Optimizing the dispatch schedule of Product Y

Bachelor Thesis

Industrial Engineering and Management

Pedersen, J.E. (Jesper. Student B-IEM)

Supervisor 1: Dr Daniela Guericke (University of Twente)
Supervisor 2: Dr Derya Demirtas (University of Twente)
Supervisor 3: Erik Keppels (Company X)

Preface

Dear reader,

This bachelor's thesis is the final part of the Bachelor of Industrial Engineering and Management programme at the University of Twente. This study was conducted for an anonymous Dutch mechanisation business. The study "Optimising the dispatch schedule of Product Y" aids the business in integrating the product into the supply chain.

I would like to take this opportunity to thank the university staff and the company for their assistance with my research and thesis writing. My first supervisor, Daniela Guericke, deserves special recognition for helping me through this procedure. It was enjoyable working with you, and I sincerely hope that this won't be the last time. Erik Keppels, who is my company's supervisor, deserves a special mention as well. You assisted me in providing an overview of the business and the product. He helped me navigate the company and was always available to answer queries. I learned a lot from the wonderful experience.

Enjoy Reading,

Kind regards,

Jesper Pedersen

Enschede, September 2023

Management Summary

Introduction

Company X is a family-owned mechanisation company that produces metal processing machines and complete machine lines. It consists of two divisions. Company X Machinery's first division manufactures Computer Numerical Control (CNC) machines for steel fabrication. Currently, the company produces 20 machines. The other division, Company X Construction, specialises in the design, production, and supply of steel projects, acting as a subcontractor that delivers steel to a project.

In September 2022, Company X presented a new sorting machine called Product Y. Company X desires to change material storage's disadvantages into a central plate handling advantage with digital inventory management. Where previously plates destinated for a beam were sorted manually, now Product Y can identify, store, and dispatch the plates in designated bins for a specific beam. The company recognises that there are problems with implementing Product Y in the supply chain and wants to improve the flow of products towards the workplace. To improve this workflow, a distribution method should be created.

Approach

In order to create a good distribution, the method Managerial Problem Solving Method (MPSM) guidelines were used. This methodological approach uses seven sequential phases to help solve the problem. These phases were followed through this research to find a solution to the company's problem. After first understanding the business and the current situation, it was time to find a possible solution via literature studies. There are three priority rules for the beam distribution over workplaces and three priority rules for bin distribution of product Y from this literature study. This means there are nine different combinations of rules to be tested (Table below)

Beam priority rules	**Objective**
Shortest Processing Time (SPT)	Distribute increasingly on the processing time of beams.
Longest Processing Time (LPT)	Distribute decreasingly on the processing time of beams.
Service in Random Order (SIRO)	Random distribution over welders.
Plate priority rules	**Objective**
Shortest Processing Time (SPT)	Distribute increasingly on the processing time of plates.
Earliest Due Date (EDD)	Sort on increasing the due date for bins.
Shortest Setup Time (SST)	Sort on increasing setup time for bins.

Simulation

Data provided by Company X was prepared into experiments and set in the suitable template. The nine experiments were evaluated in a simulation model created in Tecnomatix Plant Simulation. From here, the most surprising experiment was set for a sensitivity analysis. A dispatching order from excel is imported directly into the simulation to evaluate the rule combinations.

Results

The performance evaluation of the nine experiments gives results to be investigated. The three beam methods were first performed following the three plate rules on the beam order. In the evaluations, the distribution starting time was set at 06:00 AM with 50 bins in circulation.

Beam priority rule:	Current situation	SPT	SPT	SPT	LPT	LPT	LPT	Random	Random	Random
Plate priority rule:	Current situation	SPT	EDD	SST	SPT	EDD	SST	SPT	EDD	SST
AvgWaitingTime:	1:26:56.3	7:49.9	7:18.9	9:10.2	44:38.1	45:50.7	10:17.0	08:27	03:43.8	09:11.8
TotalProcessTime:	18:25:19.6	15:56:53.2	15:18:22.8	15:59:19.2	14:55:51.3	10:52:42.5	15:59:19.2	15:53:21.6	13:03:37.2	15:49:39.8
TotalWorkingTime	09:55:19.6	14:26:53.2	13:48:22.8	14:29:19.2	13:25:51.3	9:22:42.5	14:29:19.2	14:23:21.6	11:33:37.2	14:19:39.8
Welder Working%	67.5	58.3	58.2	58.2	58.3	73.3	58.2	58.3	62.7	58.2
Welder Walking%	0.6	0.6	0.6	0.6	0.6	0.7	0.6	0.6	0.6	0.6
Welder Waiting%	31.9	41.1	41.2	41.2	41.1	25.9	41.2	41.1	36.7	41.2

The most exciting outcome from these results was the LPT/EDD combinations, where the total working time resulted in only 9 hours and 22 minutes. So, after the execution of the nine experiments, the sensitivity analysis was performed on the LPT/EDD combination. Here the starting hour was changed to 05:00 AM and 07:00 AM. Also, the bin numbers were changed to 25, 30, 35, 40, 45, 50, 75 and 100.

starting hour: 05:00								
Number of bins	25	30	35	40	45	50	75	100
AvgWaitingTime:	0:50.1	8:42.7	18:34.1	28:53.0	39:41.5	49:47.8	1:32:21.5	1:59:24.8
TotalProcessTime:	11:38:15.4	11:20:41.7	11:13:51.9	11:07:45.4	11:06:55.9	11:06:55.9	11:06:55.9	11:06:55.9
TotalWorkingTime	9:08:15.4	8:50:41.7	8:43:51.9	8:37:45.4	8:36:55.9	8:36:55.9	8:36:55.9	8:36:55.9
Welder Working%	75.3	77.8	78.8	79.7	79.8	79.8	79.8	79.8
Welder Walking%	0.7	0.8	0.8	0.8	0.7	0.7	0.7	0.7
Welder Waiting%	24.0	21.5	20.4	19.5	19.3	19.3	19.3	19.3

starting hour: 06:00								
Number of Bins	25	30	35	40	45	50	75	100
AvgWaitingTime:	0:50.7	7:59.7	16:30.6	26:46.9	36:26.7	45:50.7	1:25:33.8	1:49:48.9
TotalProcessTime:	11:20:22.5	11:05:14.4	10:59:40.7	10:52:42.5	10:52:42.5	10:52:42.5	10:52:42.5	10:52:42.5
TotalWorkingTime	9:50:22.5	9:35:14.5	9:29:40.7	9:22:42.5	9:22:42.5	9:22:42.5	9:22:42.5	9:22:42.5
Welder Working%	69.9	71.7	72.4	73.3	73.3	73.3	73.3	73.3
Welder Walking%	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Welder Waiting%	29.4	27.5	26.8	25.9	25.9	25.9	25.9	25.9

starting hour: 07:00								
Number of bins	25	30	35	40	45	50	75	100
AvgWaitingTime:	0:50.5	7:36.2	16:00.0	26:28.4	35:52.1	44:58.5	1:22:29.5	1:22:29.5
TotalProcessTime:	11:12:14.4	10:58:41.1	10:51:44.5	10:46:43.6	10:46:43.6	10:46:43.6	10:46:43.6	10:46:43.6
TotalWorkingTime	10:42:14.4	10:28:41.1	10:21:44.5	10:16:43.6	10:16:43.6	10:16:43.6	10:16:43.6	10:16:43.6
Welder Working%	64.3	65.6	66.4	66.9	66.9	66.9	66.9	66.9
Welder Walking%	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Welder Waiting%	35.1	33.7	33,0	32.4	32.4	32.4	32.4	32.4

These results can be seen in the table above. Remarkable is that change in the number of bins can decrease the waiting time with more time and increases the total working time.

Recommendations

The company wants to sell Product Y globally, aiming to improve the efficiency and accuracy of plate sorting in welding. By implementing Product Y, the company can track the location of each plate and prevent missing plates, leading to increased efficiency for welders. However, after storage, there is still a need for a dispatch schedule to utilise the machine effectively. To address this, the recommendation is to invest in a beam ordering system, which would provide valuable information for planners on how to use the machine effectively. With a detailed schedule based on the time required for welders to work on a beam and tack weld a specific plate, Product Y would greatly benefit.

Contents

List of Figures

List of tables

1. Introduction

The first chapter introduces the research company and briefly describes the problem in section 1.1 In section 1.2, the research objective and methodology.

1.1. Company & Problem

1.1.1. Company X

Company X is a family-owned business established in 1970 as a mechanisation company, producing metal processing machines and complete machine lines. In 1976, the Company expanded its services to include the design and construction of steel structures, leading to a decision in 1980 to split the Company into two separate entities: a construction company and a machinery company.

Company X Machinery focuses on manufacturing Computer Numerical Control (CNC) machines for steel fabrication. These machines are controlled by computer programs, which direct the movements and patterns applied to the processed material. The company currently produces 20 machines, categorised into four processing types: beam, plate, pipe, angle processing, and surface treatment. Additionally, the company offers a complete process creating the possibility for a completely automated production process by connecting all standalone machines (Figure 1).

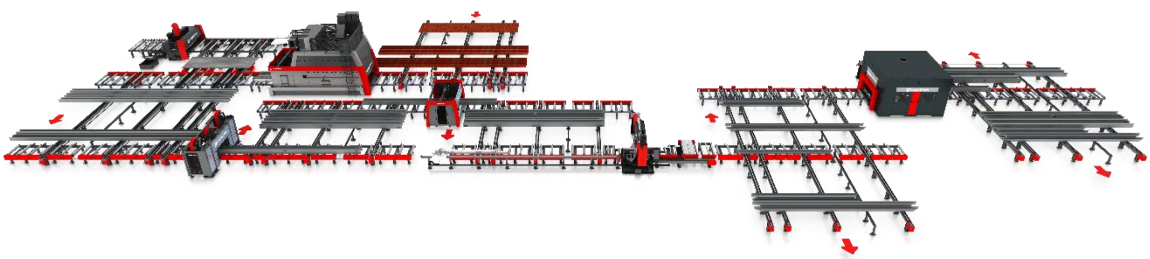

Figure 1 Example of a complete process

The other division, Company X Construction, specialises in the design, production and supply of steel projects, acting as a subcontractor that delivers steel to a project. One significant advantage is that they can utilise and test the machines developed by Company X Machinery, enabling data collection and machine improvement.

1.1.2. Management Problem

Beams are distributed over all workplaces at the beginning of the day. The specifications of beams will differ for every project. This means that every beam will require different sets of plates to be attached. A combination of specific plates and beams is called an assembly. For every assembly, at least one bin is required for the plates to be transferred from Product Y to the workplace. It is impossible to combine different assemblies for the instance that only a few plates need to be attached to the beam.

In September 2022, Company X presented a new sorting machine called Product Y. Company X desires to change material storage's disadvantages into a central plate handling advantage with digital inventory management. Previously, the plates would arrive from a plasma cutter in the production hall. Here all the plates arrive and are stored together. In the next step all these plates are manually sorted into bins (Figure 2). Once a bin is filled with the required plates, they are stored in a designated area. When required, the bins are brought to the workplace. All the plates are tack-welded to the beams at these workplaces.

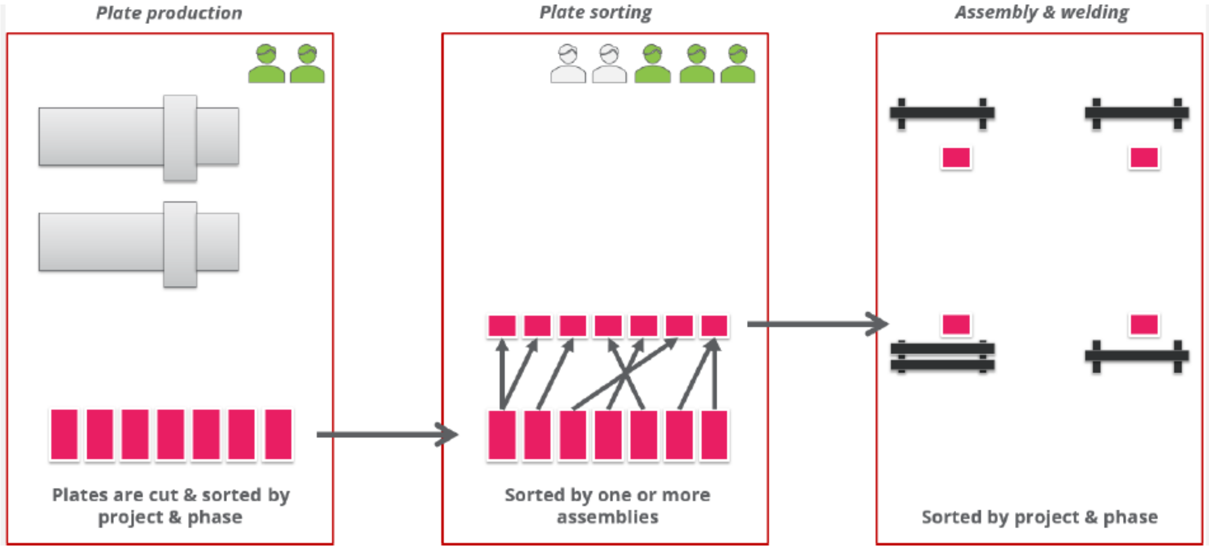

Figure 2 Current manual sorting situation

Company X Machinery is developing Product Y (Figure 3). The machine is still a prototype, so there is room for improvement in different aspects. Company X has a production hall close to the machinery office. Here Product Y is stationed and used for testing new software and collecting data on different parts. The Company recognises that there are problems with implementing Product Y in the supply chain and wants to improve the flow of products towards the workplace.

Figure 3 Render of Product Y

Company X wants to focus on the next steps of the process. Testing different dispatching schedules for Product Y is one part of that. There is no method for determining a dispatch schedule. Since the distribution time of a plate keeps improving with software updates, it is essential to keep updating the dispatching schedule for efficient usage of the machine.

