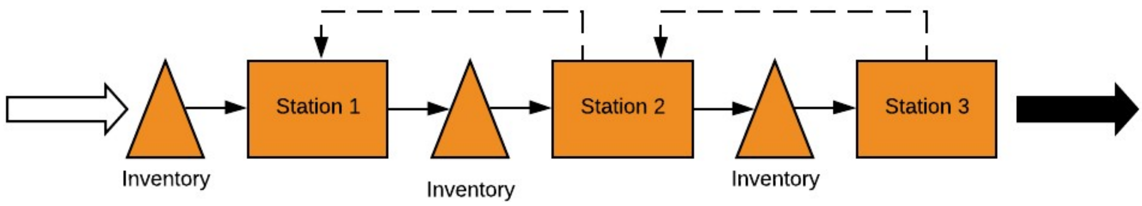



*Figure 14: Pull control*

The pull control system has some clear strengths. The system is for example controlled by focussing on WIP instead of throughput, since WIP is easier to control than throughput the pull system is inherently easier to control than the push system (Spearman & Zazanis, 1992).

(Hopp & Spearman, 2004) made a good overview of the advantages of pull control. These benefits have been widely cited. The first benefit of pull control is that it is capable of reducing work-in-progress and cycle time. By limiting the release of orders into the system there is a lower average WIP level. Using Little's law this also translates into shorter manufacturing times. The second benefit of pull control is a smoother production flow. This benefit is realized through dampening the fluctuations of the WIP level, which in its turn creates a more predictable output stream. (Spearman & Zazanis, 1992) described this by pointing out that the system contained fewer congestions. The third advantage of pull control is the improved quality of products. A system with short queues cannot tolerate high levels of yield loss and rework because these will quickly shut down the line. Additionally, short queues reduce the time between the creation and detection of a defect. As a result pressure for better quality and an environment in which it can be achieved is provided. (Ou &

Jiang, 1997) even suggest that it's not the reduction of WIP inventory but the improved quality of the process and the final products that are the most prized achievement of pull control. The fourth and final common benefit of pull control is reduced costs. By switching the control of the process from release rate to WIP level a means is provided to stress the system. By steadily reducing the WIP problems within the line will become visible, these problems can then be solved to improve the production process. This process has been widely described via the analogy of lowering the water (inventory) of a river to find rocks (problems). The result of doing this is a more efficient system that runs at lower costs. Other notable benefits of the pull system are the usage of actual demand in production and consideration of capacity utilization in setting WIP levels (Prakash & Feng, 2011). It must however be said that the benefits of a pull environment owe more to the fact that WIP is bounded than to the activity of pulling everywhere (Spearman & Zazanis, 1992).

In a good production environment, the pull system is better able to make use of the advantage because of its ability to work ahead. If there is however no ability to work ahead the pull mechanism may have more WIP than the push system. In the absence of a Master production schedule (MPS) or buffer in front of the system the pull system would stop work orders at the entry of the system while in a push process all work orders are allowed to enter. The cycle time of the push system would then be less than the cycle time of the pull system because work is never started later, therefore the average WIP would be lower. This example highlights the importance of a buffer between demand and the production process for pull systems to be used to their full potential (Spearman & Zazanis, 1992). It must also be noted that pull systems are rarely consistently implemented over time and across the whole value stream. The existence of islands of best practices, such as pull production systems (PPS), is frequent in lean systems in general. The reason for this drawback is usually that some preconditions as set by PPS are not met by the system. Examples of these preconditions are capacity slack and process stability (Gayer et al., 2020).

**Push control**

Then there is push control. Traditionally, the coordination of feeding workstations is done by the push control system. In this system, the production control group schedules the necessary quantities of parts and materials to produce all components of the desired quantities of the different products. Within the system parts and materials are released for operations at the first work station at the appropriate time. If the order is done at one work centre there is always a complete release of the work order. The decision variables are how much to release and how often these releases take place (Spearman & Zazanis, 1992). The order is then transferred to the next workstation where it waits until the station is ready to process the order. In summary, we could state that push systems control throughput by establishing a master production schedule (MPS) and detect problems by monitoring the work-in-progress (Ou & Jiang, 1997). For a system to be called a push system, all workstations within the system need to apply push. If one of the workstations has a finite buffer it applies pull which makes the overall system a hybrid push-pull control system (Grosfeld-Nir et al., 2000). We could say that to make a push system out of a pull system you could increase the authorization cards that limit the WIP within a pull process to infinite, effectively creating a push system. The push system is graphicly displayed in figure 15 in which the black arrows represent the flow of materials and the striped arrows represent the flow of information.

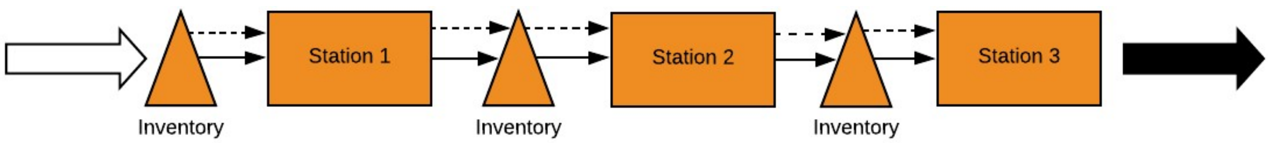



*Figure 15: Push control*

A push system has its strengths. A benefit of the push control system is that it can provide early demand information to suppliers, which might help reduce costs in the adaptation of the workforce (Dellaert et al., 2000). The main advantage of the push system is that it does not create blockages within the system, leading to high utilization of resources, hence a high throughput. The infinite buffer capacity of a push control system can however lead to unbounded WIP which is undesirable for most manufacturers (Grosfeld-Nir & Magazine, 2002).

Although the push system has shown relative success in industries it is rather viable for errors in demand. These errors can cause excess or deficient finished goods and over-or underutilization of capacity in meeting actual demand. This phenomenon results in unnecessary costs either way (Prakash & Feng, 2011). A disadvantage of the push control system is that the capacity of the system has to be known to control the process. Capacity is estimated by many variables like process time, setup time, random outages, and work efficiency. Having to combine all of these variables makes calculating the capacity and so controlling the throughput of the process difficult (Hopp & Spearman, 2004). The throughput of a process is controlled by specifying an input rate. If the input rate is less than the capacity of the process the throughput will become equal to the input rate. As a consequence, the throughput rate is likely to be lower than what the process can handle. If the input rate is however to high it causes WIP to build up in the process which again leads to a throughput that is lower than the true capability of the process (Spearman & Zazanis, 1992).

As mentioned earlier this thesis focuses on the production process from the paint shop to the final quality control. Within this scope, the process philosophy states that pull control should be applied, since the process philosophy is one of the restrictions of this thesis we will only conduct further research into monitoring and control methods that are meant for a pull control environment.

## Appendix G

**Kanban**
The first monitoring and control method to implement pull control in a production process is Kanban. The method is often used within the Lean methodology for controlling operations (Slack et al., 2016c). Kanban is usually applied in productions with little variety of products. The mean demand rate of products is high and there are minimal fluctuations in the demand rate. Therefore the demand can usually be planned rather reliable which makes a smaller amount of safety stock sufficient. The method has been implemented in a wide variety of industries, where the emphasis is on the automobile industry (Lödding, 2013). With Kanban, the part flow is organized according to the one-piece-flow concept. The main characteristics of Kanban are its operating simplicity and ability to reduce WIP. The system is based on working to a buffer with a maximum. The size of this buffer is a trade-off between protection and lead time. A higher buffer will increase will improve protection but, as a consequence, the lead time will also increase (Halevi, 2001). Three essential parameters for setting Kanban are lot size, bin contents, and number of Kanbans (Lödding, 2013). Kanbans usually take the form of cards but can also be coloured balls, lights, or electronic systems. The general idea is that it creates a mechanism that allows the one workstation to signal the preceding workstation that it is ready for the next work order (Halevi, 2001). There is not one Kanban system, there are for example systems in which there are production and transportation Kanbans. This is the so-called Two-card-Kanban system which is applicable in processes where there is a considerable distance between two consecutive workstations. Other examples are Bin Kanban and Visual Kanban (Darlington et al., 2015; Lödding, 2013).

