Redesign of the **AutoStore** order processing line

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Redesign of the AutoStore order processing line

A multi-scenario discrete-event simulation study

Conducted at PostNL E-commerce Services

Houten, The Netherlands

UNIVERSITY OF TWENTE.

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Preface

This thesis marks the end of my career as an Industrial Engineering & Management student. In the past five years, I have completed both the bachelor's and master's programme in Enschede. I enjoyed my time at the University of Twente, during which I learned a lot, got to know lots of people and had a lot of fun.

To finalize my Masters, I conducted research at PostNL in Houten, where I was granted great freedom to come up with improvements for the AutoStore order processing line. I experienced great support and willingness to think about new designs. In the final phase of my research, we even have been able to conduct some pilot tests by building parts of the proposed new layouts in Houten.

During my work at PostNL, I have worked in the pleasant environment of the operations support department. I want to thank all employees of PostNL ECS and more specifically the operations support team for creating such an environment for me and for providing me with all the required information for my research.

The FSO (IT) department also deserves a special note for helping me obtain the right data and explaining me all the systems that are involved in the AutoStore process. I would like to specifically thank Wini for taking all the time required to help me.

I would like to thank Samir, Volkan and the other members of the AutoStore team for being cooperative and enthusiastic about possible improvements and for explaining me all the details of their work. Their enthusiasm motivated me to come up with a good solution.

I would like to thank Martin Vendel, my second supervisor at PostNL, for providing me with an excellent start at PostNL. Martin organized an optimal introduction for me and helped me laying the foundation of my research. We had some very productive meetings in which we were able to boost the progression of my research.

I would like to thank Michiel Kalis, my main supervisor at PostNL, for all his support during my research. Michiel organized company visits for me and provided me with the required data, information and connections. Michiel also helped me come up with new ideas and provided me great freedom for both implementation and development of these new ideas.

I would like to express my gratitude to Martijn Mes for providing me with useful feedback as my supervisor at the University of Twente during the feedback meetings that we had and to Engin Topan for being my second supervisor and for providing me with a fresh view and useful feedback on my work.

Lastly, I would also like to thank my family and friends for supporting me during my research, helping me move to Amersfoort and for proofreading this report.

I hope you enjoy reading my master thesis.

Stefan Tjeerdsma,
Amersfoort, July 2019

Management Summary

PostNL fulfilment is a subsidiary of PostNL that offers fulfilment services to small and medium-sized web shops. The fulfilment centre in Houten has recently been modernized using a robotic automated goods-to-man system called the AutoStore, including a processing line that further processes the orders presented by the AutoStore. In the business case for this considerable investment, a productivity of at least 30 orders per invested manhour was foreseen while the average productivity should exceed 30 orders per manhour. The productivity in the current situation is insufficient for meeting this target. Although the AutoStore itself performs as planned, the processing of the orders that come out of the AutoStore requires improvement. The processing line that processes the orders presented by the AutoStore is the cause of the lacking performance and is therefore the focus of our research. The main research question of our research was therefore formulated as:

"How should the AutoStore order processing line be adjusted and redesigned such that the fulfilment centre can achieve its target productivity and output rate sustainably?"

We use layout planning, capacity planning and production management to improve the performance of the processing line.

Our research started with a thorough analysis of the current situation at PostNL fulfilment. We identified the characteristics of the orders that are processed by the AutoStore and analysed the performance of the current processing line.

We conducted a literature review to find methods and techniques that we can use to optimize and redesign the current AutoStore order processing line. We first focussed on determining how to propose new layouts for the processing line. We found that most of the sources use a distance minimization approach to solve the layout problem, while travelling distance does not seem to be of high priority at PostNL. We therefore searched for other approaches and finally used the product grouping approach to create a cellular layout next to the distance minimization layout.

Next to these new layouts, we investigated the effects of applying line-balancing and packaging automation in the current layout as well as in the new layout. Having applied all theory to the processing line at PostNL, we end up with five proposed interventions:

1. (Offline) Line balancing and minor optimizations. We shifted workload between the stations to balance workload and removed unnecessary process steps.
2. Distance minimization. Following most of the scientific literature found, we compressed the processing line to minimize the travel distance of orders and as a result, created a new layout.
3. Product grouping. We created another layout that uses specialized production lines for specific order groups. This way, orders only pass those processing stations and processing steps that they require.
4. Online pro-active line balancing. The first intervention only shifts entire processing steps between stations which still results in an imbalance in workload division. In this intervention, we proposed the use of a dynamic pick to light system that can assign workload to a processing station online (during a shift), thereby relieving a busy workstation and making use of available capacity at another workstation.
5. Automated packing. In our final intervention, we evaluated the effects of integrating an automated packing machine in the processing line, effectively leading to a reduction of the number of workplaces to be occupied in the processing line.

The effect of implementing the interventions has been evaluated using a simulation model that we created in Technomatix Plant Simulation by Siemens. Our simulation model has been verified and validated thoroughly to assure the fit between our model and reality. We evaluated the performance of the proposed interventions using various performance indicators including the cumulative number of unfinished orders in a simulation run, the number of orders processed per invested manhour (i.e. the productivity) and the utilization of the workstations in the processing line.

The results of our evaluation of the interventions in terms of the achieved productivity are displayed in Figure 1. The figure contains the productivity performance for all the tested combinations of interventions for several demand levels. For example, 200% refers to a doubled demand rate compared to the current demand level.