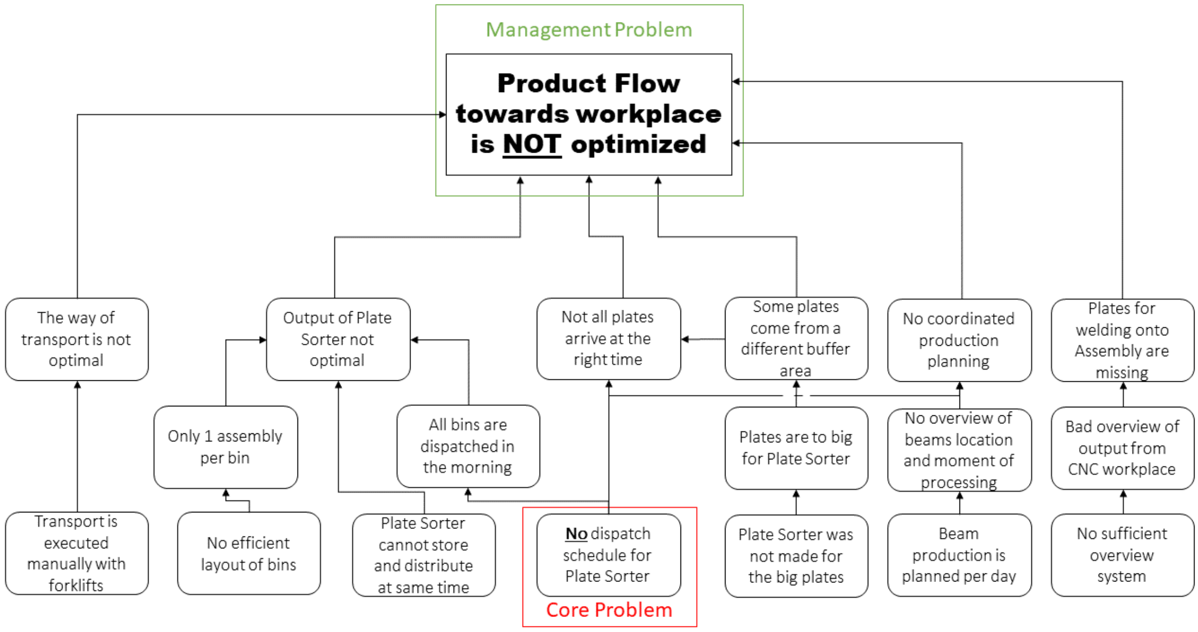

Figure 4 Problem cluster

In Figure 4, an overview of the management problem in the problem cluster can be seen. The management problem of Company X can be set into one general problem but originates from several smaller problems. Some of these problems are not influenced by Product Y such as the inefficient transport of bins, the daily production planning, or the overviews system. multiple problems also occurred with the implementation of Product Y. To conclude this cluster, it can be said that the product flow towards the workplace is not efficient. From here, the management problem can be formulated:

Management Problem: *The product flow from Product Y towards the beam workplace is not optimised.*

1.1.3. Problem Identification

As mentioned before, the problem with the distribution of Product Y is that Company X has not been working on a dispatch schedule. This means there is no knowledge of the order of bin dispatching or when the machine should start.

Product Y should distribute bins filled with plates for the concerning beams at the right moment. To minimise the downtime of the welders, the filled bins should always be present at the beam when required. On the other hand, it should not be dispatched too early because more bins are required in circulation, and a larger storage area is needed as a buffer for filled bins.

All the beams need to be finished at the end of the day. There is no planning per specific beam where it should be placed and when it should be welded. If the bins can be dispatched at the right time and the beams can be planned on a beam-specific level, then a more efficient product flow can be coordinated. This can result in more control and better usage of Product Y.

To summarise the previous points into a central problem, it has been stated below:

Core problem: *There is no dispatch planning for Product Y.*

1.1.4. The gap between Norm and Reality

In the book Solving Managerial Problems Systematically (Heerkens & van Winden, 2017), the discrepancy between the norm and reality should be stated to clarify the core problem. Once a core problem is acquired from a cluster, there needs to be a variable in which the problem can be measured. A variable will not always be quantifiable, so this requires operationalisation. Here a measurable variable will be connected to the core problem. From this point, a norm and reality should be defined.

In the case of Company X, it is about the dispatch planning of the machine. No planning or heuristic exists to determine how the bins should be dispatched. This means that all the bins should be filled before the works begin. This will result in a significant number of bins in circulation and a large buffer area to store all these bins. This means there is a long time between the moment of dispatching and the moment of usage. The time between these moment reaches the largest possible since without a dispatch schedule all the bins are dispatched before the day starts. The beams processed at the beginning of the day will have a shorter waiting time, but the beams at the end will have a very long time. So, the reality can be seen as the maximum time in the current situation. The norm, which is the time between dispatching and usage is set to be half an hour before the requirement.

1.2. Research Question & Problem-Solving Approach

1.2.1. Research Question

The main research question can be derived from the core problem. As mentioned earlier, with the implementation of Product Y into the logistical process, the company is facing problems with the dispatching of plates, resulting in an inefficient process. The dispatch schedule requires input from the beams' schedule to work. Without this schedule, it is not known when which bin is required. To make a daily schedule for the beams, the process times of each beam is needed. With this schedule, it is possible to generate a distribution order for Product Y. From this point, one can calculate the influence of the proposed dispatch planning on the logistical process. The following research question can be derived:

Research Question: *"How can Product Y improve the product flow towards the workplace?"*

1.2.2. Problem-Solving Approach

The Managerial Problem Solving Method (MPSM) guidelines are used in this research. This is a methodological approach based on seven sequential phases (Heerkens & van Winden, 2017):

1. Defining the problem
2. Formulating the approach
3. Analysing the problem
4. Formulating (alternative) solutions
5. Choosing a solution
6. Implementing the solution
7. Evaluating the solution

These phases are visited throughout this report. Chapter 1 already defined the problem in section 1.1 and formulate an approach in section 1.2. The next phase will be executed in Chapter 2, where the problem is investigated. From this point, the solutions for the problem are formulated with a literature review in Chapter 3. To implement a solution, the setup for an experiment is required. This will be presented in Chapter 4. In Chapter 5, different solutions will be chosen and implemented. The solutions are evaluated in Chapter 6. Unfortunately, it is impossible to evaluate the solutions due to the length of the research.

1.2.3. Sub-questions

To divide the primary research question into smaller parts and make it easier to execute the research sub-questions are created. These will divide the thesis into smaller parts to understand it better in the parts and.

Sub-Question 1: How is the current beam production line organised?

- How does Company X plan its beam assembly?
- How are the plates sorted for assembly?
- How do the welders execute the daily production?

Sub-Question 2: What does the implementation of Product Y change to the beam assembly?

- How does Product Y work?
- What changes for the logistical process?
- How should the beam and plates be planned?
- Which Key Performance Indicators are important for Product Y?

Sub-question 3: How can Product Y be improved?

- What are the appropriate priority rules for the beam distribution?
- What are the appropriate priority rules for the bin distribution order?
- What is the best model to evaluate the combinations of priority rules?

Sub-Question 4: How can simulation help the distribution method of Product Y?

- Which data is required for the simulation?
- How do the beam and plate priority rules work?
- What kind of simulation is used?
- How does the simulation work?

Sub-Question 5: How do the applied priority rule combinations perform?

Sub-Question 6: What recommendations can be made on Product Y with the evaluation of the simulation?

- What are the limitations of the simulation?
- How can the model help different company desires?

1.2.4. Deployment of the method

At the end of the research, a tool will create a dispatch schedule for the working Product Y. A simulation will determine how the dispatch schedules perform. The KPIs will be a result and determine if a particular schedule is good. Every Company has a different beam scheduling method, so that the input will differ. Therefore, it is also essential that the end user knows how to use the parameter and makes a well-working schedule for Product Y.

1.2.5. Assumptions

For this research, some assumptions need to be made. The final tool will have some assumptions because of external factors. Every stationed machine will have different output and input from both sides of the logistical process.

In the current situation at Company X, it is known that the plates are directly coming from the cutting hall and with the assumption that no plates are lost. The company cannot always know where their plates will be coming from. Hence, there must be an assumption on the input of Product Y's plates that this is always on time and complete.

Secondly, there is an assumption to be made about the layout of the bins. With the software now used, it is only possible to fit one assembly in the bin regardless of the number of assigned plates. This could change in the future, but it will not be reviewed since it can change the output process.

2. Problem Analysis

This chapter will provide insights into the current situation and how Product Y works. Here the first two sub-questions will be answered. First; "How is the current beam production line organised?" will be answered in section 2.1. The second question: "What does the implementation of Product Y change to the beam assembly?" will be discussed in section 2.2.

2.1. Current Situation

Product Y was launched to the market in September. The construction division tests the integration of the product into the supply chain. If the machine would be integrated into the current supply chain, it can not deliver the same throughput levels as the situation without Product Y. This means that in the current situation Product Y is not used. To explain the current situation, a closer look into Figure 2 is required. The operation consists of three main elements. The Beams, plates, and the workplace. The beams and plates both come from a different origin. At the workplace they are welded together before the finished product can leave the production hall. In the following section, these three aspects will be explained in more detail for a better understanding of the whole operation.

2.1.1. Beams

Four phases of beams will be completed at the building site per day on average. Consider each phase as a truck loaded with beams and prepared for departure. This implies that as soon as the beams are completed, they will be put onto a truck and driven to their final location. Around 30 beams need to be processed on average during a phase. The beams have undergone several procedures to meet requirements before being set up on the job site. These processes include sawing, drilling, cutting, and painting. These processes will occur in the same production hall on the beamline. A beam is positioned alongside the others in a buffer area in the hall after it is prepared for welding.

2.1.2. Plates

The plates are delivered from another production facility. There, a large metal sheet is cut into multiple plates. After a batch is produced and given the unique specifications, they are moved to the production hall. First, all the plates are manually sorted into bins designated to specific bins. On an average day, Five fulltime-equivalents (FTE) work on 1050 plates. Once a bin is finished it is transferred to a storage area for filled bins. When required for welding, the bins are transported to the workplace where the beam is located. It is not always possible to arrange these plates in the proper order. The Company cannot build the plates in a way that will make them simple to sort since plate thickness varies. This implies that the manufacturing hall's buffer space will be significant.

2.1.3. Workplace

The beam and plates come together at the workplace. The day begins at 7:00 at Company X. The employees have 30 minutes to divide the beams over the 50 workplaces. These beams will be distributed at random because there is no beam-level planning. This implies that the location will be recognised when the employee starts on a specific beam.

50 Welders in pairs of two begin at 7:30, have two breaks of 30 minutes and work until 16:30 to complete the beams. The welder pairs have eight hours to complete the daily task. The production planner has created a timetable to ensure all work can be completed during this shift. These welders use a technique called tack welding to secure all the plates to the beams. Once a beam is finished, they start the next beam on the workplace. If all the beams on a workplace are done, they choose the next workplace randomly and start working there. This process goes on until all the beams are finished.

The second shift of welders begins at 16:30. These individuals will finish welding the plates to the beams. A beam will be moved from the workplace to the truck after it is done. The truck will start heading towards its ultimate destination once the phase is loaded.

2.2. Introduction of Product Y

The introduction of Product Y removes the manual sorting of the bins and the problem of missing plates, as seen in Figure 5. The machine has two input conveyor belts and one output belt. The first input conveyor belt is for the plates. All the plates can be laid down on the belt. At the entrance of the machine, there is a 3D scanner camera. This inspects the plates and checks if they match those known to enter. If the plates match one from the database, they may continue the conveyor belt towards the storage towers. A plate will be rejected and travel an alternative route on the conveyor belt if the 3D scanner cannot identify it. All the rejected plates will be placed in a bin that is located on the conveyor belt's side.

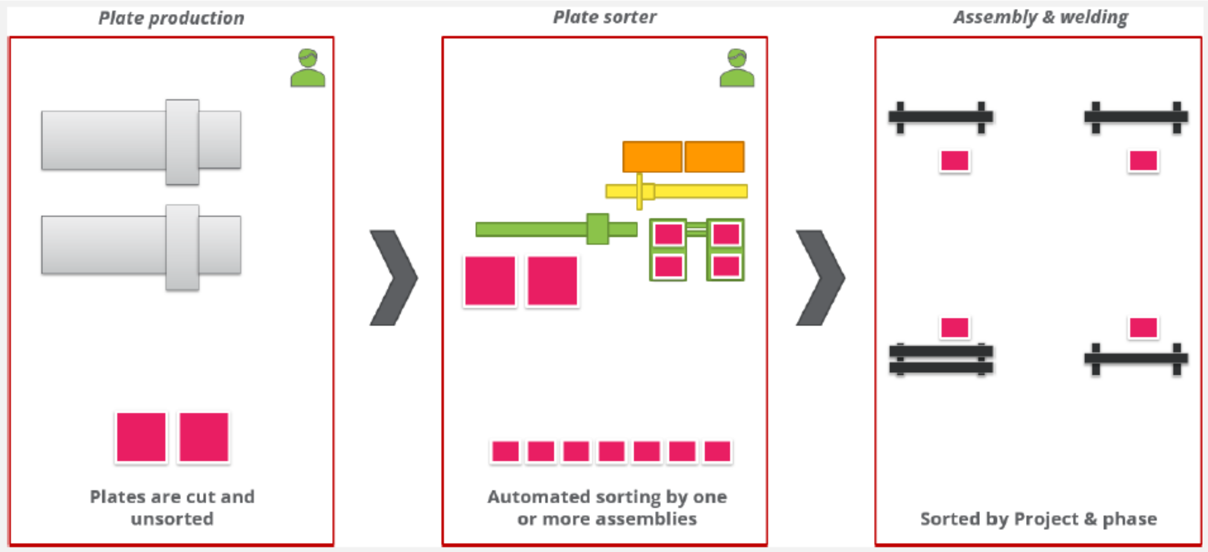

Figure 5 New automated sorting situation

After being scanned and identified, the plate will move on to the magnetic arm (manipulator in Figure 6). The storage tower will simultaneously let down a drawer. The plate will be picked up and positioned in the drawer by the arm. The drawer will go back into the tower. During the storing of plates, the locations of plates will be stored in a database and used when required.

Product Y can consist of up to three storage towers in total. Each of these towers has 145 drawers lined with rubber mats to prevent the plates from shifting while being stored. In addition to picking up plates to put them in a drawer, the arm can load plates into the bins. A double-tray method was developed to make this procedure more effective. It implies that the machine may initiate the second drawer while the first tray is descending since it already knows which drawer will be needed.

The bins are on the second input belt. Stacks of five bins can be placed on the conveyor belt. A single bin will continue to the magnetic arm with the help of an unstacking machine. Each bin will receive a unique code that the machine can read. Plates destined for a specific beam will be filled from now on. A bin will move towards the output belt once it is complete.

Additionally, a stacking device can arrange the bins in stacks of up to five bins. These are manually taken off the belt and carried across to where the beam will be placed. The overview of Product Y can be seen in Figure 6.

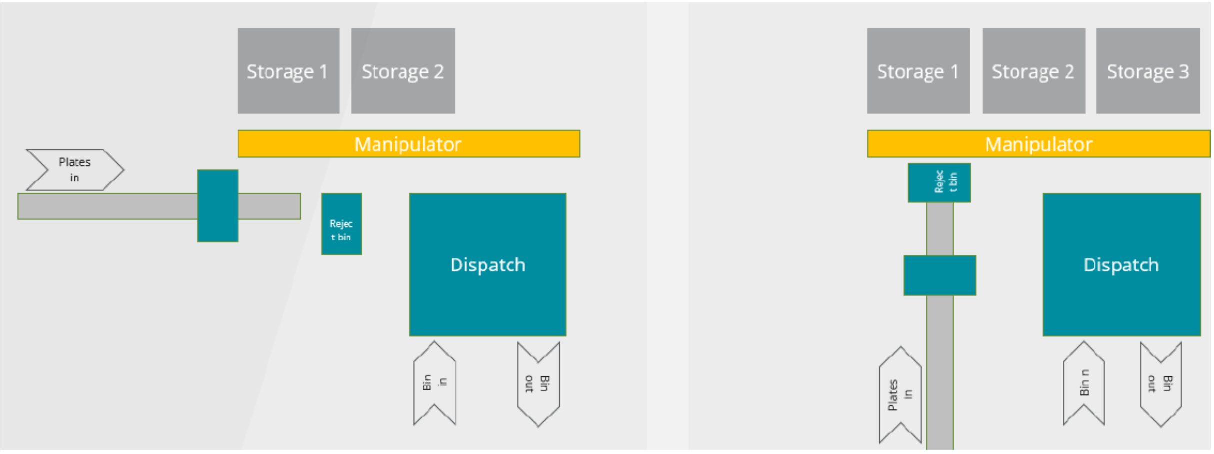

Figure 6 Product Y layout

The introduction of Product Y creates a challenge for the company's planning schedule. The machine's output is set to a beam level. This indicates that a filled bin travelling down the conveyor belt is headed for a particular beam placed at a specific location. Each day, beam output is planned. As a result, there is a difference between the schedules' levels. Since virtually all businesses use phase-based daily planning, creating a dispatch schedule that distributes the filled bins appropriately is crucial. On the other hand, it is also critical to learn more about the location of the beams.