Kanban has some advantages over other monitoring and control methods. First off, there is the fact that responsibility is delegated to the production and production supervisors. This allows for the WIP level to be evaluated on-site. In other systems, this is often done with planning software which makes it more difficult to gradually decrease the WIP within the context of an optimization process (Lödding, 2013). Another advantage of the Kanban system is called “Visual production management”. This term concludes that the flow of products through the process is visible where with other methods the half-finished products are often stored away from the production (Lödding, 2013). The goal of eliminating waste is also highlighted by Kanban. Kanban is a powerful method to reduce manpower and inventory, eliminate defective products, and prevent the recurrence of breakdowns (Halevi, 2001). Some last advantages of Kanban as mentioned by (Lödding, 2013) are the fluctuations in the demand rate are reduced and that employees that set the variables are usually directly involved in the production, and are thus confronted with the impact of their decisions.

Because Kanban is so well known and successful, business and production managers have high expectations when introducing it. However, in many cases, Kanban cannot achieve the desired result without intensively restructuring the production process and/or the product which makes Kanban, as mentioned by (Stevenson et al., 2005), hard to implement. Essential elements for the successful implementation of Kanban are short setup times, organization according to one-piece-flow, controlled process, stable product mix, standardization of jobs, and a thoroughly planned production(Darlington et al., 2015; Lödding, 2013; Monden, 1993) The success of the systems also depends heavily on the completeness of the implementation. Even when fully implemented the system might be unable to cope with the product variety and fluctuations in demand (Halevi, 2001). According to (Lödding, 2013) Kanban can only be implemented successfully if there is a low number of variants. With each product variant, a new Kanban card needs to be added, the increased number of different Kanban cards increases safety stock which in its turn leads to blocked WIP. It is further limited to processes with high volume and relatively few different parts (Bonvik et al., 1997). Another disadvantage of Kanban is the possibility of 'lock up' in a manufacturing system with complex flows where work orders can visit the same stations twice (Harrod & Kanet, 2013).

**POLCA**

POLCA is an abbreviation for Paired-Cell Overlapping Loops of Cards with Authorization. The method attains to establish localized WIP control loops between different manufacturing cells in a production process. The method is a component of the comprehensive Quick Response concept aimed in particular at organizing production into manufacturing cells and is aided by a companywide 'mindset' of Quick Response Manufacturing (QRM) focussed on operating at 70 – 80% capacity (Krishnamurthy & Suri, 2009). In the ideal case manufacturing cells operate according to the one-piece-flow principle. POLCA is characterized by the calculation of the release date for all cells through which an order flows and a local WIP control between the production's manufacturing cells (Lödding, 2013). The method differs from other pull control methods in that it controls the flow of WIP between direct pairs of manufacturing stations, instead of mere occupancy in the system.

POLCA is rather simple to perform, by limiting the WIP of individual cells it can limit the WIP of the entire process. An advantage of the method is that it like Kanban works with cards which makes the process visible (Lödding, 2013). An important difference is that the Kanban card is an inventory signal and the POLCA card is a capacity signal. In other words, a returning POLCA card signals that there is capacity at a downstream cell. If there is no card available that means that a downstream cell is backlogged which means that working on an order for it would only create more inventory. The cell can then decide to produce for a downstream cell that does have the remaining capacity to process incoming work orders (Krishnamurthy & Suri, 2009). WIP fluctuations within a POLCA process are usually less than in a process that controls the overall WIP. The reason for this is that size of the fluctuations is limited by the number of POLCA cards (Lödding, 2013). If there are fluctuations the method has options to cope with this. The cell structure, for example, allows for flexibility that can be exploited as and when necessary. This flexibility is provided by the machines within the cells that can be used to adjust the workload variations (Krishnamurthy & Suri, 2009). Another advantage is that the method can, unlike Kanban, handle highly engineered production, small batches, and high product variety (Suri, 1999).

One of POLCA's main drawbacks is the possibility of blockages. Compared to centralized order release methods it is blocked more often because it can refuse orders from being released for processing even if the orders are work-in-progress. Therefore it is advised not to use the method with highly complex material flows which would lead to the loss of efficiency (Lödding, 2013). Another disadvantage of POLCA is the risk of deadlock if orders are allowed to flow backward. If the process is in deadlock one station cannot start working on an order because all cards are elsewhere in the process. This causes the entire production to halt. Therefore it is essential to check for the possibility of deadlocks when implementing the POLCA system (Lödding, 2013). This phenomenon was also described by (Harrod & Kanet, 2013) where it was named 'Lockup'.

**Workload control**

Workload control is a relatively complex monitoring and control technique that balances the load of workstations within a manufacturing system. It can be considered as a less specific application of Kanban (Zijm et al., 2019). The basic idea is to hold back work orders that would be routed through workstations that are already overloaded. In addition to WIP on the workstations, the contents of work orders that have already been released and that will pass through the workstations are taken into consideration. To perform WLC three parameters have to be set. The first parameter is the release list, this list contains the backorder and decides which order is released based on the due date. The second parameter is the WIP account, this is the number of orders that are scheduled to pass a workstation. A WIP account consists of direct and indirect WIP, direct WIP is in the inventory and the orders in the process of the workstation and indirect WIP are the orders that are scheduled to enter the workstation. The third parameter is the WIP limit per workstation which is set per workstation. If this limit of a workstation is exceeded new orders that pass through this workstation are halted. (Lödding, 2013).

To prevent the system from being overloaded it holds back work orders that wait in front of the process. Unlike other monitoring and control methods, it can however not block work orders within the process which ensures a continuous flow of orders. Another advantage of the method is that it implicitly takes the bottleneck principle into account. The bottleneck will usually be the station whose WIP limit is exceeded the earliest. Moreover, the method is also able to cope with processes that have alternating bottlenecks (Lödding, 2013).

A disadvantage of this system is also that if the intervals with shorter and longer throughput times up to the observed working station quickly alternate, the WIP limit would then have to be constantly recalculated. This problem becomes even more evident if the position of the workstations within the order throughput strongly varies (Lödding, 2013). Another characteristic of the method is that at workstations at the end of the process, with a long throughput time before the work order reaches the station, there is usually a lot of indirect WIP. In these cases, the indirect WIP exceeds the direct WIP which creates a leeway for the fluctuations of direct WIP. The further the station is the greater this leeway is (Lödding, 2013). Something else that has to be taken into account when considering WLC is the so-called ‘WLC paradox’. Meant with this is the difference between the theory and practice of the method. There is also a lack of parameter setting guidance which makes establishing the best values for parameters hard (Stevenson et al., 2005). (Zijm et al., 2019) agreed to this and explained it by stating that Workload control is rather similar to Bottleneck control but that the workload is not directly controlled by the bottleneck, what the workload is determined by is not clearly defined.