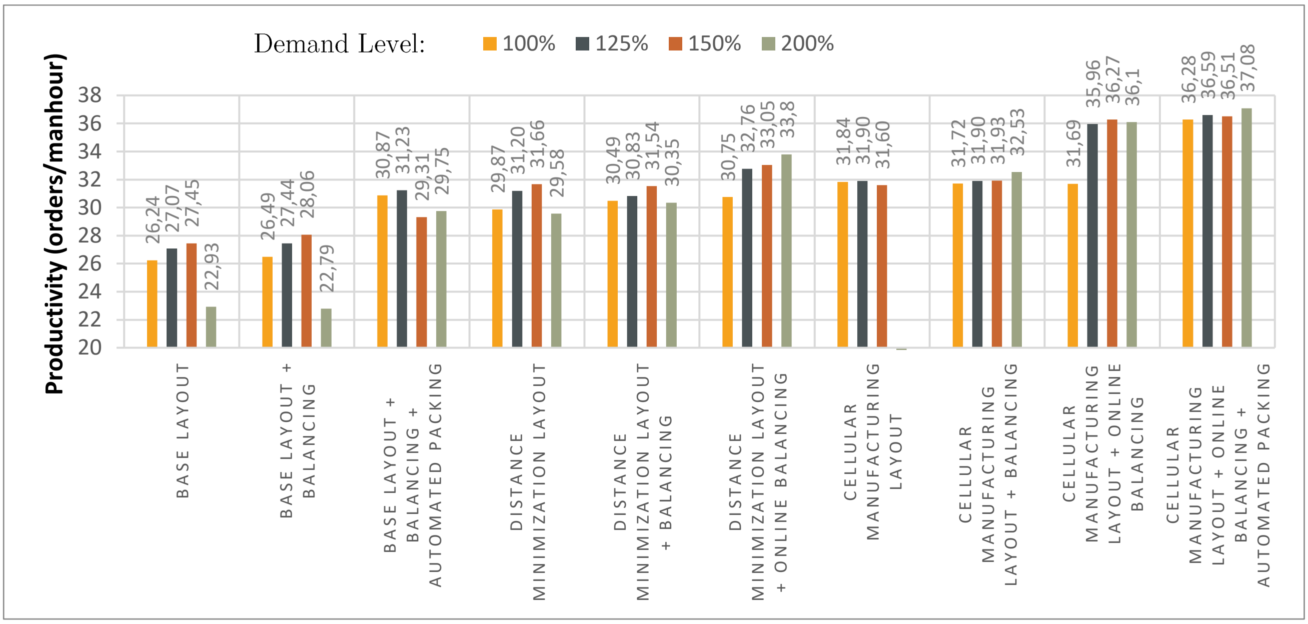

Figure 1 - An overview of the performance results of the intervention combinations per demand level

From the performance of the various intervention combinations, we conclude that the cellular manufacturing layout in combination with online line balancing performs best with a productivity score of 36,28 orders per manhour. This configuration induces potential savings of € 54.212,15 per year.

To assure ourselves of the validity of our simulation model with respect to the productivity achieved in the cellular manufacturing layout, an onsite test setup was used to test the performance of the proposed specialized order processing line for so-called Bus-parcels. The performance achieved using this test-setup closely resembled the simulated performance while the performance of this specialized processing line is expected to increase even more if the intervention is implemented entirely.

To conclude, we recommend PostNL to:

- Implement the cellular manufacturing layout in combination with the proposed line balancing if a system configuration is desired that is able to cope with the current demand rate.
- Implement online line balancing that uses a dynamic pick-to-light system to further improve the performance of the AutoStore order processing line future demand scenarios.
- Investigate the possibility for order inflow from other competence centres to justify an investment in an automated packing machine.
- Further investigate the use of the specialized bus parcel line in the cellular manufacturing layout for gift wraps, customized packing and single line batch picking.

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List of Abbreviations

Abbreviation:	Represented term:	Definition:
CC	Competence Centre	A competence centre is an operational department within the fulfilment site of PostNL that focusses on a specific type of customers.
SLP	Systematic Layout Planning	Systematic Layout Planning is a systematic procedure that can be used to create a facility layout design.
WMS	Warehouse Management System	A Warehouse Management System tracks goods throughout the site and stores data concerning these goods.
ESB	Enterprise Service Bus	An Enterprise Service Bus can be used to connect IT applications that use a different programming language.
API	Application Programming Interface	An Application Programming Interface is a set of rules and instructions that must be respected in order to interact with an IT system.
FSO	Functional Support Department	The functional support department is responsible for all IT services running at the fulfilment site. This includes maintenance, changes, and data extraction for users.
RoW	Rest of World	A Rest of World label is used for orders that are send outside of the European Union. It includes additional information compared to normal shipping labels.
KPI	Key Performance Indicator	Key Performance Indicators are variables that can be used to analyse the performance of an organization.
ILP	Integer Linear Programming	Integer Linear Programming is a mathematical formulation that aims to solve a problem to optimality where all variables are limited to integer values.

1. Introduction

Our research is performed at PostNL E-commerce services in Houten to finalize my master's degree in Industrial Engineering & Management at the University of Twente. The research concerns the redesign of a parcel processing line with the aid of simulation in Siemens' PlantSimumlation to assess future performance. We use several approaches to construct new layout alternatives and compare traditional distance-based methods with alternative methods that base the layout design on other performance measures.