2.2.1. Beam planning

As was noted earlier, daily schedules are made to complete the beams. The sequence of the completed beams is not known at the start of the day, only which beams need to be completed. The production planner uses a forecasting tool that estimates the total duration. For this tool the specifications for the whole phase are used. Welders will establish a workspace and operate in pairs. About 120 beams will need to be completed. When one group is done, they move on to the following workplace, where another set of beams will be prepared for tack welding.

2.2.2. Plate planning

The beams are explicitly planned for each day. This is not a practical option for the planning of the plate. For a specific beam, Product Y will send out a bin containing the required plates for the specific beam. This implies that Product Y must understand when the plates are needed and, consequently, when they should be dispensed. The processing of the beams is now taking place in a random sequence. This means the location only becomes known when the welders start working on it. To make this work, all the bins must be delivered in the morning before the welders begin their job. This would need the use of product Y every night, the need for several bins, and a sizable storage space for the full bins.

For product Y to function efficiently, the two planning schedules must be on the same level. The beam scheduling has to be more exact since Product Y's plate-specific level is fixed. This implies that the welders should have a timetable outlining the sequence in which the beams should be treated. When the beam's start time is known, the system can use a heuristic to ensure that all of the bins are sent out at the appropriate moment. The difficult part of this scheduling part is the difference in time for a plate. Since the there are different drawers and different towers there are different times for every plates. On average a plate takes 19 seconds for a plate to be placed in the bin. There are 145 per tower so a difference in time for every specific plate.

2.3. Key performance indicators

Key performance indicators (KPIs) will be used to measure the performance of the dispatch method. They can indicate poor performance and improvement potential. There are KPIs from different perspectives, hence the difference in weight for one use versus the other. For the industry, it can be essential to have high overall equipment effectiveness (OEE) or minimally fixed or variable costs for the project's operation. For this research and scope, the following three KPIs have been chosen to indicate the performance of the plate sorter. It's good to know that they contradict each other.

2.3.1. Average waiting time for a bin

The average time a bin waits at the workplace is the first KPI for the method. This number will indicate if the total number of bins in circulation is excessively high or too low. With a long waiting time, there is a good indication of inefficient use of bins. With many bins, a big storage place is required for empty but filled bins. At the same time, a low waiting time could mean too few bins for an efficient process.

2.3.2. Total working time

The total working time tells how long it takes for the whole process. The chosen output method can significantly influence the order of dispatching for Product Y. This sometimes can take very long or be surprisingly short. With this KPI, an indication will be given about the efficiency of the output.

2.3.3. Welder pair efficiency

The welder pair efficiency indicates the worker distribution over the beams. With different schedules, some worker pairs must wait a long on the filled bins to arrive at the next beam, while others can immediately work on the next one. The efficiency percentage will indicate the productivity of the worker distribution among beams. The efficiency is calculated with the total working time of each pair and the total process time of a day.

2.4. Conclusion

The current beam production line is organised on a daily level. This means that which beams must be finished at the end of the day is only planned and not in which order. This is why the welders do not work in a specific order. The pairs work in random order. When a workplace is finished, they randomly pick a new workstation. All the plates destined for specific beams are manually sorted into designated bins. In the current system, this takes around 5 FTE to finish and is inefficient.

Product Y is a sorting machine that optimises the product flow of plates towards the beam workplaces. With a two-input conveyor belt and one output, it is possible to store almost all the plates destined for beams and distribute them when required. There is less chance of missing plates since all the passing plates are scanned and stored in a cloud base inventory. For Product Y to work efficiently, it is required to have a beam schedule. Without the knowledge of where and when which bin needs to be, the only possibility is to dispatch all the bins in the night before the welders start. This would make a very inefficient process.

To measure the performance of the overall system, there are three key performance indicators chosen:

- Average waiting time for a bin
- Total working time
- Welder pair efficiency

The next chapter will investigate planning methods from the literature.

3. Literature Review

The third sub-research question is answered in the following chapter: *"How can Product Y be improved?"*. Literature is reviewed to answer the three parts of this question and find a method for constructing a distribution method for Product Y. To establish a successful distribution strategy, a significant amount of data from Company X must be examined and processed during the research. Some process decisions must be made to find a good distribution scheme. This will be divided into three different parts. The first part will discuss the order of beams that are used. Many businesses tend to use daily planning and are not beam-specific. A beam-specific plan cannot be made arbitrary; a priority rule for a parallel scheduling problem is required to create an order that makes sense. Second, a priority rule for the plates as a single machine scheduling problem is necessary. This is essential because the difference between a well-performing and a poorly performing distribution schedule can be made here. Finally, a model is needed to evaluate the priority rules for the operation. The production line needs to be recreated in a model to check the validity and reliability of the model.

3.1. Beam Planning as a parallel scheduling problem

It is required to know where all the beams will be located and when the welders will start working on a specific type. For a good distribution schedule for Product Y, the current daily schedule needs to be overhauled and made into a beam-level plan. Once this is created, there will be more details on the welders working schedule.

The company has indicated that beam planning is not the most critical part of the research. This is because this will be a machine that is sold to other companies. Every company will have a different way of planning their beams. With the preference the decisions are made to not apply a stochastic distribution on the process times on beams. The main focus will be on the scheduling problem of Product Y. From this information, only a few priority rules that are simple to work with and easy to calculate will be chosen.

The data provided by Company X gave three main variables, the number of beams, the number of workers and the processing time of each beam. Using this as starting point, it is possible to use the approach of a parallel machine-scheduling. The book Planning and Scheduling (Pinedo, 2009), talks about jobs and machines for a parallel scheduling problem. there are M number of machines for J numbers of jobs. The machines can be seen as the welder pairs and the jobs are the beam assemblies. Every job can be assigned over each machine which makes it reasonably easy. Unfortunately, due to the lack of data, only a few priority rules can be chosen with the process times. In the book of Pinedo, there are several dispatching rules explained. Not all of them apply to this situation because not most of these priority rules require more variables used.

There are two priority rules based on processing time. The first would be the Shortest Processing Time (SPT). "This has been shown to minimise the average number of jobs waiting for processing" (Pinedo, 2009). This rule solely looks at the processing time. The welder pairs all have zero jobs assigned. Team number one or machine one takes the job with the lowest processing time. Then the second pair gets the next lowest. When all the pairs have one job assigned, the process starts again at team one. This goes on until all the jobs are assigned.

The opposite of the SPT rule would be the Longest Processing time (LPT). "This rule orders the jobs in decreasing order of processing times. When there are machines in parallel, this rule tends to balance the workload over the machines." (Pinedo, 2009). The smaller jobs can be kept for the final few in this method. Since these are shorter, it is easier to balance out the differences made by the longer jobs in the beginning. The execution of this rule is like the SPT. All pairs start at zero jobs assigned. The first welders get the longest-taking job, and the second team will get the second-longest job. This process continues until all the jobs are equally assigned among the teams.

The Service In Random Order (SIRO) rule is the last priority rule applicable to this situation. This the rule that is used in the current system. Whenever a station is free, the next job will be assigned randomly. As mentioned earlier, this is a system that many companies use to plan the beams among workplaces. From this point of view, it will be a good experiment to compare the current dispatching system to the potential other rules.

3.2. Plate Planning as a single machine scheduling problem

The next step in the process would be to determine a dispatching order for Product Y. Where the beam scheduling problem was a parallel machine scheduling problem, the scheduling for Product Y is a single machine problem. Here, only one machine needs to execute all the given jobs for one day. This schedule aims to make a dispatching schedule that makes the production day more efficient. Since there is only one machine, knowing how long each beam takes and when the welders start working on a particular beam is essential. It is known how long a particular beam takes to be processed. The setup time for product Y can be calculated since it is known how many plates need to be drawn from the storage. Finally, it is now known when bins are required at the workplace. To summarise this, three variables can be used for applying priority rules to the dispatching: the processing time, the setup time and the due date of each beam.

The first priority rule is already used for the beam problem, the Shortest Processing Time rule (SPT). The order is evaluated on the processing time of the beams increasing from lowest to highest.

The second rule will be dependent on the due times off all beams. It is called the Earliest Due Date (EDD). The rule has the due date as an output value. For every beam, there will be a time when the bin is required. This means the first couple of bins will be required at time zero. Here the welders will start working, and the beams must be present. The due date for the next bin is when the pair is finished with the beam. They will start on the next beam, at that moment the next bin should be at the workplace. The EDD rule tends to minimise the maximum lateness among the welders waiting for a bin (Pinedo, 2009). This means the welders will not wait too long to go to the next bin.

The last rule applied to the plates will come from the last variable available, the setup time. The Shortest Setup Time (SST) will look at the time a bin takes to prepare. As mentioned earlier in the report, not all plates will fit in Product Y. This dispatching rule will maximise the early throughput of bins, so there is a large buffer of bins available at the beginning of the day.

3.3. Evaluation

After applying the different priority rules on beam and bins order, there are nine combinations of rules for the parallel and single machines scheduling problems. The outcome will be an order for Product Y. With only the order, there is nothing to say about it. It is impossible to say if the rule combination is better than the current situation or another combination. To process the stochasticity in plate moving and testing the rules, an evaluation of the performance is required. As mentioned earlier, the company provides data on a particular day. There is much variability with all the different calculations and orders in the data combining two different rules with a certain level of dependence. The components of the two will have a significant effect on each other.

The book, The Practise of Model Development and Use (Robinson, 2014) talks about how simulation models can model this complexity. To find out how the different Priority rules and stochasticity of picking up plates are performing, simulation research will be conducted. A simulation is defined as "experimentation with a simplified imitation (on a computer) of an operations system as it progresses through time, for better understanding and/or improving that system." (Robinson, 2014).

Company X does not collect data on specific beam throughput. So, it is not possible to make a simulation model on the average. This means that data from the past will be used for the simulation. If the data for a specific day is given, it is possible to make a discrete-event simulation (Robinson, 2014). A discrete-event simulation works with states and events. The bins that need to be distributed at the beginning of the day are a collection of variables, all used at a specific moment. The data acquired from the beam and plate schedule makes evaluating this process in a simulation possible.

3.4. Conclusion

The literature review was required to find the answers for the three parts of sub-question 3. For Product Y to function properly, a beam order is required. From literature, three Priority rules can be applied:

- Shortest Processing Time (SPT)
- Longest Processing Time (LPT)
- Service in Random Order (SIRO)

After finding the different beam rules, it was time to search for the appropriate rules for the single machine scheduling problem. With the data provided by the Company, it became clear that three variables can be used: Processing time, due date and setup time. With the possibility to use these three, there were three priority rules chosen from the literature:

- Shortest Processing Time (SPT)
- Earliest Due Date (EDD)
- Shortest Setup Time (SST)

A method was needed to evaluate these combinations of rules in the last part of the literature review. The book of Robinson showed that a simulation would be a good tool to try all the different priority rules combinations.

4. Simulation Model

The fourth research question will be addressed in Chapter 4: "How can a model help the distribution method of Product Y?" A simulation is required to identify improvements to the distribution system. Several strategies will be examined to determine which type of distribution can help enhance the performance of Product Y. This part will look at the input data, establish the model setup and various strategies that may be used to enhance the performance of Product Y.

4.1. Data preparation

The existing logistical process may be looked at with the aid of Company X and the data provided. Quantitative data analysis has been used to prepare the data for importation into the model. It became evident throughout the company's daily throughput inspection that there is significant daily variety in demand. Every day will be different from the one before it. Because averages cannot be taken in such a specialised business, producing an "average day" will be exceedingly challenging.

As a result, it was challenging to decide whether to use an average with a wide range of values or a single day as a sample group and base the rest of the investigation on this sample. In agreement with the company's wishes, the decision has been taken to look at just one day of data and use the distribution method.

Table 1 Example of the bill of material

MERKENPOSLIJST				Pagina: 1		aantal merken		
Model: VS23-0003 - Lemken Stekete				Project: VS23-000		aantal attachments		
Fase: 100			100	Datum: 10.03.2023				
Conservering: PC staal 60m				Tijd: 16:10:29				
Fase	Merk	Pos	Aantal	Profiel	Lengt	Breedte	Hoogte	Gewicht (kg)
100	K37	K37	1	HEA300	10750			1140.7
100		K37	1	HEA300	10711	290	300	964.0
100		P40	4	STRIP15'	276	276	15	9.3
100		P42	4	PL10*145	258	146	10	3.0
100		P43	1	STRIP15'	273	273	15	14.8
100		P44	1	STRIP15'	277	277	15	15.0
100		P72	1	STRIP20	276	276	20	13.2
100		P101	1	PL20*52	640	520	20	53.2
100		P245	2	PL15*27	370	276	15	12.3
100		P246	1	PL15*210	276	210	15	7.0
100	K38	K38	1	HEA300	11746			1197.0
100		K38	1	HEA300	11707	290	300	1053.6
100		P3	2	STRIP15'	256	256	15	6.4
100		P40	3	STRIP15'	276	276	15	9.3
100		P42	3	PL10*145	258	146	10	3.0
100		P43	1	STRIP15'	273	273	15	14.8
100		P72	1	STRIP20	276	276	20	13.2
100		P101	1	PL20*52	640	520	20	53.2
100		P221	2	STRIP15'	256	256	15	6.3
100	K40	K40	1	HEA320	12850			1360.2
100		K40	1	HEA320	12811	310	300	1273.9
100		P1	3	PL15*25	277	255	15	6.7
100		P73	1	STRIP20	296	296	20	14.2
100		P94	1	STRIP20	540	300	20	25.9
100		P219	2	PL15*25	277	256	15	6.5
100		P576	2	PL15*25	277	256	15	6.5

Microsoft Excel has been used to prepare the data. Table 1 shows an example with three beams (K37, K38 and K40) and all the plates (all letters P with a number behind) that need to be attached. The company prepares a bill of materials for the whole day that details the hours needed to finish the daily plan. Numerous beams in the data table were unrelated to Product Y and the logistical processing of the beams. This filtering process was completed after the irrelevant beams had been manually removed. The drawers of Product Y have specific dimensions. As a result, not all plates can be kept inside the tower.