| Method | Main idea | Benefits | Disadvantages |
|---|---|---|---|
| Kanban | Control the WIP of all separate stations in the process by setting limits. | 1. WIP level is evaluated on-site which allows for better accuracy.<br>2. Disruptions are discovered early.<br>3. Powerful method to eliminate waste.<br>4. Improved quality of products. | 1. The method has several prerequisites for successful implementation.<br>2. Only suitable for processes with high volume and low variety.<br>3. Possibility of lockups. |
| POLCA | Regulate the amount of WIP between couples of cells within the process. | 1. Makes the process visible on station level.<br>2. Flexibility to handle WIP fluctuations.<br>3. Ability to handle small batches and high product variety. | 1. WIP can be stopped in the process which increases throughput time.<br>2. Like Kanban there is the risk of lockups within the process. |
| ConWIP | Limit the total WIP within the process by only allowing work orders to enter if a card is free. | 1. Does not struggle with high setup times across different parts.<br>2. The throughput time of products can be predicted well allowing it to be planned easily.<br>3. Does not cause any blocked WIP in the throughput of orders. | 1. Higher variations in throughput time.<br>2. There is no control of the bottleneck which can lead to bottleneck starvation. |
| Bottleneck control | Limit the total WIP up until the bottleneck of the process. | 1. Bottleneck will always be able to continue.<br>2. Simple to implement.<br>3. Throughput times can be predicted well with constant WIP. | 1. Should only be applied if there is a clear bottleneck.<br>2. Cannot regulate WIP at station level |
| Workload control | Limit the sum of the current and future WIP for each station within the process. | 1. Can cope with alternating bottlenecks.<br>2. Implicitly applies the bottleneck principle.<br>3. Cannot block orders that are already in the process. | 1. WLC paradox, a discrepancy between theory and reality.<br>2. Lack of parameter setting guidance.<br>3. Long process creates leeway for fluctuations in direct WIP |

*Table 13: Summary of monitoring and control methods*

## Appendix H

**Warm-up**
The simulation starts with an initialization bias, the system starts empty which is not realistic in the real world. For this reason, we will only start collecting data once the simulation has reached its steady state. To determine the warm-up period we used the average daily WIP on working days. We first tried to estimate the warm-up period by letting the simulation run for 4000 days and plotting the result. From the visual inspection, it became clear that the WIP level stabilizes after approximately 40 working days. To be sure that we chose the correct value we will apply the mean standard error rule, also known as MSER. The MSER formula is displayed in equation 3 in which $d$ is the proposed warm-up period, $m$ is the number of observations and $\bar{Y}(m,d)$ is the mean of the observations from $Y_d$ to $Y_m$.

$$MSER(d) = \frac{1}{(m-d)^2} \sum_{i=d+1}^{m} \left(Yi - \bar{Y}(m,d)\right)^2$$

*Equation 3: MSER formula*

To calculate the warm-up period using the MSER formula we performed 10 runs of 4000 days. The outcome of this was that day 40 had the lowest MSER of 0,013315. This means that the simulation has a warmup period of 40 days. A rule of thumb is that you should reject the warm-up period if it is large than half the run length. 40 however is smaller than 2000 which means we do not have to reject the warm-up period of 40 days. To be safe we will use a warm-up period of 50 days while conducting the experiments. The graph in which the daily average throughput time and the MSER value are displayed can be found in figure 16.

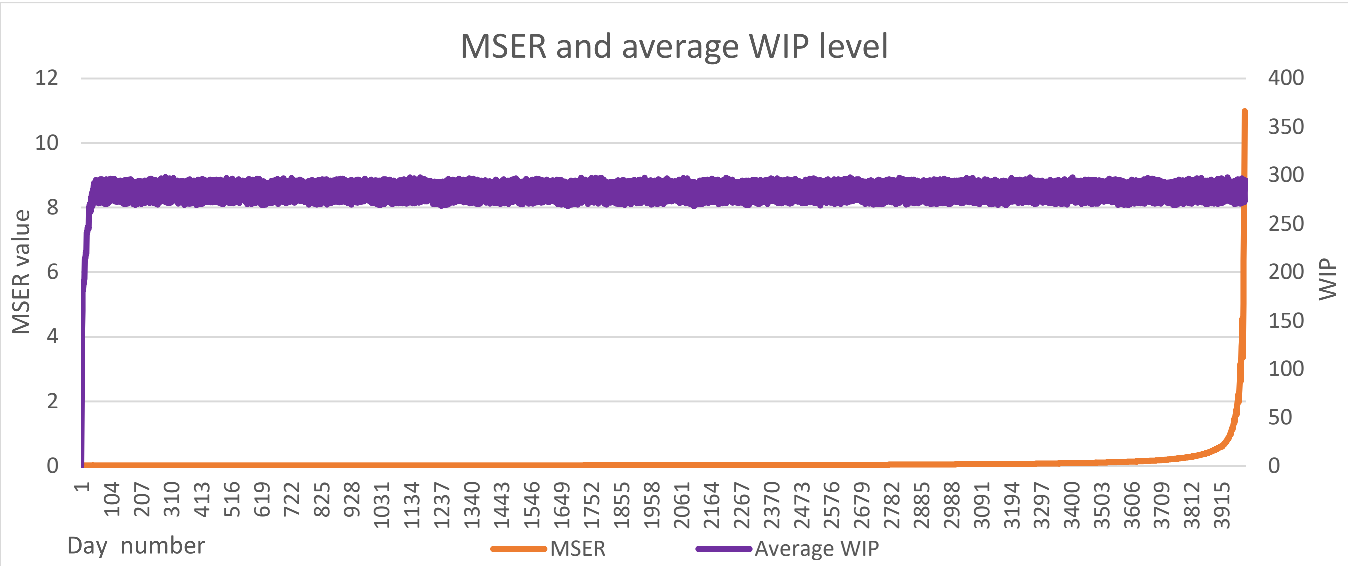



*Figure 16: Graph of MSER and average throughput time*

**Run-length**
The run length of the simulation should be sufficiently long to cancel out random variations. A rule of thumb to establish a run length is that it should be ten times longer than the warm-up period of the simulation (Siebers, 2019). Since our warm-up period is 50 days the simulation should be at least 550 days. We will however set the runtime of the simulation to 2000 days to be sure we obtain correct values.

**Number of replications**

To determine a proper number of replications we applied the confidence interval half width method (CIHW). A confidence interval is a statistical tool that can be used to calculate a range where the true mean average is expected to lie. The formula for the CIHW can be found in equation 4, in this formula $t_{n-1,1-a/2}$ is the t value, $S^2$ is the variance of the replications, $n$ is the number of observations, $\bar{X}$ is the mean of the replications and d is the relative error.

$$\frac{t_{n-1,1-a/2}\sqrt{S^2/n}}{|\bar{X}|} < d$$

*Equation 4: CIHW formula*

If the CIHW is smaller than the relative error the number of runs is accepted. A typical value for the relative error is 0,05 and therefore chose to set this value as our $d$. From our calculations, it appears that the CIHW is lower than the relative error after 2 replication as can be seen in the graph of the CIHW in figure 17. Doing only 2 replications however does not seem reasonable, (Law & McComas, 1996) recommend doing at least 3 to 5 replications. To obtain correct results we decided to set the number of replications to 10. In theory, the number of replications should be determined separately for each experiment. In practice, this is however only done for the base scenario (Siebers, 2019).