In this chapter, we introduce PostNL in Section 1.1. Section 1.2 zooms in on PostNL Fulfilment as a division of PostNL. In Section 1.3, we introduce the problem studied in this research. The research itself is introduced in Section 1.4. Our approach to the research questions and an overall research methodology is introduced in Section 1.5 and Section 1.6 respectively. Lastly, in Section 1.7, we shed a light on the structure of the rest of the present report.

1.1 Introduction to PostNL

In this section, we provide information and background on PostNL as an organization.

PostNL is the market leader in parcel and postal services in the Netherlands. PostNL originates from PTT Post that was originally founded in 1795. PostNL was founded after a transition from PTT post to TPG Post in 2002, a transition from TPG Post to TNT Post in 2006 and a subsequent split-up of TNT Post into PostNL and TNT Express in 2011. PostNL performs its main activities around three core business pillars being parcels, mail and international services.

In 2018, PostNL generated a revenue of 2.772 million euro of which 1.330 million euro was generated by the parcel department of PostNL by delivering over 251 million parcels. The total revenue of PostNL is related to its parcel department for 48% and the handled parcel volume shows an increasing growth pattern with a 21.3% increase in 2018 while the mail volume is decreasing at a rate of 10.7% in 2018. All in all, it can be concluded that the parcel department of PostNL is the department with most potential for the future due to rapidly increasing demand for the parcel services. PostNL expects 50% of its revenue to be raised by its e-commerce activities in 2020. In Figure 2, the volume development of both the parcel and mail market for PostNL is displayed.

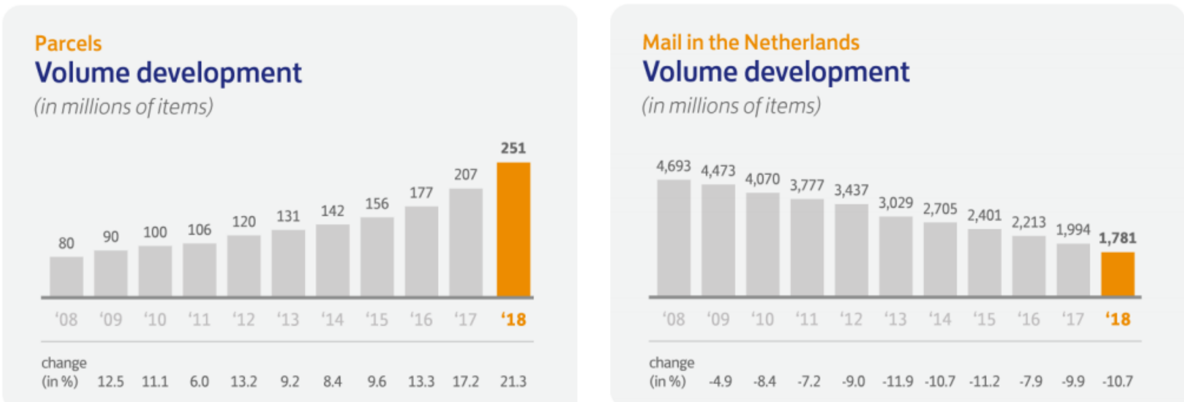

Figure 2 – Mail and parcel volume development for PostNL

1.2 Introduction to PostNL Fulfilment

In this section, we introduce PostNL E-commerce services, the division of PostNL where we conduct our research.

To sustain the competitive leading position of PostNL in the dynamic parcel market, PostNL launched and supported several activities that attract additional customers around its parcel delivery services. These include, for example, installing washing machines for consumers (Extra@Home) or secured delivery of valuable goods (Mikropakket).

Next to these initiatives, PostNL offers fulfilment services. The aim of this service is to provide small to medium-sized web shops with the possibilities that large players in the market have due to their size. At the PostNL fulfilment centre in Houten, webshops can outsource their inventory holding, order picking, packaging and backend service activities. Using the fulfilment service of PostNL, these web shops are then able to offer the same service to their customers compared to companies such as Amazon or Bol.com. Among other advantages, this includes order processing up to 24.00 o'clock, scaling possibilities during peak demand, professional packaging and high pick accuracies.

The aim of PostNL E-commerce services is to pursue a "best in class" position in this market to assure a sustainable future for its parcel delivery network that can be partially fed by the fulfilment centre.

1.3 Problem Introduction

In this section, we introduce the problem in scope of our research. We first give a problem background that introduces the environment of the problems and then select the core problem to be solved using a structured problem cluster.

1.3.1 Problem Background

In the PostNL fulfilment centre in Houten several processes are executed. These contain the intake of stock from customers, the long-term storage of stock, transferring long term stock to pick storage, picking of goods for an order and packing orders. A rough overview of the sequence of processes is provided in Figure 3.

Figure 3 - Overview of the fulfilment process

The fulfilment centre in Houten is organized in six so called competence centres. These competence centres are the departments within the site. All competence centres have their own specific function. The six competence centres are AutoStore, Bulk, Expedition, Depot Lost and Found Parcels (DLFP), Secured Storage and Production. The Bulk competence centre focusses on the long-term storage of goods in large quantities and the storage of goods that are exceptionally large or heavy. The Expedition competence centre receives and handles incoming goods (from customers) and ships finished orders at the end of the fulfilment process. Depot Lost and Found Parcels handles all lost parcels that cannot be returned to the owner due to a variety of reasons. At this competence centre, parcels are either sold or destroyed. At secured storage, expensive items such as laptops or prepaid cards are stored and handled in a secured area with limited access. At the production competence centre, large volume, low variability orders are fulfilled. An example of these type of orders are the orders of the company "X". This company sells large amounts of one single product per day. It is thus more efficient to handle these orders separately compared to integrating the orders in other processes.