Table 2 Number of plates per beam handled by Product Y

phase 100	#plates 100	Phase101	#plates 101	Phase 102	#plates 102	Phase 103	#plates 103
K28	13	K231	50	K14	31	K7	33
K37	15	K232	33	K194	2	K9	40
K38	13	K296	46	K195	2	K11	37
K40	9	K297	47	K196	2	K267	35
K42	13	K311	33	K197	2	K308	37
K62	16	K317	35	K198	2	K311	33
K183	3	L4	3	K199	2	L4	3
K184	3	L35	3	K200	2	L7	0
K187	3	L36	5	K201	2	L37	2
K188	3	L37	2	K237	2	L41	3
K192	2	L41	3	K238	2	L78	0
K193	2	L78	0	K293	45	L81	7
K239	2	L158	0	K294	44	L158	0
K257	2	L217	4	K310	32	L188	3
K290	4	L221	4	K312	34	L216	4
K291	4	L279	0	K314	37	L217	4
K295	42	L280	0	L7	0	L220	4
K306	33	L313	0	L37	2	L222	4
L3	2	L318	2	L78	0	L280	0
L8	0	L344	9	L158	0	L313	0
L14	8	L347	8	L161	0	L314	0
L16	4	L361	3	L193	2	L321	2
L17	6	L367	5	L195	0	L322	2
L18	6	L370	3	L196	0	L344	9
L19	4	L372	3	L216	4	L370	3
L23	0	L382	2	L313	0	L384	2
L24	4	L390	4	L315	0	L393	3
L80	7	L394	4	L345	7	L416	5
L147	16	L418	3	L350	3	L418	3
L155	19	L419	3	L370	3	L419	3
L159	0	L422	4	L371	3	L422	4
L163	0	L440	3	L392	3	L440	3
L164	0	L441	3	L393	3	L441	3
L192	2	L442	3	L416	5	L476	3
L202	0			L417	5		
L244	4			L420	4		
L253	3			L424	4		
L254	3						
L257	10						
L258	8						
L281	0						
L316	0						
L319	2						
L330	2						
L334	2						
L403	0						

The large plates had to be removed to create a clean dataset with only the plates for Product Y and determine the beams process time. To determine the sorting machine's and the beams' respective processing times, both types of data were necessary. The setup time for Product Y was determined using the data with just the plates, the process times for each beam were determined using the data set with all plates. Table 2 shows the number of plates per beam handled by the sorting machine. Some of these beams have zero plates. This means that all the plates are too big to handle by the machine. As a result of the data cleaning of the company, it was possible to calculate the average process time for a beam which can be used for the next part.

4.2. Conceptual model

A conceptual model is used to overview the process that needs to be integrated into the simulation. All the steps that are made during the simulation will be described in the model. Next, a general overview of the simulation also gives an idea of the different steps the user needs to go through to get to the final result of the simulation. Since different steps need to be made in the data cleansing part, a larger model is required with more than only the parts executed in the simulation. Figure 8 gives an overview of this process.

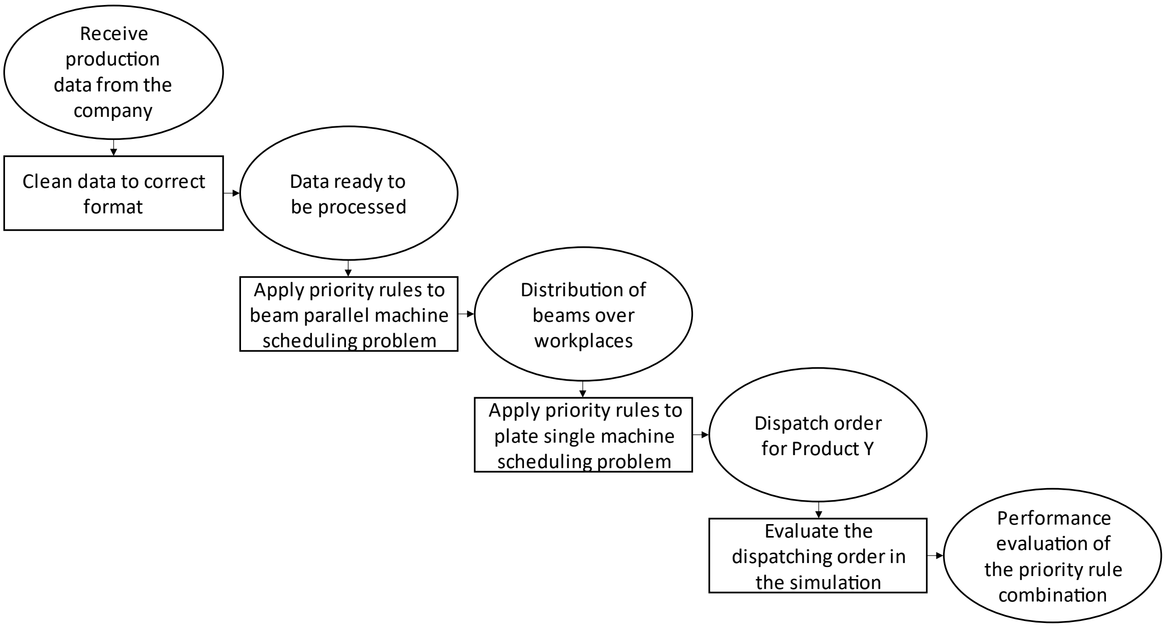

Figure 8 Conceptual framework

4.3. Scheduling algorithm

There are two different kinds of scheduling problems used in the simulation models. It is known how long each beam will process after the data for the beams has been collected. Two distinct priority rules are be applied from here to the beam order. As previously noted, the shortest process time and longest process time methods are employed for the beams. Additionally, beams are used in a random sequence. The order of the present beams can be regarded as random because it is not planned. It is, therefore, comparable to the actual scenario.

Table 3 Beam priority rules.

Beam priority rules	Objective
Shortest Processing Time (SPT)	Distribute increasingly on the processing time of beams
Longest Processing Time (LPT)	Distribute decreasingly on the processing time of beams
Service in Random Order (SIRO)	Random distribution over welders

The priority rules on the single machine scheduling problem are be applied to the plates once the beams are divided over all the workplaces. There will be a working order for the welders. From this moment, the bins filled with plates must be prepared for the beams. Here there will be three different priority rules applied towards the Product Y distribution: shortest process time, shortest setup time and earliest due date. With these rules, it will be possible to evaluate the different strategies for the machine.

Table 4 Plate priority rules

Plate priority rules	Objective
Shortest Processing Time (SPT)	Distribute increasingly on the processing time of plates
Earliest Due Date (EDD)	Sort on increasing due date for bins
Shortest Setup Time (SST)	Sort on increasing setup time for bins

4.4. Discrete event simulation

A simulation is the chosen method for our experiments. It involves simulating processes by focusing on specific events and skipping the time between them instead of continuously simulating (Robinson, 2014). Each event triggers actions and can lead to the planning of future events. In this case events are used to represent the arrival of jobs at buffers, completion of jobs, filling of workstations, movement of jobs, and events for initialisation purposes. All the priority rules are applied in excel. This means that as an output from here, there is a good overview of where which beam should go. This has been transformed into a plant simulation input template. Here the evaluation in Plant Simulation starts.

First, the Excel template can be copied and inserted into the plant simulation (Figure 9). The DataTable, ProductDataBase and ProcessTimes are used for input. These will be read out to determine the beam process times, the number of plates that must be put in the bins and the destination.

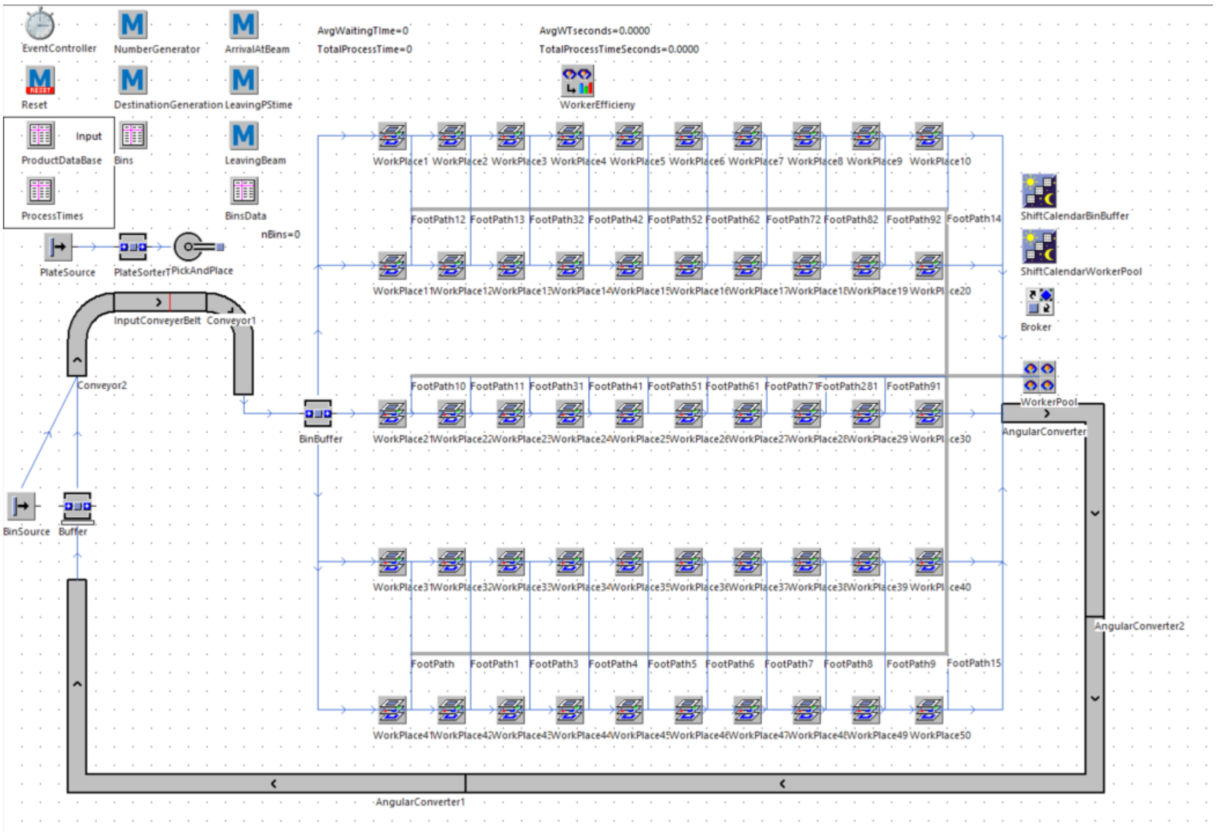

Figure 9 Simulation Model

The simulation starts at 6:00 AM with the distribution of bins to the buffer area and a total of 50 bins in circulation. At 7:00, these bins will be divided over the workplaces. The welder pairs start working at 7:30. When welders are done with a workplace, they will head to the following workplace in the schedule to start working.

When the whole simulation is finished, the data of all the bins is stored in BinsData. Here the time leaving Product Y, arrival time at the workplace, leaving time at the workplace and waiting time at the workplace are stored. This table shows that the average waiting time of a bin at the workplace can be calculated, and the total simulation time is noted. The total simulation time is not equal to the total working time. The time between the start of distribution and the starting moment of the welder pair first needs to be subtracted from the total simulation time. Once this is calculated, the total working time is also acquired.

Lastly, the welder efficiency needs to be exported from the simulation model. This can be done via the WorkerEfficiency widget. The average working, waiting and walking time is exported into a pie chart. This whole process is stated in Figure 10, where the flow chart of the steps is put together.

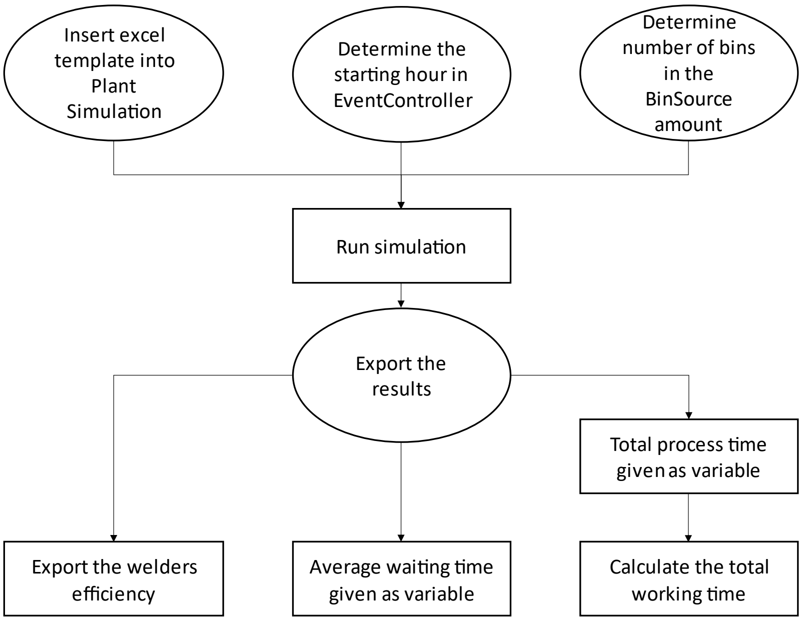

Figure 10 Simulation Flow

4.5. Validation and verification

The validity of a simulation model depends on whether the model is a good representation of the actual system. By staying in touch with the company and making sure all the choices and presumptions were accurate, the validity was confirmed. The conceptual model and the simulation matched up against each other. These decisions and meetings ensured that it was possible to validate the model.

In this discrete event simulation, most data are a constant. From the data, the processing times are constant and will not change during the test. The same is true for the transportation speed of the Bins and workers. These will not change during the simulation and the replications. The only thing where a difference can occur is the dispatching speed of Product Y. On average, it will take between 14 and 24 seconds with a normal distribution to take out a plate from the drawer and place it into the bin. However, a plate can be placed in the top or bottom drawer, which can be a difference in the dispatching speed.

From this knowledge, the decision has been made to make five runs for every different combination of rules. This means that with nine different combinations of rules, there are 45 simulations to be executed and investigated for the data.

The verification of the model was more complex than the validation. Since the machine is not in use yet, comparing the simulation output to real-world data is challenging. It was only possible to get a sense of the real-world output by using a random beam order since that is also happening in real-time. Nevertheless, no factual verification is possible for the distribution of Product Y in the real world since the machine has no real-time data about the performance.

4.6. Conclusion

In this chapter, the possibilities of the simulation model were investigated, and how it can help the distribution method of Product Y. With the data provided by Company X, it was possible to calculate the processing time for every beam. This meant a beam priority rule could be applied to the beams.

The beam scheduling problem is dependent on the processing time of a beam. Determining a beam schedule introduces two new variables in the data, setup time and due date. This created possibilities to make a new Product Y dispatch schedule.

This schedule can be implemented in the Plant simulation where the values are processed, and every beam gets its own process time and number of plates. Here the welders' pair will start working. Once the simulation is finished, the simulation will give values for the three KPIs.

5. Computational results and analysis

The outcomes of the various rule combinations are be analysed and compared with reality in this chapter. These outcomes will answer sub-question 5: "How do the applied priority rule combinations perform? The experiment's setup will be described in the first part, and the various phases will be added to get the outcome. Following the introduction, Section 5.2 will study and compare the outcome to the existing performance. The various rules combinations will be looked at and assessed in Section 5.3. In the last part, there will be a conclusion to this chapter.

5.1. Experiment setup

It was essential to design and conduct several tests to determine how well the chosen rule combinations performed. The chosen data was significant to start. The placement of the beams must be determined in the next step. Scheduling techniques can then be used to construct an order of dispatch for Product Y. As a result, there are now nine separate experiments that need to be conducted. The most effective combination will then be selected, and the logistical process's parameters will be tested with a sensitivity analysis.