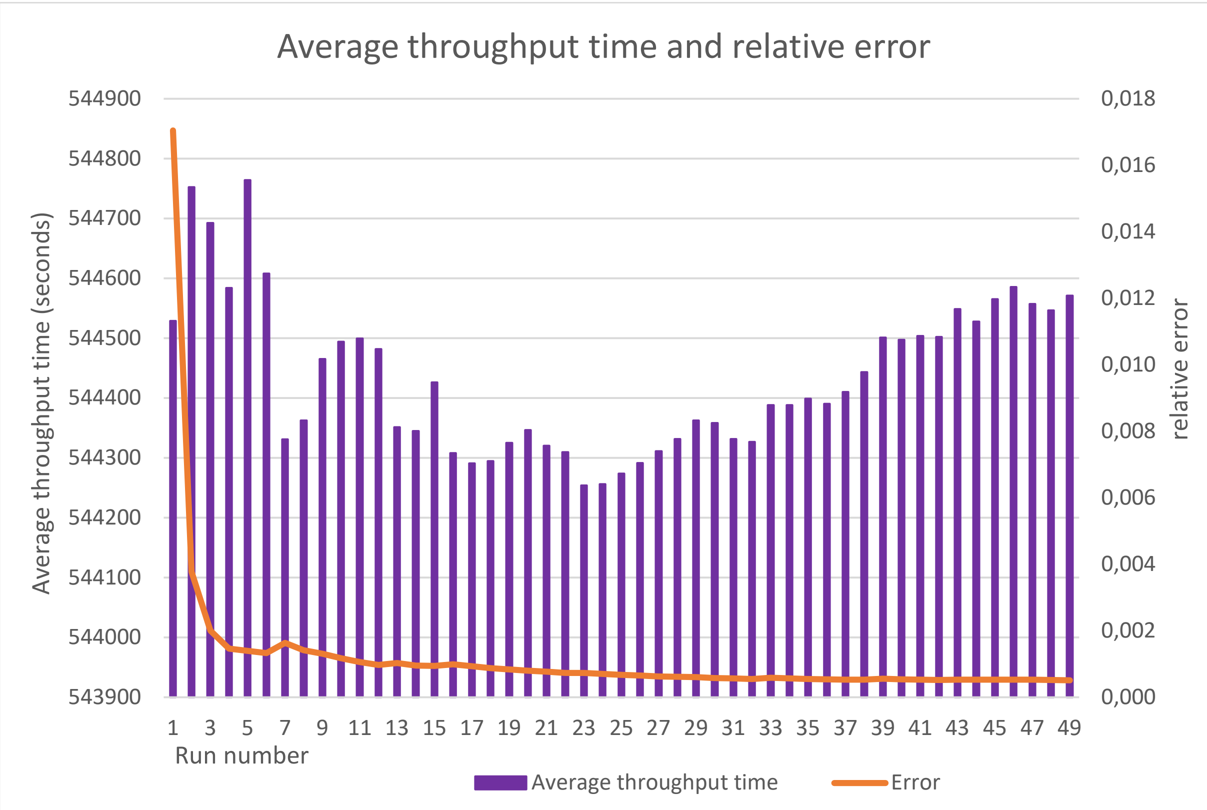



*Figure 17: Graph of average throughput time and relative error*

## Appendix I

| | | |
|---|---|---|
| Lijn | Midi/maxi: | 6 werkplekken |
| | | 30min per werkplek |
| | ER2/Noorwegen: | 6 werkplekken |
| | | 50min per werkplek |
| | ER3: | 8 werkplekken |
| | | 30min per werkplek |
| | Fun2Go: | 8 werkplekken |
| | | 45min per werkplek |
| Cel | Velo: | Totale dlt 8:30u |
| | Opair: | Totale dlt 7:30u |
| Regulier | Kivo 3W | Totale dlt 7:00u |
| | Kivo 2W | Totale dlt 7:00u |
| | Twinny 2W | Totale dlt 7:00u |
| | Twinny 3W | Totale dlt 8:00u |
| | Easy Go | Totale dlt 8:00u |
| | ER Junior | Totale dlt 4:00u |
| | ER sport | Totale dlt 7:00u |
| | Maxi comfort | Totale dlt 4:00u |
| | Chat | Totale dlt 13:00u |
| | LoopHulp | Totale dlt 1:30u |
| | Mini | Totale dlt 7:00u |
| | FunTrain | Totale dlt 7:00u |
| | Balance | Totale dlt 5:00u |
| | Husky | Totale dlt 4:00u |