The last competence centre is the AutoStore competence centre in scope of this research project. PostNL invested in an advanced AutoStore system in 2017 to be able to handle a large variety of fulfilment services efficiently and to improve its competitiveness in the fulfilment market. An AutoStore is a highly automated goods-to-man system that is used to automate the picking of orders. A goods-to-man system picks the items in an order and delivers these items in the right sequence to an operator. An AutoStore uses autonomous robot carts that pick goods and bring these goods to the operator. Although the AutoStore system is currently implemented and functioning as expected, the process that follows upon the new AutoStore, from now on denoted by *the AutoStore order processing line*, is not able to cope with the high output speed of the AutoStore.

In practice this results in an unbalanced processing line in which the order pickers (that operate the pickports of the AutoStore) must wait for empty space on the conveyer belt to put their processed orders on before they can continue with the next order. The imbalance in the processing line leads to a decreased output of the entire system. Due to this bottleneck, the target productivity and output rates that have been set during the purchasing process of the AutoStore cannot be met.

To get an idea of the current setup of the AutoStore order processing line, an overview of the AutoStore order processing line is displayed in Figure 4. In the figure, we roughly distinguish between the AutoStore itself, that is highlighted by the blue line and is not in scope of this research, and the AutoStore order processing line, highlighted by the red line. The order processing line that receives order from the AutoStore starts at the pickports attached to the AutoStore. From heron, several processing stations are visited using a conveyor belt. The stations are marked using numbers in Figure 4 and include the Pickports (1), Consolidation area (2), Order reject (3), Order Control (4) and the Expedition area(5). We will elaborate on the stations in more detail in Chapter 3.

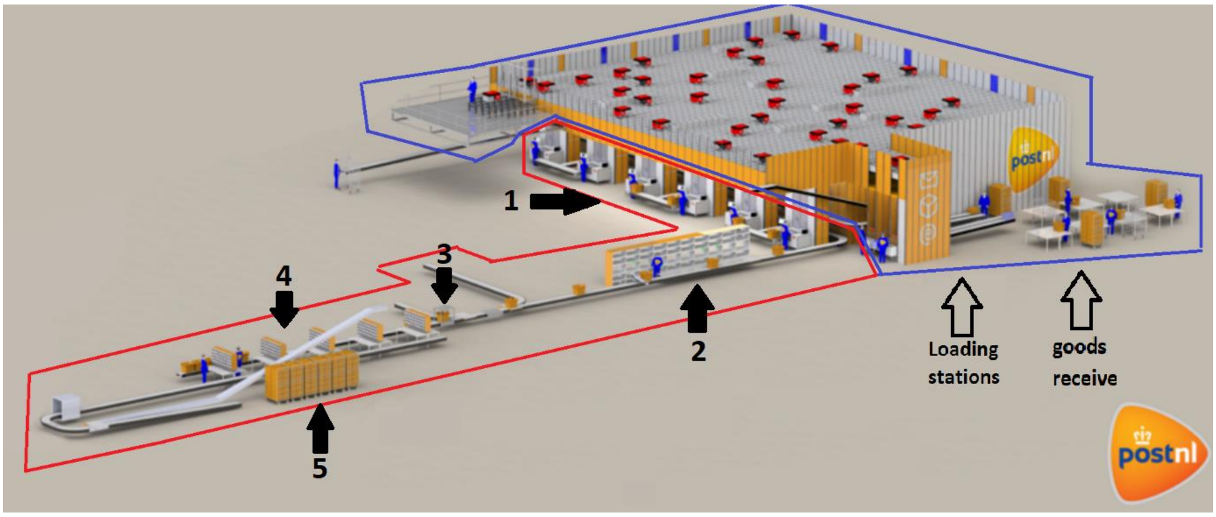

Figure 4 - Overview of the AutoStore and the order processing line

The AutoStore has a capacity of 21,000 containers that are being handled by 42 robots. The autostore is designed to be able to deliver more than 1200 different SKUs per hour to 6 different pickstations. The AutoStore is filled using two loading stations that receive their goods from the goods receive area. Note that the loading process of the AutoStore and the AutoStore itself (all highlighted in blue in Figure 4) are not in scope of this research.

1.3.2 Problem Cluster

To clarify the problem context and to display the coherence between problems that occur in the AutoStore order processing line, the observed problems are displayed in the problem cluster of Figure 5.