5.1.1. Data set

Company X provided data for this experiment. Since the daily output varies drastically, it is inaccurate to estimate an average day. Instead, an average number of beams with a matching number of plates as input is used. As was already explained, this experiment uses data from one particular day. The company has decided to look for a day with a workload equivalent to the preceding days. The information for March 10, 2023, has been gathered from this search. This equates to four phases of steel, with each phase being a truckload of beams.

5.1.2. Current Performance

The current performance of Product Y is different compared evaluation of the machine. Within the current supply chain, the machine is not used. All the bins are manually sorted beforehand and delivered to the workplace when required. In reality, there is no data available for the waiting time of a bin or the total production time. The solution to this problem is to simulate the reality in the simulation.

To replicate the reality in the model, the most essential part is to prepare all the bins before the days start. To make this possible, the number of bins needed to be equal to the number of beams, and the starting time needed to be early enough so all the bins could be dispatched before 07:30 when the employees would start their shift. This meant the starting time of the simulation was set to 23:00 to recreate this situation. Since the beams are randomly ordered, the simulation was executed five times with a different order of randomly created beams.

Table 5 Current situation performance

Key Performance Indicator	Output value (n=5)
Number of bins	123
Starting hour	23:00 (a day earlier)
AvgWaitingTime	1:26:56.3
TotalProcessTime	18:25:19.6
TotalWorkingTime	09:55:19.6
Welder Working (%)	67.5
Welder Walking (%)	0.6
Welder Waiting (%)	31.9

In Table 5, the performance of the current situation can be seen. Here the three most important values are the average waiting time, total working time and the percentage of time the welders work. This data indicates the upcoming experiments to understand better what these rule combinations will have to influence the total time.

5.1.3. Beam scheduling

As previously indicated, this experiment combines the parallel and single machine scheduling problems for two stages of the logistical process. The scheduling procedure will start with the beams. The processing time for each beam may be retracted from the data set. The shortest process time and longest process time method can be introduced based on this data.

Fifty workplaces must share 123 beams, meaning there are 23 workplaces with three beams and 27 with only two beams. This is from the perspective of the availability of workplaces. When considering the employees' sides, 25 pairs of two workers are available. This indicates that two groups will finish four beams, and 23 will work on five. A random distribution of beams has been created, as seen in Table 5 and Table 6.

The welder pair distribution is used to apply the priority rules on the next step. When a duo has finished at one location, they move on to the following location to work on the next allocated beam. The workplace distribution is a simulation of the 50 workplaces in real life.

The first rule applied on the beams was the shortest process time. This strategy rule states that all the jobs are divided over the workplaces, which increases processing time. Essentially, this means the data table is sorted and, from here, divided over the welders. This would put the welders in a position where they would work on the shortest beams first and switch to a new bin reasonably quickly. As a result, new bins should arrive soon enough for the welders to avoid waiting.

The second ordering approach makes use of the longest processing time. In this case, the first rule's reverse would be appropriate. The information is ordered in order of decreased processing times. Where the most extended beams are used to begin welding, this implies that while the welders are at work, Product Y can construct a type of buffer.

The last rule would be applicable in the current situation. As indicated in Chapter 2, the beams are now randomly distributed among the workstations between 07:00 and 07:30. To simulate this scenario. It was decided to randomly distribute the beams throughout the workspaces and see how this order would be carried out.

Table 5 Workplace distribution

1	L334	K238	L347
2	L37	L193	L361
3	L382	L345	L418
4	L37	L81	L419
5	L37	L321	L350
6	L384	L322	L392
7	K192	L370	L393
8	K193	L372	L4
9	K239	L440	L41
10	K257	L441	L188
11	L3	L442	L393
12	L80	L370	L418
13	L192	L371	L419
14	L319	L370	L476
15	L330	L440	K290
16	L318	L441	K291
17	K194	K183	L16
18	K195	K184	L19
19	K196	K187	L24
20	K197	K188	L244
21	K198	L253	L217
22	K199	L254	L221
23	K200	L4	L344
24	K201	L35	
25	K237	L41	
26	L390	L155	
27	L394	K62	
28	L422	K38	
29	L216	K42	
30	L420	K37	
31	L424	K310	
32	L216	K306	
33	L217	K232	
34	L220	K311	
35	L222	K14	
36	L344	K311	
37	L422	K312	
38	L36	K317	
39	L367	K7	
40	L416	K267	
41	L417	K314	
42	L416	K308	
43	L14	K11	
44	L17	K295	
45	L18	K9	
46	K28	K294	
47	L257	K293	
48	L258	K296	
49	K40	K297	
50	L147	K231	

Table 6 Welder pair distribution

WelderPair	1	2	3	4	5
1	L334	K238	L347	L390	L155
2	L37	L193	L361	L394	K62
3	L382	L345	L418	L422	K38
4	L37	L81	L419	L216	K42
5	L37	L321	L350	L420	K37
6	L384	L322	L392	L424	K310
7	K192	L370	L393	L216	K306
8	K193	L372	L4	L217	K232
9	K239	L440	L41	L220	K311
10	K257	L441	L188	L222	K14
11	L3	L442	L393	L344	K311
12	L80	L370	L418	L422	K312
13	L192	L371	L419	L36	K317
14	L319	L370	L476	L367	K7
15	L330	L440	K290	L416	K267
16	L318	L441	K291	L417	K314
17	K194	K183	L16	L416	K308
18	K195	K184	L19	L14	K11
19	K196	K187	L24	L17	K295
20	K197	K188	L244	L18	K9
21	K198	L253	L217	K28	K294
22	K199	L254	L221	L257	K293
23	K200	L4	L344	L258	K296
24	K201	L35	K40	K297	
25	K237	L41	L147	K231	

5.1.4. Plate Scheduling

From the three scenarios created in the previous section, the next step is applying the different methods on the bins destined for the beams. At every moment, there will be 25 pairs working on the beams. These pairs all start working at 07:30 AM. Because Product Y can only dispatch one bin at a time, it is essential to create an ordering strategy. In the previous part, the order was created. This means the due date for every beam is known, and so is when every bin should be dispatched. Every bin also has a specific setup time. This is calculated with the number of plates dispatched from the sorting machine. For this day chosen there is a total of 930 plates to divided over the 123 beams. The dispatched time of one plate will take between 14 and 24 seconds with a normal distribution. From this number, it is also possible to consider the setup time for the priority rule. The following three priority rules have been applied to product Y dispatched schedule from all this data. All these numbers are noted from the beam rules and placed into a table to determine the plate order. Table 7 is an example of this data.

Table 7 Data for plate priority rules

BeamID	Due date(Seconds)	Process time(Seconds)	Setup times(Seconds)
L384	2291	2291	0
L382	2291	2291	0
L37b	2291	2291	0
L37a	2291	2291	0
L37	2291	2291	0
L334	2291	2291	0
L442	5757	3447	0
L441a	5757	3447	0
L441	5757	3447	0
L440a	5757	3447	0
L440	5757	3447	0
L372	5757	3447	0
L371	5757	3447	0
L370b	5757	3447	0
L370a	5757	3447	0
L370	5757	3447	0
K193	2310	2310	19
K192	2310	2310	19
L41	5776	3466	19
L35	5776	3466	19
L392	8068	3466	19
L361	8068	3466	19
L476	9223	3466	19
L41a	9223	3466	19
L393a	9223	3466	19
L393	9223	3466	19
L394	12688	4621	19
L390	12688	4621	19
L80	2310	2310	38
L330	2310	2310	38
L319	2310	2310	38
L318	2310	2310	38
L3	2310	2310	38
L192	2310	2310	38
K257	2310	2310	38
K239	2310	2310	38
K237	2310	2310	38
K201	2310	2310	38
K200	2310	2310	38
K199	2310	2310	38
K198	2310	2310	38
K197	2310	2310	38
K196	2310	2310	38
K195	2310	2310	38
K194	2310	2310	38
L81	4602	2310	38
L345	4602	2310	38

The first priority rule is based on the shortest process time. The beam scheduling already uses this rules, and the plate's principle is unchanged. All the beams are sorted in increasing process time, and the shortest processing times are chosen first. For this method the data acquired by the beam scheduling is not required.

Since the due date is available for every beam, the earliest due date method is also possible. The data is sorted on every due date, and the required bin is chosen and distributed.

Lastly, the shortest setup time for the bins is used for the order strategy. This rule uses the number of plates stored in the machine to calculate the setup time. This can differ per beam because sometimes there are plates which are too big for the machine but are considered for the total process time of the beams.

5.1.5. Parameters

Within the simulation, some parameters can be changed during the execution of the simulation. The primary essential parameters are the number of bins in circulation and the starting moment of distribution.

The number of bins can be changed in the simulation. This may influence the average waiting time for a bin at a station or welders at a workplace. The starting time for the sorting machine can also be adjusted. The earlier this starts, the more bins can be prepared before the welders start work. Of course, this moment also depends on the number of bins in circulation because the starting moment is very early. However, if there are not enough bins in circulation, this machine will stand still.

5.2. Experiment Results

In this section, the results of the different experiments will be discussed. First, the current situation of Company X will be evaluated, and after the different variants of methods. Once the best priority rule combinations are found, a small sensitivity analysis will be executed to determine how the parameter difference impacts the combination.

5.2.1. Evaluation of Scheduling rules

In this section, all the different priority rule combinations are be evaluated. During the nine experiments, the starting hour is fixed at 6:00 AM, and the number of bins in circulation is set to 50. After these experiments, different values will be investigated with a sensitivity analysis where the values for the starting hour and the number of bins will be changed.

Shortest Processing Time (SPT) beam order

The due dates of the first beams are zero. This is set to zero because the bins are required when the welders start working. If the clock hits 7:30 AM and the welders pair start working, the bins should already be stationed at the workplace. With this data acquired, applying the rule to the bins dispatched is possible. This resulted in the orders shown in Table 6.

Table 6 Plate priority rule performance values (SPT)

Beam priority rule:	Current situation	Beam priority rule:	SPT	Beam priority rule:	SPT	Beam priority rule:	SPT
Plate priority rule:	Current situation	Plate priority rule:	SPT	Plate priority rule:	EDD	Plate priority rule:	SST
AvgWaitingTime:	1:26:56.3	AvgWaitingTime:	7:49.9	AvgWaitingTime:	7:18.9	AvgWaitingTime:	9:10.2
TotalProcessTime:	18:25:19.6	TotalProcessTime:	15:56:53.2	TotalProcessTime:	15:18:22.8	TotalProcessTime:	15:59:19.2
TotalWorkingTime	09:55:19.6	TotalWorkingTime	14:26:53.2	TotalWorkingTime	13:48:22.8	TotalWorkingTime	14:29:19.2
Welder Working%	67.5	Welder Working%	58.3	Welder Working%	58.2	Welder Working%	58.2
Welder Walking%	0.6	Welder Walking%	0.6	Welder Walking%	0.6	Welder Walking%	0.6
Welder Waiting%	31.9	Welder Waiting%	41.1	Welder Waiting%	41.2	Welder Waiting%	41.2

It can be seen from table 7 that the average waiting time for a bin drastically decreases with the implementation of SPT compared to the current situation. These values have decreased to around 8 minutes per bin, while previously, this time was around one and a half hours. On the other hand, the total time for production has increased by more than three to four hours for each plate rule. Moreover, for the last rule, the efficiency of the welders is the same. The percentage of time the welders are working has decreased by around 9 percent.

Longest Processing Time (LPT) beam order

With the LPT beam rule, the three plates' rules were applied to the beams. This resulted in the performance in Table 9.

Table 7 Plate priority rule performance values (LPT)

Beam priority rule:	Current situation	Beam priority rule:	LPT	Beam priority rule:	LPT	Beam priority rule:	LPT
Plate priority rule:	Current situation	Plate priority rule:	SPT	Plate priority rule:	EDD	Plate priority rule:	SST
AvgWaitingTime:	1:26:56.3	AvgWaitingTime:	44:38.1	AvgWaitingTime:	45:50.7	AvgWaitingTime:	10:17.0
TotalProcessTime:	18:25:19.6	TotalProcessTime:	14:55:51.3	TotalProcessTime:	10:52:42.5	TotalProcessTime:	15:59:19.2
TotalWorkingTime	09:55:19.6	TotalWorkingTime	13:25:51.3	TotalWorkingTime	9:22:42.5	TotalWorkingTime	14:29:19.2
Welder Working%	67.5	Welder Working%	58.3	Welder Working%	73.3	Welder Working%	58.2
Welder Walking%	0.6	Welder Walking%	0.6	Welder Walking%	0.7	Welder Walking%	0.6
Welder Waiting%	31.9	Welder Waiting%	41.1	Welder Waiting%	25.9	Welder Waiting%	41.2

The table shows that the average waiting time decreases halves for SPT and EDD, and the SST decreases to only approximately 10 minutes per bin. For the total working time, it can be seen that for SPT and SST, the value increases by at least three and a half hours. While for the earliest due date rule, the total working time decreases. The main surprise is the welder efficiency for the EDD method. Here an increase of around 6 percent can be seen compared to the current situation.

Random beam order

For the last experiment, the current situation of beam division is investigated. In a typical situation, the beams are randomly distributed over the workplace. With this experiment, the goal is to keep this system. Nevertheless, the difference now applies a method to the plate dispatched and sees the influence. For this experiment, five different beam orders are used. The three plate rules are applied, and an average is taken for the output values. The order and values for processing time and the due date can be seen for one of the five experiments in Appendix C to indicate the randomiser's influence on the data.

Table 8 Plate priority rule performance values (random n=5)

Beam priority rule:	Current situation	Beam priority rule:	Random	Beam priority rule:	Random	Beam priority rule:	Random
Plate priority rule:	Current situation	Plate priority rule:	SPT	Plate priority rule:	EDD	Plate priority rule:	SST
AvgWaitingTime:	1:26:56.3	AvgWaitingTime:	08:27	AvgWaitingTime:	03:43.8	AvgWaitingTime:	09:11.8
TotalProcessTime:	18:25:19.6	TotalProcessTime:	15:53:21.6	TotalProcessTime:	13:03:37.2	TotalProcessTime:	15:49:39.8
TotalWorkingTime	09:55:19.6	TotalWorkingTime	14:23:21.6	TotalWorkingTime	11:33:37.2	TotalWorkingTime	14:19:39.8
Welder Working%	67.5	Welder Working%	58.3	Welder Working%	62.7	Welder Working%	58.2
Welder Walking%	0.6	Welder Walking%	0.6	Welder Walking%	0.6	Welder Walking%	0.6
Welder Waiting%	31.9	Welder Waiting%	41.1	Welder Waiting%	36.7	Welder Waiting%	41.2

The results (Table 10) show that the waiting times for bins have dropped below ten minutes for all combinations. For the total production times, EDD performs the best of the three, with 11 hours and 33 minutes. This also is the case for efficiency, where EDD is the only one reaching a percentage over 60 percent.

5.2.2. Sensitivity analysis

One priority rule combination gave a remarkable outcome from the nine different experiments outcomes. All the combinations resulted in a higher total working time except the longest processing time with the earliest due date.