*Table 14: Designed throughput time of the assembly department*

## Appendix J

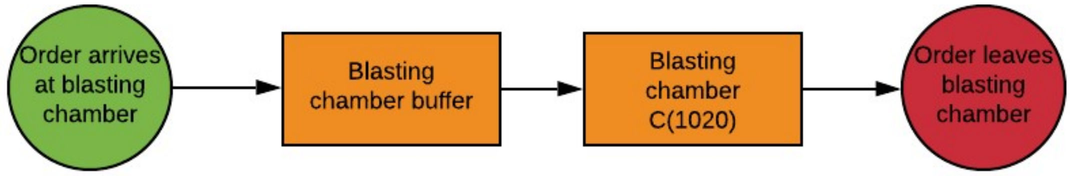



*Figure 18: Process at blasting station*

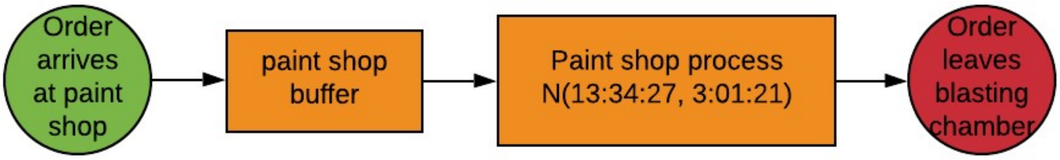



*Figure 19: Process at the paint shop*

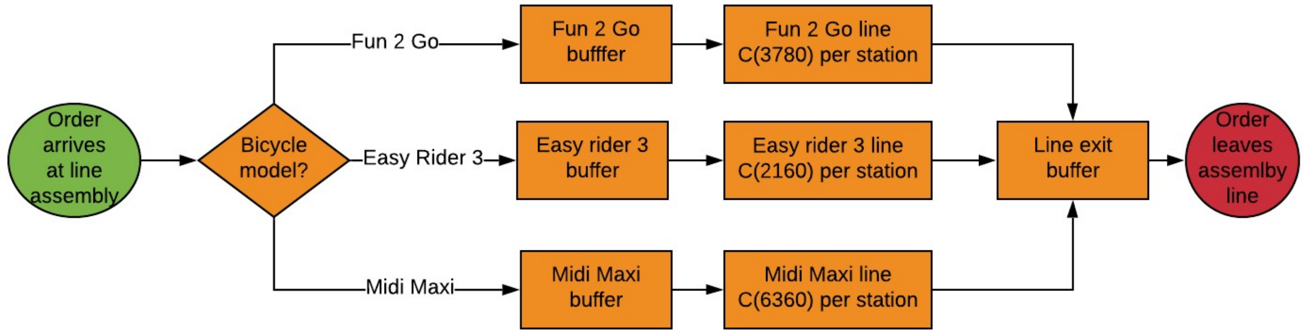



*Figure 20: Line assembly*

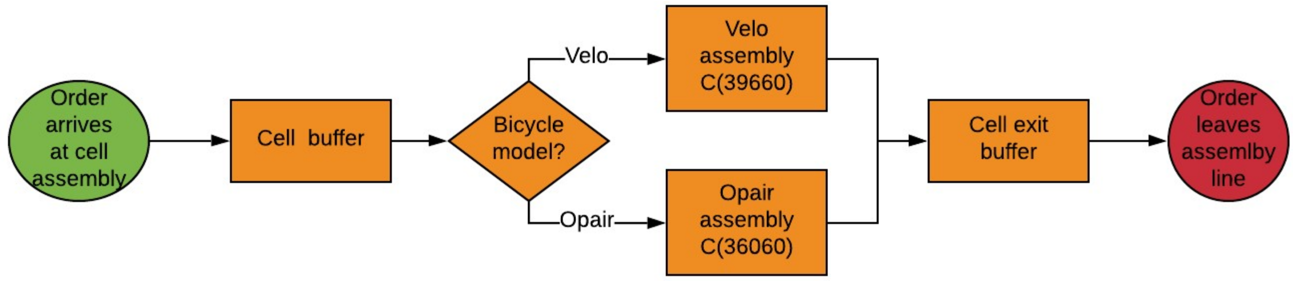



*Figure 21: Cell assembly*

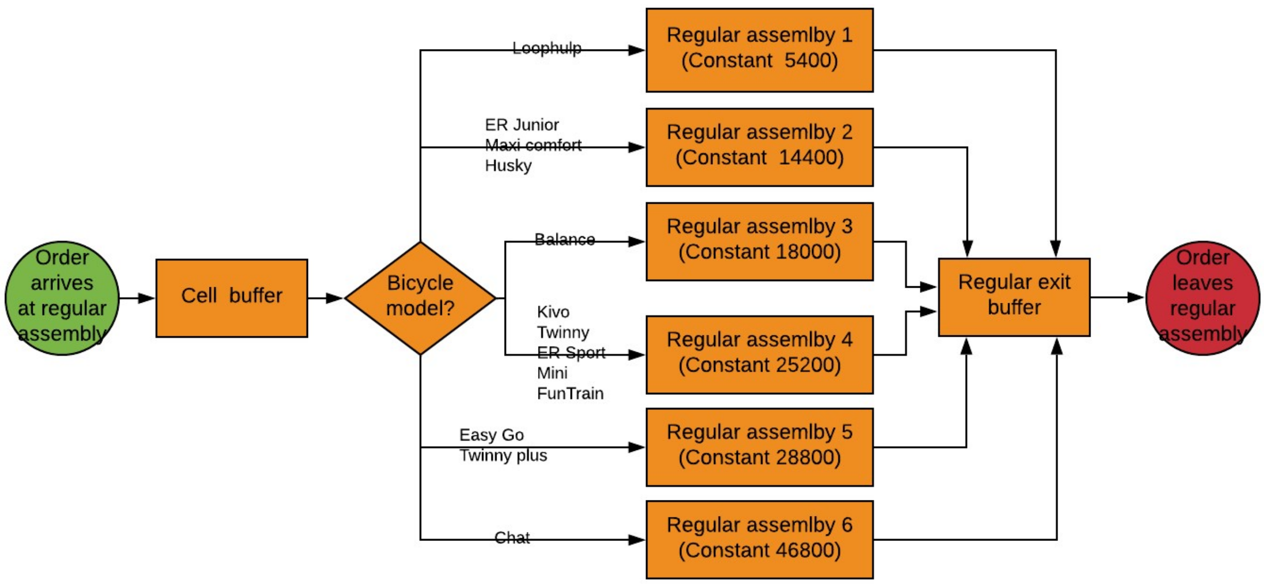



*Figure 22: Regular assembly*

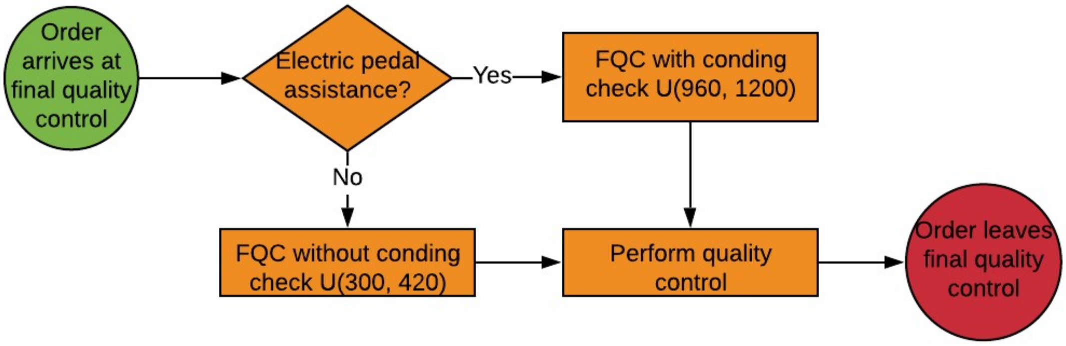



*Figure 23: Process at final quality control*

## Appendix K

**Calculation of throughput times**
To create the simulation the throughput time of the different steps within the process was required. The main sources for this data were the ERP system, the company that designed the process, and the employees working in the process.

**Blasting stations**
On the ERP system, there was no information about the processing time of the blasting station. The throughput time of the blasting station was based on conversations with the employees working at the station. The chamber has two programs, in the first program is used for thin parts. The intensity of the blasting is lower in the first program and it only takes 5 minutes. Parts that are processed using the first program are for example the plates from which the name of the bicycle is cut out. For the second program the blasting chamber functions at full power, the treatment is more intensive and the parts stay in the chamber, the program takes 17 minutes. Almost all batches receive the second treatment and since we apply aggregation of parts we will simulate that all operations at the blasting chamber have a deterministic processing time of 17 minutes.

**Paint shop**
Within the ERP system, there was information available about the time orders spend within the paint shop. The moment at which an order enters and leaves the station is recorded. As can be read in the process description order go through multiple steps after entering the paint shop. In discussion with the company supervisor we however decided to consider the paint shop as one process, the data was also considered valid but we did clean the data from outliers using the 1,5 x IQR rule. At the lower end, this meant we had to delete 322 data points and at the upper end we had to delete 2139 data points, this left us with 19810 data points. From the dataset, we could calculate that the mean throughput time of the paint shop process was 13 hours and 35 minutes. Using SPSS figure 24 and tables 15 and 16 were created. Based on the analysis it is assumed that the paint shop is normally distributed with 13:34:27 as mean, 3:01:21 as standard deviation, 8:09:57 as a lower bound, and 20:43:30 as an upper bound.