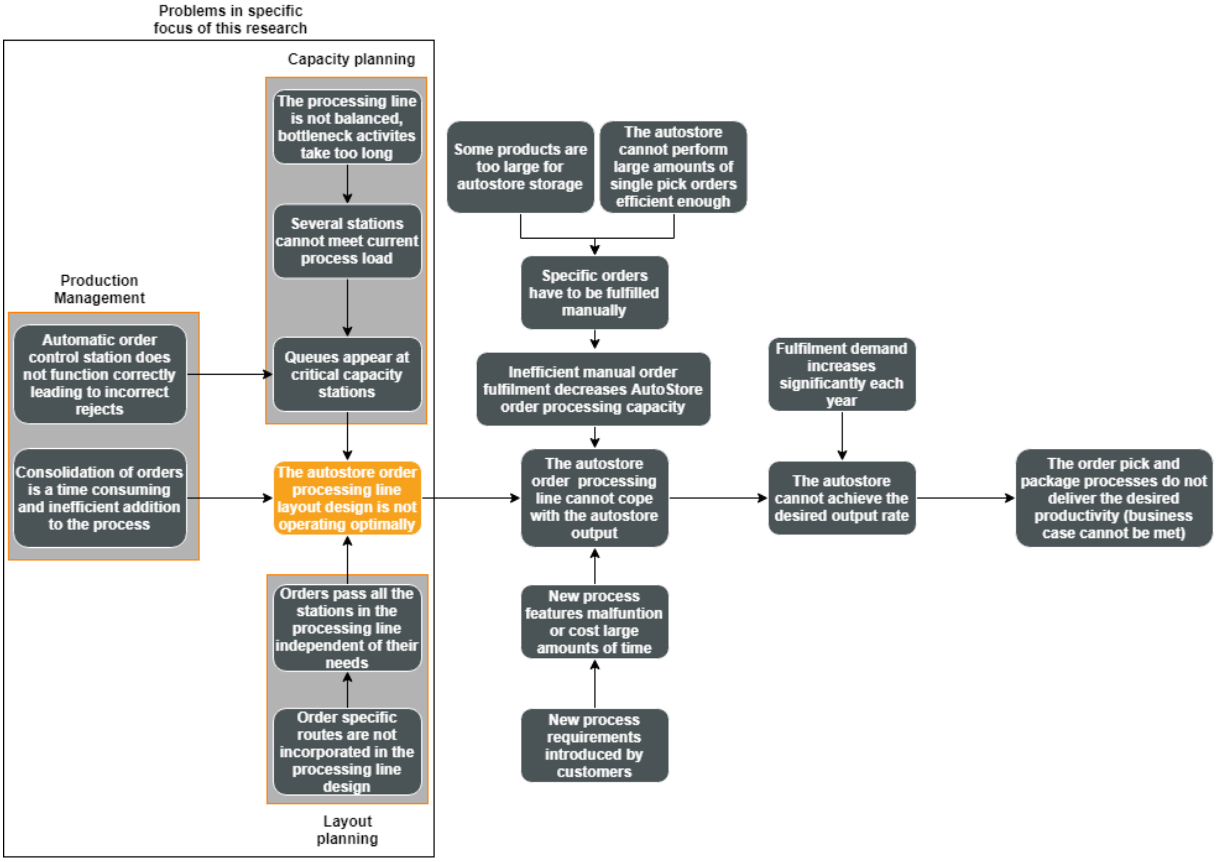

Figure 5 - Problem cluster

The initial problem statement by PostNL is the problem at the end of the causal chain displayed in the problem cluster: *The order pick and package processes do not deliver the desired productivity.* The current average productivity achieved is 23.5 orders per man hour while the business case for the AutoStore requires the productivity to be 50 orders per man hour with a minimum of 30 orders per man hour. The desired productivity is thus structually above 30 orders per man hour.

From hereon, investigation and observation of the processes led to several causes. Some of these causes, such as the strong demand increase, the size limit of the AutoStore and the current inability to pick large amounts of single item orders efficiently using the AutoStore are considered to be either causes that cannot be influenced or that we, in case of the strong demand increase, do not want to change. At least, these causes are not in scope for this research because they either are provided by the environment or caused by the bought AutoStore system.

Lastly, we will not incorporate the problems "New process requirements introduced by customers" and "New process features malfunction or cost large amounts of time" since PostNL has to fulfil the process requirements of customers to remain competitive in the e-fulfilment market. For example, PostNL offers a service to add inserts (i.e. advertising materials) to the processed orders. This service requries additional processing steps, however, it has to be offered since competitors in the market offer the same service. The requirements of customers can thus hardly be renounced. As a result, we cannot influence arrising customer requirements and the extent to which PostNL should comply with the requirements remains a management decision. We therefore consider this problem to be out of scope.

The problems that are in scope of our research can be divided into three research dimensions being capacity planning, production management and layout planning. The dimensions and the problems that are associated with them are displayed in Figure 5. These three dimensions form the foundation of this reasearch and represent the scientific research areas the problems are considered to be part of. Moreover, the tools that we use to encounter the selected problems also come from these three research dimensions.

1.3.3 Selecting the Core Problem

To select the core problem, we follow the causal chain upstream as far as possible starting from the problem statement by PostNL at the rightest position. Branches that cannot be influenced as explained in the previous paragraph are not followed to their root cause.

In the problem cluster displayed in Figure 5, the selected core problem is displayed in orange. Although there are several problems that cause the selected problems, we chose to not follow the causal chain further upstream. The upstream problems are strongly related and can therefore be solved efficiently simultaneously. In other words, we will solve all problems that lead towards the selected core problem and thus solve this core problem as well. The selected core problem to be studied and solved in this research therefore is:

"The AutoStore order processing line layout design is not operating optimally"

In solving the selected core problem, all sub-problems that cause the core problem will be solved and new customer requirements will be incorporated in the solutions provided at the end of this report. A possible example of new customer requirements is providing a picture to the customer from the content of a parcel just before it is closed and send away.