This resulted in the decision for sensitivity analysis with different parameter values for the Starting time and the number of bins in circulation. The starting time values are set to 05:00 AM, 06:00 and 07:00. These were chosen because the spread in time can significantly influence the number of bins that can be prepared before the welders start their shift. The other parameter is the number of bins in circulation. The values 25, 30, 35, 40, 45, 50, 75 and 100 are chosen for this parameter.

Table 9 Sensitivity analysis results

starting hour: 05:00								
Number of bins	25	30	35	40	45	50	75	100
AvgWaitingTime:	0:50.1	8:42.7	18:34.1	28:53.0	39:41.5	49:47.8	1:32:21.5	1:59:24.8
TotalProcessTime:	11:38:15.4	11:20:41.7	11:13:51.9	11:07:45.4	11:06:55.9	11:06:55.9	11:06:55.9	11:06:55.9
TotalWorkingTime	9:08:15.4	8:50:41.7	8:43:51.9	8:37:45.4	8:36:55.9	8:36:55.9	8:36:55.9	8:36:55.9
Welder Working%	75.3	77.8	78.8	79.7	79.8	79.8	79.8	79.8
Welder Walking%	0.7	0.8	0.8	0.8	0.7	0.7	0.7	0.7
Welder Waiting%	24.0	21.5	20.4	19.5	19.3	19.3	19.3	19.3

starting hour: 06:00								
Number of Bins	25	30	35	40	45	50	75	100
AvgWaitingTime:	0:50.7	7:59.7	16:30.6	26:46.9	36:26.7	45:50.7	1:25:33.8	1:49:48.9
TotalProcessTime:	11:20:22.5	11:05:14.4	10:59:40.7	10:52:42.5	10:52:42.5	10:52:42.5	10:52:42.5	10:52:42.5
TotalWorkingTime	9:50:22.5	9:35:14.5	9:29:40.7	9:22:42.5	9:22:42.5	9:22:42.5	9:22:42.5	9:22:42.5
Welder Working%	69.9	71.7	72.4	73.3	73.3	73.3	73.3	73.3
Welder Walking%	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Welder Waiting%	29.4	27.5	26.8	25.9	25.9	25.9	25.9	25.9

starting hour: 07:00								
Number of bins	25	30	35	40	45	50	75	100
AvgWaitingTime:	0:50.5	7:36.2	16:00.0	26:28.4	35:52.1	44:58.5	1:22:29.5	1:22:29.5
TotalProcessTime:	11:12:14.4	10:58:41.1	10:51:44.5	10:46:43.6	10:46:43.6	10:46:43.6	10:46:43.6	10:46:43.6
TotalWorkingTime	10:42:14.4	10:28:41.1	10:21:44.5	10:16:43.6	10:16:43.6	10:16:43.6	10:16:43.6	10:16:43.6
Welder Working%	64.3	65.6	66.4	66.9	66.9	66.9	66.9	66.9
Welder Walking%	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Welder Waiting%	35.1	33.7	33,0	32.4	32.4	32.4	32.4	32.4

The results in Table 11 indicate the impact of the number of bins and the starting hour. The number of bins drastically influences the average waiting time when the number of bins is between 25 and 50. Here the ratio of bins per welder becomes more critical. With 50 bins in circulation, would be two bins available for every worker. This means the following bins will be available for the welders when the jobs are finished. Between 25 and 50 bins, a moment comes when the bins will not arrive on time. This influences the total working time, as can be seen between 35 and 30 bins.

The starting moment of the distribution also is essential. When the bin starts distributing at 5:00, there is enough time to dispatch all the plates in the bins and get the shortest total process time. On the other hand, the earlier the distribution start, the higher the waiting time will be.

5.3. Conclusion

This research aims to answer the question: *"How can Product Y improve the product flow towards the workplace?"* This question should be answered differently to keep it interesting for various companies.

The first perspective would be the Company with no beam-specific planning. This would be the case for most of the companies. Five experiments were run for this beam order, each with a completely random beam order. From this situation, there were three results due to the randomisation of the beams. Some long beams are at the beginning, and some are at the end. The same can be said for the short-taking beams. This causes a very balanced order of beams. Hence, the beams have a short waiting time for every bin order. So that means the total working time would be looked at. From this result, the EDD was the best by far. Looking at the due date for every beam was very important to create an efficient process.

To conclude the answer to the research question from this perspective, the product flow from Product Y towards the workplaces can be improved by applying the Earliest due date rule to the random order of beams.

The next step would be to look at companies planning their beams depending on some priority rule. If a company already does this, it can adjust this to an LPT or SPT rule. If there were to be chosen an priority rule combination, then that would be the LPT/EDD combinations. These were the only combinations where the total working time was lower than the current situation. After that, from the sensitivity analysis, the average waiting time for a bin could be lowered to a minimum of around eight minutes.

To answer the main research question from the beam planning company perspective. The product flow from Product Y towards the workplace can be improved with the longest process time and earliest due date combinations. In this situation, the welders can start with the longer-taking beams and divide the last shorter-taking beams to balance the work. The decision can also be made to start earlier or later with distributing plates into bins. Starting at 5:00 AM, a total working time of 8 hours and 50 minutes can be achieved with only 30 beams in circulation. The side note to this solution would be that employees need to start earlier in this system which can cost more money. Also, if the machine starts earlier with the distribution of bins, more bins will be filled before the welders can start. This means a larger buffer area is required, which will also cost more space in the layout of a production hall.

6. Conclusion and recommendations

The main goal of this research is to help Company X integrate Product Y into the supply chain, not only for the Company's construction division but also to help other companies which acquire the sorting machine. In the last chapter of this research, the main findings of the experiments will be discussed, the recommendations for distribution methods, the limitations of the research, and future research on the subject.

6.1. Conclusion

In this research the goal was to answer the main research question: *"How can Product Y improve the product flow towards the workplace?"*. Through out the research different sub research question have been answered to come to an answered.

The first step of the research was to identify the main problem of Product Y. After investigating different problems of the machine, the core problem became clear; there is no dispatching strategy for the machine which causes a decrease in efficiency for the supply chain. The next step was the analyse this problem and see how it can be processed. The problem consists of three different parts: the beams, the bins and the place where these to come together, the workplace.

The beams have no detailed planning system which leads into no knowledge about beams specific working schedule for welders. Hence it is not possible to know when which plates are required at the workplace to be used.

The literature review research was done to find applicable order methods for the data provided by the company. For the beams a method for a parallel machine scheduling problem was needed where the only variable known is the process time. From the literature came two different priority rules. The longest and shortest process time. Next to these two a decision was made to also use a randomizer in beam order. With a beam schedule acquired the next problem to investigate was the dispatching of plates. This could be seen as a single machine scheduling problem. with the new variables due date and setup time there were three priority rules chosen: earliest due date, shortest setup time and shortest process time.

These methods required a form of evaluation. From the literature came the solution to use a discrete event simulation where the combinations of priority rules for both problems could be investigated. In the chapter 4 the simulation model is introduced and explained that evaluates these combinations.

All the priority rule combinations have given different outputs in Chapter 5. Some of the results were similar, and some were very different. With nine combinations and a sensitivity analysis of the LPT/EDD combinations, some exciting findings must be made. There are different points of view for different companies, to be made. That is why the following sections discuss results from other perspectives.

6.2. Limitations

The setup of the simulation model and experiments were discussed in chapters 4 and 5. To make a working simulation, some assumptions needed to be made and processed into the execution. This led to a couple of limitations in the research.

- The processing time of beams was calculated via the bill of material, and the hours it calculated to process the four phases. This was done by taking averages of the plates. Each plate was seen as equal and had certain times for the processing time. In this way, the total process time for a beam was calculated. Of course, there would be differences between certain plates and how long they take to weld.

- The priority rule combinations were only applied to one daily production for this research. Due to the high variability in daily production, it was decided in agreement with the construction employees to look for an "average day". With this data, the priority rules would be executed and evaluated.
- A simulation model always brings limitations compared to reality. Product Y used a normal distribution to simulate the difference in plate dispatched, but there will always be a difference. The same is true for the process times of beams. In this research, the decision was made to keep the processing time fixed and not let a distribution change the times per run. This was done because the focus was not on the beam schedule. Every Company has a unique way of planning the beams, which should be used as input to evaluate Product Y.

6.3. Recommendations

The gap between norm and reality has not precisely been filled. Although some reasonable beginning steps have been made, there are still some recommendations for progress. Company X wants to sell Product Y worldwide to make the sorting process of plates more efficient and less influenced by human mistakes.

The implementation of Product Y gives the advantage of a database with all the plates locations. When a plate did not yet arrive to the machine it will also be known, so employee can search in previous locations of the supply chain. This will increase the efficiency of welders since the problem of missing plates at the workplace will not occur anymore. If other companies want efficient machine usage, a dispatching order is required. The machine can be used as perfect storage. However, without a dispatch schedule, all the beams still need to be stored in a different area because there is no knowledge about when the bins are required.

The recommendation would be to invest in a beam ordering system. Implementing this schedule will create much knowledge for planners and how to use the machine. A detailed schedule can be made if it is known how long a sure welder works on a beam and how long a specific plate takes to be tack welded. Moreover, that is what Product Y would benefit from.

6.4. Future Research

Product Y is a new product in the market with few competitors. Future research in the machine could create an even more efficient product flow towards the workplace and maximise the use of towers as storage areas. For this, future research should be done on more single and parallel machine scheduling problems. For this research, only three are used for product Y while there are many more.

As mentioned in the limitations, this research has been executed on only one dataset for one day. It would be better to execute the research on multiple daily data sets and not one to better understand the rule combination.

In the sensitivity analysis, there was a small amount of research towards the number of bins in circulations at the starting time for the distribution of bins. The results showed that the influence of the value changes is quite significant average waiting time could be decreased from 50 minutes to around 8 minutes while the total working time only increased to around 15 minutes. A more in-depth analysis of the number of bins per working pair should give exciting results.

References

Chopra, S., & Meindl, P. (2019). *Supply Chain Management.* Pearson Education Limited.

Cooper, D. R., & Schindler, P. S. (2014). *Business Research Methods.* Mcgraw-Hill Education Ltd.

Heale, R., & Twycross, A. (2015). *Validity and reliability in quantitative studies.* Ontario: Crossmark.

Heerkens, H., & van Winden, A. (2017). *Solving Managerial Problems Systematically.* Wolters-Noordhoff B.V.

Hull, J. (2003). *Options, Futures, And Other Derivatives.* Pearson Education Limited.

Lindberg, C. F. (2015). *Key Performance Indicators Improve Industrial Performance.* Energy Procedia.

Pinedo, M. L. (2009). *Planning and scheduling in manufacturing and services.* Springer-Verlag New York Inc.

Rahi, S. (2017). *Research Design and Methods: A Systematic Review of Research.* International journal of Economics and Management.

Robinson, S. (2014). *The Practise of Model Development and Use.* Red Globe Press.

Sharda, R., Delen, D., & Turban, E. (2018). *Business Intellgence, Analytics, and Data Science: A managerial Perspective.* New York: Pearson.

Appendices

Appendix A: Deliverables

During this research, several preparation, calculations, and evaluation are needed. There will also be extra files for the research to give a better understanding compared to the tables and figures mentioned in the chapters and the appendix.

- Phase

From the Company, there is a daily production schedule. In this file, all the details of the beams and attachments are given. Some of the data does not apply to the research, so there is a straightforward overview of which parts are used and which are not.

- Beam and plate distribution

With the data provided by the Company, there are distributions to be made with the chosen methods. This file gives a clear overview of all the orders and the input for the simulation.

- Simulation model

A simulation model was set up in Tecnomatix Plant Simulation 16.1 to evaluate the used methods.

- Report

The report contains the different results for the evaluations that have been executed. Together with this, the overall structure of the research will be explained.

Appendix B: Current Situation Performance

Table 10 Reality experiments

Number of bins	123	Number of bins	123
Starting hour	23:00	Starting hour	23:00
AvgWaitingTime:	55:45.99125549052	AvgWaitingTime:	1:48:39.53016244442
TotalProcessTime:	18:40:10.4855693333	TotalProcessTime:	18:33:04.9402979999
TotalWorkingTime	10:10:10.4855693333	TotalWorkingTime	10:03:04.9402979999
Welder Working%	67,6	Welder Working%	68,4
Welder Walking%	0,6	Welder Walking%	0,7
Welder Waiting%	31,8	Welder Waiting%	30,9
Number of bins	123	Number of bins	123
Starting hour	23:00	Starting hour	23:00
AvgWaitingTime:	1:08:19.6469525149	AvgWaitingTime:	1:39:42.66261692835
TotalProcessTime:	18:23:07.428357	TotalProcessTime:	18:04:13.9044769999
TotalWorkingTime	9:53:10.4855693333	TotalWorkingTime	9:34:13.9044769999
Welder Working%	67,6	Welder Working%	70,9
Welder Walking%	0,6	Welder Walking%	0,7
Welder Waiting%	31,8	Welder Waiting%	28,4
Number of bins	123	Number of bins:	123
Starting hour	23:00	Starting hour(hh:mm):	23:00
AvgWaitingTime:	1:40:19.69511415716	AvgWaitingTime(hh:mm:ss)	1:26:56.333
TotalProcessTime:	18:26:02.1283589998	TotalProcessTime(hh:mm:s	18:25:19.6
TotalWorkingTime	9:56:10.4855693333	TotalWorkingTime(hh:mm:s	09:55:19.6
Welder Working%	63,1	Welder Working(%)	67,5
Welder Walking%	0,3	Welder Walking(%)	0,6
Welder Waiting%	36,6	Welder Waiting(%)	31,9

Appendix C: Beam priority rule SPT Evaluation

Table 11 Welder pair distribution SPT

WelderPair	1	2	3	4	5
1	L334	L321	K184	K290	L155
2	L37	L322	K187	K291	K62
3	L37a	L330	K188	L16	K38
4	L37b	L345	L188	L19	K42
5	L382	L80	L253	L216	K37
6	L384	L81	L254	L216a	K310
7	K192	L370	L347	L24	K14
8	K193	L370a	L350	L244	K232
9	K194	L370b	L4	L344	K306
10	K195	L371	L4a	L344a	K311
11	K196	L372	L418	L422	K311a
12	K197	L440	L418a	L422a	K312
13	K198	L440	L419	L36	K7
14	K199	L441	L419a	L367	K267
15	K200	L441	L390	L416	K317
16	K201	L442	L394	L416a	K308
17	K237	L35	L217	L417	K314
18	K238	L361	L217a	L14	K11
19	K239	L392	L220	L17	K295
20	K257	L393	L221	L18	K9
21	L192	L393a	L222	K28	K294
22	L193	L41	L420	L257	K293
23	L3	L41a	L424	L258	K296
24	L318	L476	K40	K297	
25	L319	K183	L147	K231	