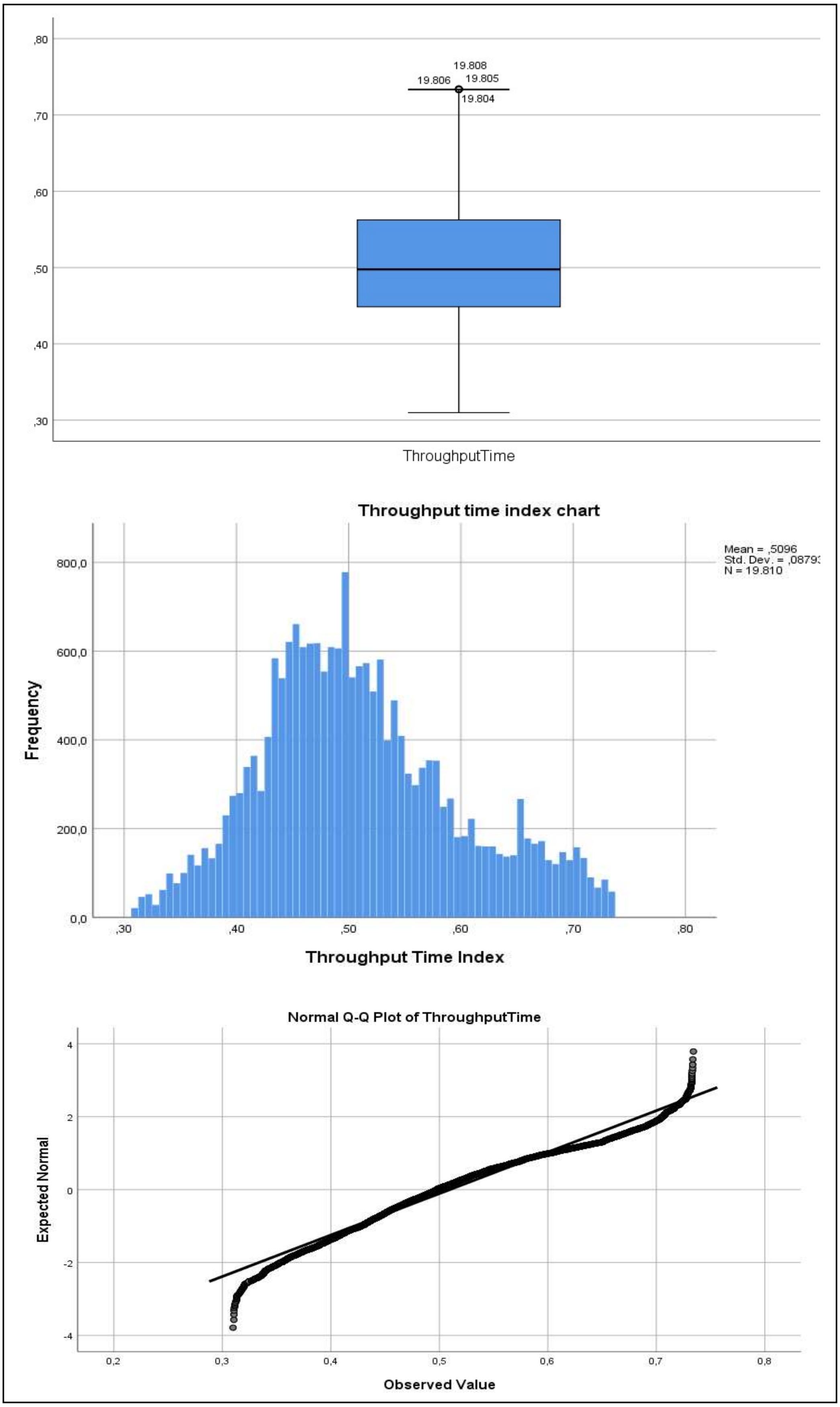



*Figure 24: SPSS output*

**Descriptives**

| | | | Statistic | Std. Error |
|---|---|---|---|---|
| ThroughputTime | Mean | | ,5096 | ,00062 |
| | 95% Confidence Interval for Mean | Lower Bound | ,5084 | |
| | | Upper Bound | ,5108 | |
| | 5% Trimmed Mean | | ,5075 | |
| | Median | | ,4977 | |
| | Variance | | ,008 | |
| | Std. Deviation | | ,08793 | |
| | Minimum | | ,31 | |
| | Maximum | | ,73 | |
| | Range | | ,42 | |
| | Interquartile Range | | ,11 | |
| | Skewness | | ,458 | ,017 |
| | Kurtosis | | -,215 | ,035 |

*Table 15: Descriptives SPSS*

**Percentiles**

| | | Percentiles | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 5 | 10 | 25 | 50 | 75 | 90 | 95 |
| Weighted Average (Definition 1) | ThroughputTime | ,3791 | ,4062 | ,4485 | ,4977 | ,5625 | ,6462 | ,6812 |
| Tukey's Hinges | ThroughputTime | | | ,4485 | ,4977 | ,5625 | | |

*Table 16: Percentiles SPSS*

**Line assembly**

We first established throughput times for the lines of the assembly department based on the designed throughput time. As can be found in table 14 in appendix I the throughput times for the Fun 2 Go line, Easy Rider 3 line, and Midi Maxi line are 45 minutes, 30 minutes, and 30 minutes per station respectively. The number of stations per line can also be found in table 14. Using this input the output of the simulation was however way too high. We, therefore, decided to calculate the throughput times of the different lines based on the required output. These values were later validated with the company supervisor. This resulted in a deterministic processing time of 66 minutes per station for the F2G line, a throughput time of 38 minutes per station for the ER3 line, and a throughput time of 110 minutes per station for the MiMa line. Especially the MiMa line has a higher throughput time than the designed capacity, this is likely caused by the fact that the demand was lower than expected while designing the line. The last orders for the Easy Rider 2 were also assembled in the MiMa line which also has its influence on the throughput time.

**Cell assembly**
On the production floor, there are 7 cells for assembly, these cells produce the Velo and Opair models. For the throughput times of these cells, we used the historical data and calculate the average throughput time necessary to meet the required output. The result of this was again higher than the designed throughput time which can be found in appendix I in table 14. The average deterministic processing time for the cell assembly was calculated to be 632 minutes which is 10 hours and 32 minutes. Since there was no data on the separate production times of the bicycles we decided to maintain the hour difference in the production time as designed which meant the Opair is assembled in 10 hours and 2 minutes and the Velo is assembled in 11 hours and 2 minutes. The cell is expected to have a higher output in the simulation than the model since production in the cell was only started halfway through 2020. For the simulation, we calculated what the cell would have produced if it was productive all year long.

**Regular assembly**
As described in the process description in *section 2.1* the regular assembly consists of three steps: the modular assembly, the pre-assembly, and the final assembly. Within the ERP system, there was however no data available on how much time the 14 different models spent at each of the three steps. We, therefore, decided to see the three steps as one and calculate how many stations would be necessary to meet demand. The weighted average processing time based on the designed throughput time is 6,87 production hours, the required yearly demand is 2777 bicycles, and in the simulation there are 52 weeks with 38,75 working hours per week per station. This resulted in equitation 5.

$$\frac{(2777 \ \times 6{,}87)}{52 \ \times 38{,}75} = 9{,}47$$

*Equation 5: Calculation of regular working stations*

From the equation, we learn that the amount of working stations required to meet weekly demand is 9,47. Since it is however impossible to create a 0,47 working station we will create 10 working stations to be able to meet demand. The time required to assemble the order that arrives at these stations is based on the designed deterministic processing time since there is no better data available.

**Final quality control**
Within the ERP system, there was no information about the throughput time of the final quality control. The data on when the process started is not saved in the ERP system, only the moment at which the bicycle passed the quality control. The processing time of this department was based on conversations with the employees. For non-electric bicycles, the final quality control took 5 to 7 minutes. Because there was no other data we fitted a uniform distribution to this. From the ERP system, it could be determined that 17% of the bicycles are non-electric, the other 83% are fitted with electric pedal assistance. The software of these bicycles has to be checked which takes 15 minutes, after the software is checked some last tests are done which take another 1 to 5 minutes. It was therefore decided to simulate the final quality control with two uniform distributions. The processing time of the non-electric bicycles has a stochastic uniform distribution of 5 to 7 minutes and the electric bicycles have a stochastic uniform processing time of 16 to 20 minutes.

## Appendix L

**Validation of current monitoring and control method**
For validation, the monitoring and control method as described in the interview with the employee responsible for the flow of the products was used. This is called the base model. The interview where the current monitoring and control method is explained can be found in *section 2.4*. The orders are released from the backorder once per day and the stock of the assembly department is kept at 3 production days. Using the base model the values visible in table 17 were obtained.

| | Throughput time | Average orders in the system (weekly) | Total output | Average weekly output |
|---|---|---|---|---|
| Mean | 6:09:36:26 | 297,27 | 58872 | 210,5 |
| Standard deviation | 08:44 | 0,5223 | 48,7635 | 0,1735 |
| 95% confidence interval | (6:09:32:20; 6:09:40:30) | (297,02; 297,51) | (58849; 58895) | (210,4; 210,6) |

*Table 17: Base model KPIs*

This method resulted in a throughput time of 6 days, 9 hours, and 35 minutes, an average of 297 orders in the system, and a total output of 58884 units. In this configuration, the average weekly output was 210,5 orders. These values have all been validated in *section 5.5*. Besides these KPI's we also kept track of the weekly output per assembly station, these outputs can be found in appendix L. In table 18 the weekly output values of the base model are displayed per assembly type.

| | Weekly output F2G (orders) | Weekly output ER3 (orders) | Weekly output MiMa (orders) | Weekly output Cell (orders) | Weekly output Regular (orders) |
|---|---|---|---|---|---|
| Mean | 36,77 | 64,35 | 21,86 | 25,70 | 61,83 |
| Standard deviation | 0,0018 | 0,0015 | 0,0018 | 0,0133 | 0,1729 |
| 95% confidence interval | (36,77; 36,77) | (64,35; 64,35) | (21,85; 21,86) | (25,69; 25,71) | (61,75; 61,91) |