1.4 Research Introduction

Now that we identified the core problem to be solved, we introduce our approach to solve it. That is, we define what must be done to solve the problem. We introduce the aim and scope of our research and then define the research questions that should be answered to solve the core problem chosen in the previous section. Next to defining the research questions, we also explain our approach to solving each individual research question. Lastly, we show where the answer to each research question can be found in this report.

1.4.1 Aim of our Research

The aim of the research conducted in this report is to improve the design of the AutoStore order processing line in such a way that the productivity of the fulfilment process is not limited by the processing line both in the current situation as well as in the expected future operating environment.

The new design for the AutoStore order processing line should thus be able to cope with future demand growth and the line should be able to perform all activities required by the future customers of PostNL fulfilment.

The product of this research eventually contributes to the operational productivity of the e-fulfilment centre of PostNL and, as a result, to the role that PostNL can play in the e-fulfilment market.

1.4.2 Scope of our Research

To ensure a successful completion of this master thesis project, the research conducted is limited to relevant and known scope.

Although the facility studied in this research project is a facility in which several processes run in parallel as described under Section 1.3.1 “Problem environment”, this research only focusses only on the process that follows upon the AutoStore. Moreover, we do not consider the distribution of parcels or any other activity that is not performed within the fulfilment site in Houten.

The process steps that are in the scope of this research are displayed in orange in the earlier introduced process diagram in Figure 6.

Figure 6 - Scope process steps

The process that comprises the orange steps are performed using one conveyor belt system. This conveyor belt system entrails the scope field of the research.

1.4.3 Research Questions

In order to achieve the goals mentioned in Section 1.4.1 we formulated several research questions that must be answered. These research questions form the backbone of the research and together contribute to a satisfying result for all stakeholders. The research questions can be divided into groups relating to the phase of the research they belong to. The questions presented below will be linked to their respective research phase in the next chapter.

To start with, we now formulate the main research question to be answered in this research. The main research question is formulated as follows:

"How should the AutoStore order processing line be adjusted and redesigned such that the fulfilment centre can achieve its target productivity and output rate sustainably?"

Next to the main research question, we formulate several sub-research questions that must be answered to be able to successfully answer the main research question. The sub-research questions are listed below.

1. What is the current design layout of the AutoStore order processing line and what is the current performance of the layout?

- What does the current processing line layout look like?
- Which stations make up the current AutoStore order processing line layout?
- What is the utilization of the stations in the current processing line?
- Which stations are the bottleneck in the current processing line? Are all stations required?
- Which discrepancies exist between the designed use of the processing line and the actual use of the processing line?
- Which product groups are currently being handled by the processing line?
- What is the downtime percentage of the current processing line?
- How does PostNL assess the current performance of the order processing line?
- What is the maximum capacity of the current processing line layout?

2. How should an order processing line be designed according to existing literature?

- Which methods can be used to come to a new layout design for a production line?
- Which solutions are currently available to efficiently process products in a factory?
- How can manufacturing system designs be evaluated?
- How can evaluation results be validated and verified?

3. How can the order processing line be designed in such a way that it is able to cope with future demand and capacity growth?

- What future demand growth is expected in the e-fulfilment market? To what degree is this growth also applicable for PostNL?
- Which future requirements should be incorporated in the processing line design?
- Which functionalities do competitors in the market offer?
- What layout designs can be used to process high volumes of demand?

4. How will the new processing line layout designs perform with respect to the current situation under various system and capacity settings?

- What are the advantages and disadvantages of the different layout proposals?
- What capacity is needed at each station in the new setups?
- What are the capacity limits of the new layout designs for future growth?
- Which output rate can be achieved in the new layout designs?
- What is the average processing time of an order in the new layout designs?
- Which productivity can be achieved in the new layout designs?
- What are the projected costs of the various layout adjustments suggested?
- What operational cost reduction can be achieved using the new design layouts?
- What is the robustness of the proposed layout designs with respect to order characteristics and demand variation?

5. What will be the effects on the requirements for the IT systems of the AutoStore order processing line and what are the other consequences of the new processing line layout designs?

- What changes in the IT landscape are required for adapting a new processing line layout?
- What is the effect of the new processing line layouts on the requirements set for items to be suitable for the processing line?
- What will be the effects for other processes steps in the fulfilment centre such as long-term storage?
- What instructions are needed for correct implementation of the new layout design?

1.5 Approach to the Research Questions

Although the previous section provides a decent basis for our research, we now clarify the specific actions required to answer the individual research questions. We will repeat the provided research questions and include a short explanation of the approach for each research question below.

1. What is the current design layout of the AutoStore order processing line and what is the current performance of the layout?

For the first research question, we will use both available data at PostNL and our own observation to base our answer on. During the procurement of the AutoStore system, extensive documentation has been created on almost all aspects of the AutoStore system ranging from software documentation to flowcharts. We will validate the provided data by PostNL and enrich the data with observations at the site where needed. We will then translate the data into a comprehensive answer to the research question, existing out of a process description, visual representation and an overview of the applicable and used performance indicators with their respective performance values.

2. How should an order processing line be designed according to existing literature?

We will conduct a systematic literature review to answer research question two. Next to the articles that we find in scientific databases, we will also use knowledge and study materials obtained during the Industrial Engineering and Management master's course. We will, in the latter case try to reproduce the sources of the study materials as much as possible.

3. How can the order processing line be (re)designed in such a way that it is able to cope with future requirements and demand growth?