Table 12 Process times and Due dates of beams SPT

process time					due date				
2291	2310	3466	4621	11552	0	2291	4602	8068	12688
2291	2310	3466	4621	13863	0	2291	4602	8068	12688
2291	2310	3466	4621	15018	0	2291	4602	8068	12688
2291	2310	3466	4621	15018	0	2291	4602	8068	12688
2291	2310	3466	4621	17328	0	2291	4602	8068	12688
2291	2310	3466	4621	32346	0	2291	4602	8068	12688
2310	3447	3466	4621	33501	0	2310	5757	9223	13844
2310	3447	3466	4621	33501	0	2310	5757	9223	13844
2310	3447	3466	4621	33501	0	2310	5757	9223	13844
2310	3447	3466	4621	33501	0	2310	5757	9223	13844
2310	3447	3466	4621	33501	0	2310	5757	9223	13844
2310	3447	3466	4621	34657	0	2310	5757	9223	13844
2310	3447	3466	5776	35812	0	2310	5757	9223	14999
2310	3447	3466	5776	35812	0	2310	5757	9223	14999
2310	3447	4621	5776	35812	0	2310	5757	10378	16154
2310	3447	4621	5776	38122	0	2310	5757	10378	16154
2310	3466	4621	5776	38122	0	2310	5776	10397	16173
2310	3466	4621	6931	40433	0	2310	5776	10397	17328
2310	3466	4621	6931	42743	0	2310	5776	10397	17328
2310	3466	4621	6931	43899	0	2310	5776	10397	17328
2310	3466	4621	9242	45054	0	2310	5776	10397	19639
2310	3466	4621	9242	46209	0	2310	5776	10397	19639
2310	3466	4621	9242	47364	0	2310	5776	10397	19639
2310	3466	10397	48519		0	2310	5776	16173	
2310	3466	10397	51985		0	2310	5776	16173	

Table 13 Bin dispatch order (SPT)

Number	Destination	SPT	EDD	SST			SPT	EDD	SST			SPT	EDD	SST
1	workplace1.Beam1	L334	L334	L334	42	workplace17.Beam50	K183	K183	L318	83	workplace35.Beam92	L344a	L244	L216a
2	workplace2.Beam4	L37	L37	L37	43	workplace18.Beam53	L35	L35	L319	84	workplace36.Beam94	L422	L344	L344a
3	workplace3.Beam7	L37a	L37a	L37a	44	workplace19.Beam56	L361	L361	L330	85	workplace37.Beam96	L422a	L344a	L422a
4	workplace4.Beam10	L37b	L37b	L37b	45	workplace20.Beam59	L392	L392	L80	86	workplace38.Beam98	L36	L422	L36
5	workplace5.Beam13	L382	L382	L382	46	workplace21.Beam62	L393	L393	K238	87	workplace39.Beam100	L367	L422a	L367
6	workplace6.Beam16	L384	L384	L384	47	workplace22.Beam65	L393a	L393a	L193	88	workplace40.Beam102	L416	L36	L416
7	workplace7.Beam19	K192	K192	L370	48	workplace23.Beam68	L41	L41	L321	89	workplace41.Beam104	L416a	L367	L417
8	workplace8.Beam22	K193	K193	L370a	49	workplace24.Beam71	L41a	L41a	L322	90	workplace42.Beam106	L417	L416	L416a
9	workplace9.Beam25	K194	K194	L370b	50	workplace25.Beam73	L476	L476	L345	91	workplace43.Beam108	L14	L416a	L14
10	workplace10.Beam28	K195	K195	L371	51	workplace1.Beam3	K184	K184	L81	92	workplace44.Beam110	L17	L417	L17
11	workplace11.Beam31	K196	K196	L372	52	workplace2.Beam6	K187	K187	K183	93	workplace45.Beam112	L18	L14	L18
12	workplace12.Beam34	K197	K197	L440	53	workplace3.Beam9	K188	K188	K184	94	workplace46.Beam114	K28	L17	K28
13	workplace13.Beam37	K198	K198	L440a	54	workplace4.Beam12	L188	L188	K187	95	workplace47.Beam116	L257	L18	L257
14	workplace14.Beam40	K199	K199	L441	55	workplace5.Beam15	L253	L253	K188	96	workplace48.Beam118	L258	K28	L258
15	workplace15.Beam43	K200	K200	L441a	56	workplace6.Beam18	L254	L254	L217	97	workplace49.Beam120	K40	L257	K40
16	workplace16.Beam46	K201	K201	L442	57	workplace7.Beam21	L347	L347	L221	98	workplace50.Beam122	L147	L258	L147
17	workplace17.Beam49	K237	K237	K192	58	workplace8.Beam24	L350	L350	L420	99	workplace26.Beam75	L155	L155	L155
18	workplace18.Beam52	K238	K238	K193	59	workplace9.Beam27	L4	L4	L424	100	workplace27.Beam77	K62	K62	K62
19	workplace19.Beam55	K239	K239	L35	60	workplace10.Beam30	L418	L418	L217a	101	workplace28.Beam79	K38	K38	K38
20	workplace20.Beam58	K257	K257	L41	61	workplace11.Beam33	L418a	L418a	L220	102	workplace29.Beam81	K42	K42	K42
21	workplace21.Beam61	L192	L192	L361	62	workplace12.Beam36	L419	L419	L222	103	workplace30.Beam83	K37	K37	K37
22	workplace22.Beam64	L193	L193	L392	63	workplace13.Beam39	L419a	L419a	L253	104	workplace31.Beam85	K310	K310	K310
23	workplace23.Beam67	L3	L3	L393	64	workplace14.Beam42	L4a	L4a	L254	105	workplace32.Beam87	K14	K14	K14
24	workplace24.Beam70	L318	L318	L393	65	workplace15.Beam45	L390	L390	L4	106	workplace33.Beam89	K232	K232	K232
25	workplace25.Beam72	L319	L319	L41a	66	workplace16.Beam48	L394	L394	L347	107	workplace34.Beam91	K306	K306	K306
26	workplace1.Beam2	L321	L321	L476	67	workplace17.Beam51	L217	L217	L350	108	workplace35.Beam93	K311	K311	K311
27	workplace2.Beam5	L322	L322	L390	68	workplace18.Beam54	L217a	L217a	L418	109	workplace36.Beam95	K311a	K311a	K311a
28	workplace3.Beam8	L330	L330	L394	69	workplace19.Beam57	L220	L220	L419	110	workplace37.Beam97	K312	K312	K312
29	workplace4.Beam11	L345	L345	K194	70	workplace20.Beam60	L221	L221	L188	111	workplace38.Beam99	K267	K267	K7
30	workplace5.Beam14	L80	L80	K195	71	workplace21.Beam63	L222	L222	L4a	112	workplace39.Beam101	K7	K7	K317
31	workplace6.Beam17	L81	L81	K196	72	workplace22.Beam66	L420	L420	L418a	113	workplace40.Beam103	K317	K317	K267
32	workplace7.Beam20	L370	L370	K197	73	workplace23.Beam69	L424	L424	L419a	114	workplace41.Beam105	K308	K308	K314
33	workplace8.Beam23	L370a	L370a	K198	74	workplace26.Beam74	K290	K40	K290	115	workplace42.Beam107	K314	K314	K308
34	workplace9.Beam26	L370b	L370b	K199	75	workplace27.Beam76	K291	L147	K291	116	workplace43.Beam109	K11	K297	K11
35	workplace10.Beam29	L371	L371	K200	76	workplace28.Beam78	L16	K290	L16	117	workplace44.Beam111	K295	K231	K295
36	workplace11.Beam32	L372	L372	K201	77	workplace29.Beam80	L19	K291	L19	118	workplace45.Beam113	K9	K11	K9
37	workplace12.Beam35	L440	L440	K237	78	workplace30.Beam82	L216	L16	L24	119	workplace46.Beam115	K294	K295	K294
38	workplace13.Beam38	L440a	L440a	K239	79	workplace31.Beam84	L216a	L19	L244	120	workplace47.Beam117	K293	K9	K293
39	workplace14.Beam41	L441	L441	K257	80	workplace32.Beam86	L24	L216	L344	121	workplace48.Beam119	K296	K294	K296
40	workplace15.Beam44	L441a	L441a	L192	81	workplace33.Beam88	L244	L216a	L216	122	workplace49.Beam121	K297	K293	K297
41	workplace16.Beam47	L442	L442	L3	82	workplace34.Beam90	L344	L24	L422	123	workplace50.Beam123	K231	K296	K231

Appendix D: Beam priority rule LPT Evaluation

Table 14 Welder pair distribution LPT

WelderPair	1	2	3	4	5
1	K231	K40	L244	L4	K198
2	K297	L147	L344	L4a	K199
3	K296	K28	L344a	L41	K200
4	K293	L257	L390	L41a	K201
5	K294	L258	L394	L418	K237
6	K9	L14	L420	L418a	K238
7	K295	L17	L422	L419	K239
8	K11	L18	L422a	L419a	K257
9	K308	L36	L424	L476	L192
10	K314	L367	K183	L370	L193
11	K267	L416	K184	L370a	L3
12	K317	L416a	K187	L370b	L318
13	K7	L417	K188	L371	L319
14	K312	K290	L188	L372	L321
15	K14	K291	L253	L440	L322
16	K232	L16	L254	L440a	L330
17	K306	L19	L347	L441	L345
18	K311	L216	L35	L441a	L80
19	K311a	L216a	L350	L442	L81
20	K310	L217	L361	K192	L334
21	K37	L217a	L392	K193	L37
22	K38	L220	L393	K194	L37a
23	K42	L221	L393a	K195	L37b
24	K62	L222	K196	L382	
25	L155	L24	K197	L384	

Table 15 Process time and due date of Beams LPT

process time						due date				
51985	10397	4621	3466	2310		0	51985	62382	67003	70469
48519	10397	4621	3466	2310		0	48519	58916	63537	67003
47364	9242	4621	3466	2310		0	47364	56606	61227	64693
46209	9242	4621	3466	2310		0	46209	55451	60072	63537
45054	9242	4621	3466	2310		0	45054	54296	58916	62382
43899	6931	4621	3466	2310		0	43899	50830	55451	58916
42743	6931	4621	3466	2310		0	42743	49675	54296	57761
40433	6931	4621	3466	2310		0	40433	47364	51985	55451
38122	5776	4621	3466	2310		0	38122	43899	48519	51985
38122	5776	3466	3447	2310		0	38122	43899	47364	50811
35812	5776	3466	3447	2310		0	35812	41588	45054	48500
35812	5776	3466	3447	2310		0	35812	41588	45054	48500
35812	5776	3466	3447	2310		0	35812	41588	45054	48500
34657	4621	3466	3447	2310		0	34657	39278	42743	46190
33501	4621	3466	3447	2310		0	33501	38122	41588	45035
33501	4621	3466	3447	2310		0	33501	38122	41588	45035
33501	4621	3466	3447	2310		0	33501	38122	41588	45035
33501	4621	3466	3447	2310		0	33501	38122	41588	45035
33501	4621	3466	3447	2310		0	33501	38122	41588	45035
32346	4621	3466	2310	2291		0	32346	36967	40433	42743
17328	4621	3466	2310	2291		0	17328	21949	25415	27725
15018	4621	3466	2310	2291		0	15018	19639	23104	25415
15018	4621	3466	2310	2291		0	15018	19639	23104	25415
13863	4621	2310	2291			0	13863	18484	20794	
11552	4621	2310	2291			0	11552	16173	18484	

Table 8 Bin dispatch order (LPT)

Number	Destination	SPT	EDD	SST
1	workplace1.Beam1	L384	K231	L384
2	workplace2.Beam4	L382	K297	L382
3	workplace3.Beam7	L37a	K296	L37a
4	workplace4.Beam10	L37b	K293	L37b
5	workplace5.Beam13	L37	K294	L37
6	workplace6.Beam16	L334	K9	L334
7	workplace7.Beam19	K193	K295	L440
8	workplace8.Beam22	K192	K11	L440a
9	workplace9.Beam25	K197	K308	L441
10	workplace10.Beam28	K196	K314	L441a
11	workplace11.Beam31	K194	K267	L442
12	workplace12.Beam34	K195	K317	L372
13	workplace13.Beam37	L322	K7	L370a
14	workplace14.Beam40	L330	K312	L370b
15	workplace15.Beam43	L345	K14	L371
16	workplace16.Beam46	L80	K232	L370
17	workplace17.Beam49	L81	K306	L393
18	workplace18.Beam52	L321	K311	L393a
19	workplace19.Beam55	L3	K311a	L392
20	workplace20.Beam58	L318	K310	K193
21	workplace21.Beam61	L319	K37	L361
22	workplace22.Beam64	L193	K38	L35
23	workplace23.Beam67	L192	K42	K192
24	workplace24.Beam70	K257	K62	L476
25	workplace25.Beam72	K239	L155	L394
26	workplace1.Beam2	K238	L24	L390
27	workplace2.Beam5	K237	L222	L41a
28	workplace3.Beam8	K201	L220	L41
29	workplace4.Beam11	K200	L221	K197
30	workplace5.Beam14	K199	K197	L222
31	workplace6.Beam17	K198	L217a	L220
32	workplace7.Beam20	L440	K196	L221
33	workplace8.Beam23	L440a	L384	K196
34	workplace9.Beam26	L441	L393	L217a
35	workplace10.Beam29	L441a	L393a	K194
36	workplace11.Beam32	L442	L382	K195
37	workplace12.Beam35	L372	L392	L217
38	workplace13.Beam38	L370a	K194	K184
39	workplace14.Beam41	L370b	K195	K187
40	workplace15.Beam44	L371	K193	K188
41	workplace16.Beam47	L370	L37a	L322

Number	Destination	SPT	EDD	SST
42	workplace17.Beam50	L393	L37b	L330
43	workplace18.Beam53	L393a	L37	L345
44	workplace19.Beam56	L392	L217	L80
45	workplace20.Beam59	L361	K291	L81
46	workplace21.Beam62	L35	L16	K183
47	workplace22.Beam65	L476	L19	L321
48	workplace23.Beam68	L41a	L216	L424
49	workplace24.Beam71	L41	L216a	L3
50	workplace25.Beam73	K184	K290	L318
51	workplace1.Beam3	K187	L416	L319
52	workplace2.Beam6	K188	L416a	L193
53	workplace3.Beam9	K183	L417	L192
54	workplace4.Beam12	L253	L361	L420
55	workplace5.Beam15	L254	L36	K257
56	workplace6.Beam18	L347	L367	K239
57	workplace7.Beam21	L350	L253	K238
58	workplace8.Beam24	L188	L254	K237
59	workplace9.Beam27	L419a	L347	K201
60	workplace10.Beam30	L419	L35	K200
61	workplace11.Beam33	L418a	L350	K199
62	workplace12.Beam36	L418	L188	K198
63	workplace13.Beam39	L4a	L18	K291
64	workplace14.Beam42	L4	K192	K290
65	workplace15.Beam45	L394	K184	L253
66	workplace16.Beam48	L390	K187	L254
67	workplace17.Beam51	L222	K188	L347
68	workplace18.Beam54	L220	L440	L350
69	workplace19.Beam57	L221	L440a	L188
70	workplace20.Beam60	L217a	L441	L419a
71	workplace21.Beam63	L217	L441a	L419
72	workplace22.Beam66	L424	L442	L418a
73	workplace23.Beam69	L420	L17	L418
74	workplace26.Beam74	K291	L372	L4a
75	workplace27.Beam76	K290	L334	L4
76	workplace28.Beam78	L24	L14	L24
77	workplace29.Beam80	L16	L424	L16
78	workplace30.Beam82	L19	K183	L19
79	workplace31.Beam84	L216	L322	L216
80	workplace32.Beam86	L216a	L330	L216a
81	workplace33.Beam88	L422a	L345	L36
82	workplace34.Beam90	L422	L80	L367