*Table 18:Base model weekly output per assembly type*

**ConWIP**

In table 19 the weekly output values of the ConWIP model are displayed per assembly type.

| | Weekly output F2G (orders) | Weekly output ER3 (orders) | Weekly output MiMa (orders) | Weekly output Cell (orders) | Weekly output Regular (orders) |
|---|---|---|---|---|---|
| Mean | 36,77 | 64,35 | 21,85 | 25,71 | 61,78 |
| Standard deviation | 0,0023 | 0,0034 | 0,0017 | 0,0171 | 0,1596 |
| 95% confidence interval | (36,77; 36,78) | (64,34; 64,36) | (21,85; 21,86) | (25,69; 25,75) | (61,66; 61,89) |

*Table 19: ConWIP model weekly output per assembly type*

To determine the number of ConWIP cards per assembly type we performed OFAT experiments. In these experiments, all but one variable were kept constant which allowed us to determine the lowest number of cards for which the output would be similar to the base model. The results of these experiments can be found in tables 20 to 24. The result of these experiments was a set-up of the ConWIP system with 29 cards for the F2G assembly, 46 cards for the ER3 assembly, 18 cards for the MiMa assembly, 22 cards for the cell assembly, and 48 cards for the regular assembly.

| **ConWIP ER3 Cards** | **Weekly output ER3 (Orders)** | **Total output** | **Total weekly output** |
|---|---|---|---|
| 47 | 64,35 | 58884 | 210,6 |
| 46 | 64,35 | 58861 | 210,5 |
| 45 | 64,34 | 58865 | 210,5 |
| 44 | 64,26 | 58849 | 210,4 |
| 43 | 63,95 | 58762 | 210,1 |

*Table 20: Experiments for ConWIP cards ER3*

| **ConWIP Regular Cards** | **Weekly output Regular (Orders)** | **Total output** | **Total weekly output** |
|---|---|---|---|
| 49 | 61,80 | 58874 | 210,5 |
| 48 | 61,83 | 58884 | 210,6 |
| 47 | 61,77 | 58867 | 210,5 |
| 46 | 61,61 | 58824 | 210,3 |
| 45 | 61,44 | 58775 | 210,2 |

*Table 21: Experiments for ConWIP cards Regular*

| ConWIP F2G Cards | Weekly output F2G (Orders) | Total output | Total weekly output |
|---|---|---|---|
| 31 | 36,77 | 58869 | 210,5 |
| 30 | 36,77 | 58861 | 210,5 |
| 29 | 36,77 | 58869 | 210,5 |
| 28 | 36,75 | 58872 | 210,5 |
| 27 | 36,56 | 58832 | 210,4 |

*Table 22: Experiments for ConWIP cards F2G*

| ConWIP Cell Cards | Weekly output Cell (Orders) | Total output | Total weekly output |
|---|---|---|---|
| 24 | 25,75 | 58869 | 210,5 |
| 23 | 25,75 | 58857 | 210,5 |
| 22 | 25,74 | 58869 | 210,5 |
| 21 | 25,72 | 58860 | 210,5 |
| 20 | 25,63 | 58837 | 210,4 |

*Table 23: Experiments for ConWIP cards Cell*

| ConWIP MiMa Cards | Weekly output MiMa (Orders) | Total output | Total weekly output |
|---|---|---|---|
| 20 | 21,85 | 58864 | 210,5 |
| 19 | 21,85 | 58860 | 210,5 |
| 18 | 21,85 | 58866 | 210,5 |
| 17 | 21,75 | 58816 | 210,3 |

*Table 24: Experiments for ConWIP cards MiMa*

**Bottleneck control**

Of the three remaining processes (blasting station, paint shop, and assembly) one has to be set as the bottleneck. To uncover which station is the true bottleneck we will establish the number of cards for all three stations and test their separate performance. First, we will set the assembly as our bottleneck the KPIs of this configuration can be found in table 25 and 26. Tables 27 to 31 display the tests that were performed to find the correct number of bottleneck cards. The result of the test is 29 cards for the F2G line, 46 cards for the ER3 line, 18 cards for the MiMa line, 21 cards for the cell assembly, and 48 cards for the regular assembly

| | Throughput time | Average orders in the system | Total output | Average weekly output |
|---|---|---|---|---|
| Mean | 3:23:34:52 | 175,85 | 58.866 | 210,5 |
| Standard deviation | 06:14 | 0,4875 | 44,9376 | 0,1644 |
| 95% confidence interval | (3:23:30:24; 3:23:39:20) | 173,99; 174,69) | (58833; 58898) | (210,4; 210,6) |

*Table 25: KPIs of Bottleneck control with the assembly as the bottleneck*

| | Weekly output F2G (orders) | Weekly output ER3 (orders) | Weekly output MiMa (orders) | Weekly output Cell (orders) | Weekly output Regular (orders) |
|---|---|---|---|---|---|
| Mean | 36,77 | 64,35 | 21,85 | 25,73 | 61,78 |
| Standard deviation | 0,0036 | 0,0017 | 0,0019 | 0,0101 | 0,1605 |
| 95% confidence interval | (36,77; 36,77) | (64,35; 64,35) | (21,85; 21,85) | (25,72; 25,74) | (61,66; 61,89) |

*Table 26: Weekly KPIs of bottleneck control with assembly as the bottleneck*

| Bottleneck Regular Cards | Weekly output Regular (Orders) | Total output |
|---|---|---|
| 54 | 61,75 | 58862 |
| 53 | 61,76 | 58865 |
| 52 | 61,78 | 58872 |
| 51 | 61,76 | 58865 |
| 50 | 61,73 | 58855 |
| 49 | 61,84 | 58886 |
| 48 | 61,75 | 58862 |
| 47 | 61,66 | 58835 |
| 44 | 61,18 | 58700 |

*Table 27: Bottleneck cards regular with assembly as the bottleneck*

| Bottleneck ER3 Cards | Weekly output ER3 (Orders) | Total output |
|---|---|---|
| 48 | 64,35 | 58886 |
| 47 | 64,35 | 58875 |
| 46 | 64,35 | 58864 |
| 45 | 64,34 | 58858 |
| 44 | 64,27 | 58857 |
| 43 | 63,97 | 58750 |

*Table 28: Bottleneck cards ER3 with assembly as the bottleneck*

| Bottleneck F2G Cards | Weekly output F2G (Orders) | Total output |
|---|---|---|
| 31 | 36,77 | 58855 |
| 30 | 36,77 | 58864 |
| 29 | 36,77 | 58862 |
| 28 | 36,75 | 58859 |
| 27 | 36,55 | 58804 |
| 26 | 35,96 | 58646 |
| 25 | 35,07 | 58385 |

*Table 29: Bottleneck cards F2G with assembly as the bottleneck*

| Bottleneck cell Cards | Weekly output Cell (Orders) | Total output |
|---|---|---|
| 25 | 25,74 | 58878 |
| 24 | 25,75 | 58862 |
| 23 | 25,74 | 58871 |
| 22 | 25,74 | 58879 |
| 21 | 25,73 | 58858 |
| 20 | 25,64 | 58843 |

*Table 30: Bottleneck cards cell with assembly as the bottleneck*

| Bottleneck MiMa Cards | Weekly output MiMa (Orders) | Total output |
|---|---|---|
| 22 | 21,85 | 58867 |
| 21 | 21,85 | 58877 |
| 20 | 21,85 | 58871 |
| 19 | 21,85 | 58869 |
| 18 | 21,85 | 58851 |
| 17 | 21,75 | 58843 |