To be able to answer research question three, we will start to determine what future requirements and expected demand growth will be. Requirements and expected demand growth can be determined by investigating market demand growth patterns and by looking at competitors in the industry. Forecasting of demand is not in scope of our research. Instead, we will use existing forecasts made by PostNL to determine the requirements for our system design. The requirements will then be incorporated in the design process of a new layout. As a part of the last phase of our research, the performance and requirements of the final layout will be assessed.

4. How will the new processing line layout designs perform with respect to the current situation under various system and capacity settings?

We will evaluate the performance of the new layout designs compared to the current situation using simulation. We use simulation to be able to deal with the large number of variables that influence the AutoStore order processing line and to assess the effects of changing these variables both individually and jointly. The variables that influence the AutoStore will be addressed in Chapter 3. Especially the effects of changing several variables simultaneously are hard to capture in mathematical models that can be used as an alternative to simulation. Evaluation using simulation translates into building models of the new layout options and creating a version of the model that resembles the layout as it is today. For each configuration, we then find the optimal system settings in terms of the number of employees used and the number of workstations used. The performance obtained using the optimal settings can then be compared for all configurations.

5. What will be the effects on the requirements for the IT systems of the AutoStore order processing line and what are the other consequences of the new processing line layout designs?

The operational effects of the new processing line layout can be assessed using the output of our simulation model. Using this output, we can investigate how the rest of the organization responds to the changed performance using some experiments in the current facility.

1.6 Research Methodology

To structure our approach to the observed problems at PostNL, we use a structured approach that introduces phases in our research. We selected the managerial problem-solving method (MPSM) (Heerkens & van Winden, 2012) as this approach is suitable for problems encountered in operational and business environments. The MPSM exists out of 7 phases as displayed in Figure 7.

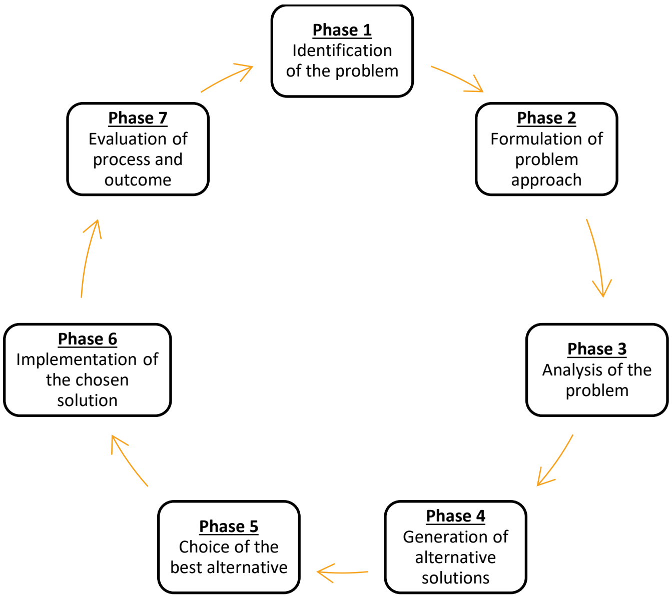

Figure 7 - The managerial problem-solving method cycle

Although we follow all steps in the MPSM up to and including the fifth phase, we do not implement the solutions since significant time is needed to change the facility layout. Instead, we replace phase 6 and 7 in the MPSM by a simulation study that should be reliable enough to be able to evaluate the different solutions proposed in our research.

A more low-level problem approach (that is formulated in phase 2 of the MPSM) is displayed in Figure 8. We here show in more detail what is included in phases 3, 4, 5 and the introduced simulation study phase. Note that we also propose a separate step for evaluation of the effects of the solutions for daily operations and the environment of the new system layout.