Number	Destination	SPT	EDD	SST
83	workplace35.Beam92	L344a	L81	L422a
84	workplace36.Beam94	L344	L258	L422
85	workplace37.Beam96	L244	L370a	L344a
86	workplace38.Beam98	L36	L370b	L344
87	workplace39.Beam100	L367	L371	L244
88	workplace40.Beam102	L416	L321	L416
89	workplace41.Beam104	L416a	L257	L416a
90	workplace42.Beam106	L417	K28	L417
91	workplace43.Beam108	L18	L422a	L18
92	workplace44.Beam110	L17	L370	L17
93	workplace45.Beam112	L14	L3	L14
94	workplace46.Beam114	L258	L318	L258
95	workplace47.Beam116	L257	L319	L257
96	workplace48.Beam118	K28	L147	K28
97	workplace49.Beam120	L147	L476	L147
98	workplace50.Beam122	K40	L422	K40
99	workplace26.Beam75	L155	L193	L155
100	workplace27.Beam77	K62	L420	K62
101	workplace28.Beam79	K38	K40	K38
102	workplace29.Beam81	K42	L419a	K42
103	workplace30.Beam83	K37	L192	K37
104	workplace31.Beam85	K310	L394	K310
105	workplace32.Beam87	K14	L419	K14
106	workplace33.Beam89	K232	L390	K232
107	workplace34.Beam91	K306	K257	K306
108	workplace35.Beam93	K311	L418a	K311
109	workplace36.Beam95	K311a	L344a	K311a
110	workplace37.Beam97	K312	K239	K312
111	workplace38.Beam99	K7	L418	K7
112	workplace39.Beam101	K267	L344	K267
113	workplace40.Beam103	K317	K238	K317
114	workplace41.Beam105	K308	L41a	K308
115	workplace42.Beam107	K314	L41	K314
116	workplace43.Beam109	K11	K237	K11
117	workplace44.Beam111	K295	L244	K295
118	workplace45.Beam113	K9	K201	K9
119	workplace46.Beam115	K294	L4a	K294
120	workplace47.Beam117	K293	K200	K293
121	workplace48.Beam119	K296	L4	K296
122	workplace49.Beam121	K297	K199	K297
123	workplace50.Beam123	K231	K198	K231

Table 16 Welder pair distribution Random

WelderPair	1	2	3	4	5
1	K197	L4	K295	L36	K237
2	K40	L440a	K199	L37	L419a
3	L19	K14	K192	L216	L222
4	K187	L334	K37	L319	L417
5	L394	K62	L24	L41	L441
6	L254	K311	L14	L416a	L422
7	L18	L371	L384	L4a	L37a
8	L419	K238	K310	K196	K9
9	K314	L188	L253	K232	L416
10	L390	K184	K290	L17	K306
11	K193	L361	L81	L350	K231
12	L16	K296	L155	L440	L35
13	K183	K188	L192	K194	L216a
14	K11	K312	L318	L37b	K297
15	L372	L41a	K291	L344	K201
16	L321	L80	L370b	L322	K311a
17	L147	L258	L420	K317	K257
18	L344a	L370a	L347	L418	L393
19	L345	L3	K267	L217	K38
20	L330	L393a	L244	L221	L257
21	L367	L370	K42	L442	K294
22	L422a	K200	K198	L382	K239
23	K7	L392	K293	L220	L424
24	L441a	L217a	L476	K195	
25	K28	L418a	L193	K308	

Appendix E: Beam priority rule Random Evaluation

Table 17 Example of Process time and due date of Beams random

process time						due date				
2310	3466	42743	5776	2310		0	2310	5776	48519	54296
10397	3447	2310	2291	3466		0	10397	13844	16154	18446
4621	33501	2310	4621	4621		0	4621	38122	40433	45054
3466	2291	17328	2310	5776		0	3466	5757	23085	25396
4621	13863	4621	3466	3447		0	4621	18484	23104	26570
3466	33501	6931	5776	4621		0	3466	36967	43899	49675
6931	3447	2291	3466	2291		0	6931	10378	12669	16135
3466	2310	32346	2310	43899		0	3466	5776	38122	40433
38122	3466	3466	33501	5776		0	38122	41588	45054	78555
4621	3466	4621	6931	33501		0	4621	8087	12707	19639
2310	3466	2310	3466	51985		0	2310	5776	8087	11552
4621	47364	11552	3447	3466		0	4621	51985	63537	66984
3466	3466	2310	2310	4621		0	3466	6931	9242	11552
40433	34657	2310	2291	48519		0	40433	75090	77400	79691
3447	3466	4621	4621	2310		0	3447	6912	11533	16154
2310	2310	3447	2310	33501		0	2310	4621	8068	10378
10397	9242	4621	35812	2310		0	10397	19639	24260	60072
4621	3447	3466	3466	3466		0	4621	8068	11533	14999
2310	2310	35812	4621	15018		0	2310	4621	40433	45054
2310	3466	4621	4621	9242		0	2310	5776	10397	15018
5776	3447	15018	3447	45054		0	5776	9223	24241	27687
4621	2310	2310	2291	2310		0	4621	6931	9242	11533
35812	3466	46209	4621	4621		0	35812	39278	85487	90107
3447	4621	3466	2310			0	3447	8068	11533	
9242	3466	2310	38122			0	9242	12707	15018	

Table 18 Example of bin dispatched order (Random)

Number	Destination	SPT	EDD	SST			SPT	EDD	SST			SPT	EDD	SST
1	workplace1.Beam1	L334	K308	L384	42	workplace17.Beam50	L393a	L222	K196	83	workplace35.Beam92	L24	L192	L422a
2	workplace2.Beam4	L384	L347	L382	43	workplace18.Beam53	L188	K193	K194	84	workplace36.Beam94	L221	K294	L344
3	workplace3.Beam7	L382	L16	L37a	44	workplace19.Beam56	K184	L155	L193	85	workplace37.Beam96	L344a	L80	L216a
4	workplace4.Beam10	L37b	L18	L37b	45	workplace20.Beam59	L253	L334	K201	86	workplace38.Beam98	L416	L217a	L36
5	workplace5.Beam13	L37	L393a	L37	46	workplace21.Beam62	L419a	L4a	L318	87	workplace39.Beam100	L416a	K200	L367
6	workplace6.Beam16	L37a	L422	L334	47	workplace22.Beam65	L419	K257	L319	88	workplace40.Beam102	L417	K297	L417
7	workplace7.Beam19	K193	L370b	L370a	48	workplace23.Beam68	L392	K314	L81	89	workplace41.Beam104	L36	K197	L416
8	workplace8.Beam22	L318	L344a	L442	49	workplace24.Beam71	L41a	K28	L330	90	workplace42.Beam106	L367	L440	L416a
9	workplace9.Beam25	L192	K11	L440a	50	workplace25.Beam73	L418a	L318	L322	91	workplace43.Beam108	L14	L345	L17
10	workplace10.Beam28	K239	L371	L371	51	workplace1.Beam3	K188	L37a	K199	92	workplace44.Beam110	L17	L147	L14
11	workplace11.Beam31	L81	L319	L440	52	workplace2.Beam6	L418	L416a	K184	93	workplace45.Beam112	L18	K239	L18
12	workplace12.Beam34	K198	K192	L370b	53	workplace3.Beam9	L4a	L419	K187	94	workplace46.Beam114	L258	K184	K28
13	workplace13.Beam37	K196	L384	L441a	54	workplace4.Beam12	L476	L424	K183	95	workplace47.Beam116	L257	L361	L258
14	workplace14.Beam40	K197	L36	L370	55	workplace5.Beam15	L393	L442	K188	96	workplace48.Beam118	K28	L17	L257
15	workplace15.Beam43	K195	L244	L372	56	workplace6.Beam18	L35	K183	L217	97	workplace49.Beam120	K40	K291	L147
16	workplace16.Beam46	K238	L330	L441	57	workplace7.Beam21	L347	L420	L420	98	workplace50.Beam122	L147	L393	K40
17	workplace17.Beam49	K200	K196	K192	58	workplace8.Beam24	K187	L350	L424	99	workplace26.Beam75	L155	K37	L155
18	workplace18.Beam52	L345	K310	K193	59	workplace9.Beam27	L350	K295	L221	100	workplace27.Beam77	K62	K232	K62
19	workplace19.Beam55	K201	L188	L41	60	workplace10.Beam30	L4	L216a	L222	101	workplace28.Beam79	K42	L257	K42
20	workplace20.Beam58	L321	L476	L393	61	workplace11.Beam33	K183	K199	L220	102	workplace29.Beam81	K38	L221	K38
21	workplace21.Beam61	K237	L370a	L361	62	workplace12.Beam36	L361	L392	L217a	103	workplace30.Beam83	K37	K14	K37
22	workplace22.Beam64	L80	L14	L41a	63	workplace13.Beam39	L41	K7	L254	104	workplace31.Beam85	K310	K293	K310
23	workplace23.Beam67	L330	K198	L393a	64	workplace14.Beam42	L254	K306	L350	105	workplace32.Beam87	K232	K62	K14
24	workplace24.Beam70	L319	L367	L392	65	workplace15.Beam45	L217a	L422a	L253	106	workplace33.Beam89	K306	L418a	K306
25	workplace25.Beam72	K192	K195	L476	66	workplace16.Beam48	L217	L37b	L418a	107	workplace34.Beam91	K14	K238	K311a
26	workplace1.Beam2	K257	K194	L35	67	workplace17.Beam51	L420	K311	L4	108	workplace35.Beam93	K311a	L394	K232
27	workplace2.Beam5	K194	L344	L394	68	workplace18.Beam54	L394	K42	L419	109	workplace36.Beam95	K311	L24	K311
28	workplace3.Beam8	L193	L440a	L390	69	workplace19.Beam57	L244	L35	L4a	110	workplace37.Beam97	K312	L41	K312
29	workplace4.Beam11	L3	K231	K238	70	workplace20.Beam60	K291	L253	L419a	111	workplace38.Beam99	K267	L416	K7
30	workplace5.Beam14	K199	K296	L345	71	workplace21.Beam63	L216	K311a	L418	112	workplace39.Beam101	K317	L418	K267
31	workplace6.Beam17	L322	L417	K257	72	workplace22.Beam66	L344	L41a	L347	113	workplace40.Beam103	K7	L322	K317
32	workplace7.Beam20	L441a	K312	K200	73	workplace23.Beam69	K290	L419a	L188	114	workplace41.Beam105	K314	L390	K314
33	workplace8.Beam23	L441	L37	L80	74	workplace26.Beam74	L222	L441a	K291	115	workplace42.Beam107	K308	L217	K308
34	workplace9.Beam26	L370	L441	L3	75	workplace27.Beam76	L19	L370	K290	116	workplace43.Beam109	K11	L258	K11
35	workplace10.Beam29	L442	L254	K239	76	workplace28.Beam78	L390	K187	L19	117	workplace44.Beam111	K295	L193	K295
36	workplace11.Beam32	L370a	K290	K198	77	workplace29.Beam80	L422	L216	L216	118	workplace45.Beam113	K9	L382	K9
37	workplace12.Beam35	L440a	L372	L321	78	workplace30.Beam82	L422a	K188	L244	119	workplace46.Beam115	K294	K40	K294
38	workplace13.Beam38	L372	K38	K237	79	workplace31.Beam84	L220	L4	L24	120	workplace47.Beam117	K293	L3	K293
39	workplace14.Beam41	L371	K9	K197	80	workplace32.Beam86	L216a	L19	L422	121	workplace48.Beam119	K296	K237	K296
40	workplace15.Beam44	L440	L81	L192	81	workplace33.Beam88	L424	K267	L344a	122	workplace49.Beam121	K297	K201	K297
41	workplace16.Beam47	L370b	L321	K195	82	workplace34.Beam90	L16	K317	L16	123	workplace50.Beam123	K231	L220	K231

Table 19 Random Beam priority rule 5 experiment results

	Beam Heurestic:	Random		Beam Heurestic:	Random		Beam Heurestic:	Random
	Plate Heuristics:	SPT		Plate Heuristics:	EDD		Plate Heuristics:	SST
1	AvgWaitingTime:	8:42.233315187465	1	AvgWaitingTime:	4:36.648228310786	1	AvgWaitingTime:	9:10.195410787876
1	TotalProcessTime:	15:52:26.6884027931	1	TotalProcessTime:	12:39:56.1372515075	1	TotalProcessTim	15:59:19.2301318852
	Welder Working%	58,5		Welder Working%	63,0		Welder Working%	58,2
	Welder Walking%	0,6		Welder Walking%	0,6		Welder Walking%	0,6
	Welder Waiting%	40,9		Welder Waiting%	36,4		Welder Waiting%	41,2
2	AvgWaitingTime:	9:11.320286071473	2	AvgWaitingTime:	1:14.0823550596172	2	AvgWaitingTime:	9:14.250564428214
2	TotalProcessTime:	15:50:45.4491809163	2	TotalProcessTime:	12:43:15.4518972765	2	TotalProcessTim	15:11:03.4491728094
	Welder Working%	58,5		Welder Working%	63,0		Welder Working%	58,2
	Welder Walking%	0,6		Welder Walking%	0,6		Welder Walking%	0,6
	Welder Waiting%	40,9		Welder Waiting%	36,4		Welder Waiting%	41,2
3	AvgWaitingTime:	8:08.855186979143	3	AvgWaitingTime:	4:55.338275964164	3	AvgWaitingTime:	9:10.195410787876
3	TotalProcessTime:	15:54:13.9146675455	3	TotalProcessTime:	12:58:47.060939578!	3	TotalProcessTim	15:59:19.2301318852
	Welder Working%	58,4		Welder Working%	62,9		Welder Working%	58,2
	Welder Walking%	0,6		Welder Walking%	0,6		Welder Walking%	0,6
	Welder Waiting%	41,0		Welder Waiting%	36,5		Welder Waiting%	41,2
4	AvgWaitingTime:	8:09.181074232294	4	AvgWaitingTime:	4:48.892135270756	4	AvgWaitingTime:	9:10.195410787876
4	TotalProcessTime:	15:54:09.3565959565	4	TotalProcessTime:	14:10:52.6210066404	4	TotalProcessTim	15:59:19.2301318852
	Welder Working%	58,4		Welder Working%	61,7		Welder Working%	58,2
	Welder Walking%	0,6		Welder Walking%	0,6		Welder Walking%	0,6
	Welder Waiting%	41,0		Welder Waiting%	37,7		Welder Waiting%	41,2
5	AvgWaitingTime:	8:05.174731827744	5	AvgWaitingTime:	3:04.351559497462	5	AvgWaitingTime:	9:10.195410787876
5	TotalProcessTime:	15:55:11.903559396	5	TotalProcessTime:	12:45:14.5574165792	5	TotalProcessTim	15:59:19.2301318852
	Welder Working%	58,4		Welder Working%	63,0		Welder Working%	58,2
	Welder Walking%	0,6		Welder Walking%	0,6		Welder Walking%	0,6
	Welder Waiting%	41,0		Welder Waiting%	36,4		Welder Waiting%	41,2