*Table 31: Bottleneck cards MiMa with assembly as the bottleneck*

As a second potential bottleneck, we will consider the paint shop as the bottleneck of the process. The result of the test is 12 cards for the F2G line, 22 cards for the ER3 line, 6 cards for the MiMa line, 8 cards for the cell assembly, and 23 cards for the regular assembly. The number of cards necessary to achieve an output similar to the base model led to unreasonably high WIP and waiting time as can be seen in tables 32 and 33. The tests are displayed in tables 34 to 38.

| | Throughput time | Average orders in the system | Total output | Average weekly output |
|---|---|---|---|---|
| Mean | 44:00:15 | 4491,19449973211 | 58.844 | 210,4 |
| Standard deviation | 21:32 | 91,2212 | 51,2145812586892 | 0,1869 |
| 95% confidence interval | (43:08:50:05; 44:15:40:52) | 4425,88; 4556,50) | (58808; 58881) | (210,3; 210,5) |

*Table 32: KPIs of Bottleneck control with the paint shop as the bottleneck*

| | Weekly output F2G (orders) | Weekly output ER3 (orders) | Weekly output MiMa (orders) | Weekly output Cell (orders) | Weekly output Regular (orders) |
|---|---|---|---|---|---|
| Mean | 36,77 | 64,35 | 21,85 | 25,70 | 61,73 |
| Standard deviation | 0,0019 | 0,0041 | 0,0089 | 0,0232 | 0,1852 |
| 95% confidence interval | (36,77; 36,77) | (64,35; 64,35) | (21,85; 21,86) | (25,69; 25,72) | (61,60; 61,86) |

*Table 33: Weekly KPIs of bottleneck control with paint shop as the bottleneck*

| **Bottleneck Regular Cards** | **Weekly output Regular (Orders)** | **Total output** | **Orders in the system** |
|---|---|---|---|
| 23 | 61,73 | 58844 | 4491 |
| 22 | 61,71 | 58838 | 3756 |
| 21 | 61,72 | 58840 | 3000 |
| 20 | 61,67 | 58827 | 2259 |
| 19 | 59,25 | 58150 | 2167 |

*Table 34: Bottleneck cards Regular with paint shop as the bottleneck*

| **Bottleneck ER3 Cards** | **Weekly output ER3 (Orders)** | **Total output** | **Orders in the system** |
|---|---|---|---|
| 22 | 64,35 | 58851 | 5245 |
| 21 | 64,35 | 58844 | 4491 |
| 20 | 62,20 | 58255 | 4305 |
| 19 | 59,49 | 57515 | 4276 |

*Table 35: Bottleneck cards ER3 with paint shop as the bottleneck*

| **Bottleneck F2G Cards** | **Weekly output F2G (Orders)** | **Total output** | **Orders in the system** |
|---|---|---|---|
| 12 | 36,77 | 58865 | 5114 |
| 11 | 36,77 | 58844 | 4491 |
| 10 | 35,83 | 58578 | 4163 |
| 9 | 33,57 | 57964 | 4135 |

Table 36: Bottleneck cards F2G with paint shop as the bottleneck

| Bottleneck Cell Cards | Weekly output Cell (Orders) | Total output | Orders in the system |
|---|---|---|---|
| 8 | 25,70 | 58844 | 4491 |
| 7 | 24,96 | 58647 | 3102 |
| 6 | 22,23 | 57902 | 3070 |

Table 37: Bottleneck cards Cell with paint shop as the bottleneck

| Bottleneck MiMa Cards | Weekly output MiMa (Orders) | Total output | Orders in the system |
|---|---|---|---|
| 6 | 21,85 | 58844 | 4491 |
| 5 | 20,40 | 58468 | 4355 |
| 4 | 19,00 | 58054 | 4371 |

Table 38: Bottleneck cards MiMa with paint shop as the bottleneck

As can be seen in the tables the number of cards required to maintain similar weekly and total output leads to an unreasonable high number of orders in the process. The paint shop, therefore, does not appear to be the bottleneck of the process.

Based on these results it was decided not to run similar tests for the blasting station. In the base model, the utilization of the paint shop was already higher than the utilization of the blasting station which indicates it is even less suitable as a bottleneck. We will therefore not conduct further experiments to test if the blasting station is the bottleneck.

# Appendix M

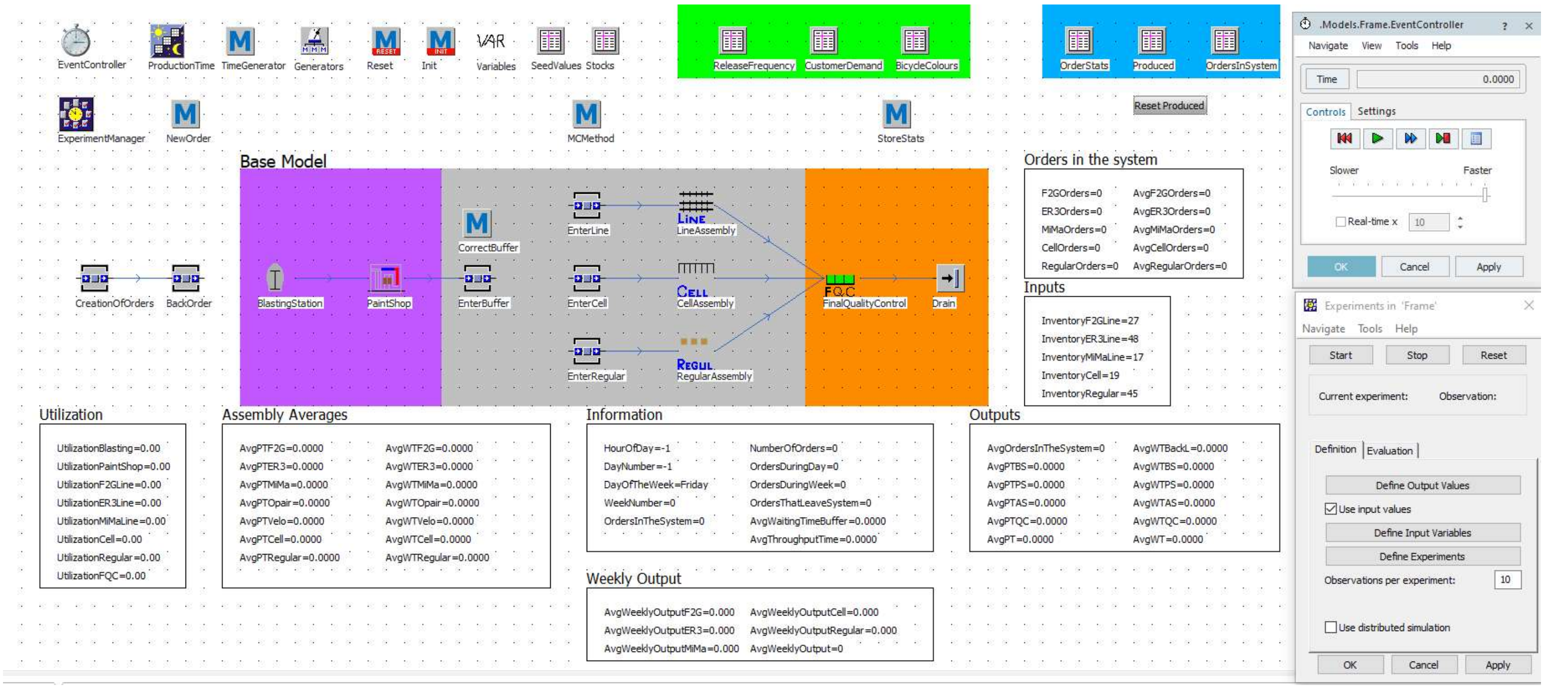



*Figure 25: Screenshot of simulation mode Plant Simulation*

## Appendix N

Confidential

[redacted]