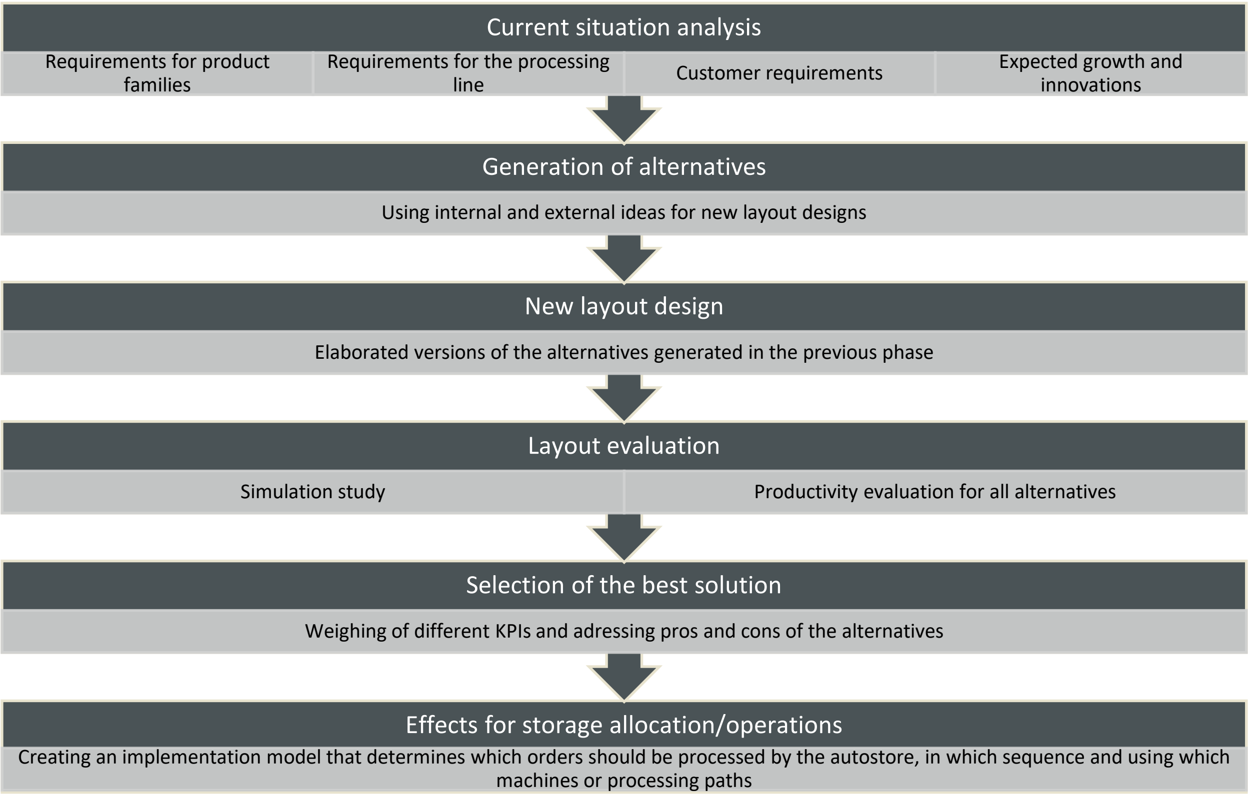

Figure 8 - Detailed action plan for phases 3, 4 and 5 of the MPSM.

1.7 Structure of the Report

In this section, we introduce the structure of the report. The structure of the report is strongly related to the chronological sequence of the research itself. In this chapter, we introduced the problem, the problem environment and the research itself. The structure of the rest of the report will follow the order displayed in Figure 9. The chevron on the left side of each chapter contains the number of the research question that will be answered in that chapter.

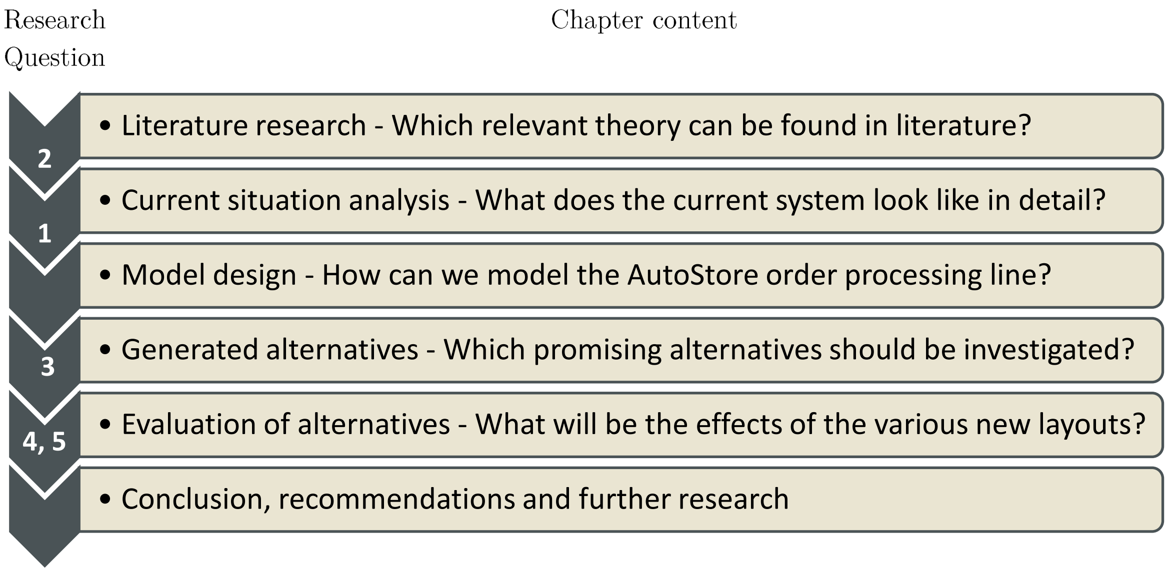

Figure 9 - Readers guide, an overview of the chapters

1.8 Conclusion

In this chapter, we introduced our research topic and PostNL Fulfilment, the subsidiary of PostNL where we conduct our research. This research focusses on improving the performance of the AutoStore order processing line that processes all orders picked from the AutoStore storage. The AutoStore itself is not in scope of our research. We improve the performance of the processing line by applying existing and new techniques in the line balancing and capacity planning, production management and the layout planning domain. We identified problems that occur in the AutoStore order processing line and provided a structured overview of these problems using a problem cluster. We then determined the core problem to be "*The AutoStore order processing line layout design is not operating optimally*" and introduced our main research question as *"How should the AutoStore order processing line be adjusted and redesigned such that the fulfilment centre can achieve its target productivity and output rate today and in the future?"*. Thereafter, we introduced several sub-research questions that help us answer the main research question. For each of these research questions, we provided our approach to the questions next to an overall research methodology. The overall research methodology used for our research is the Managerial Problem-Solving Method Heerkens & van Winden, 2012).

2. Literature Review

In this chapter, we review existing literature that addresses problems comparable to the problems we try to solve in our research. Moreover, we provide background information on some important methods that we use to solve the problems at hand. In Section 2.1, we describe the research field that we conduct our research in while Section 2.2 provides an overview of the techniques used in the research field. Section 2.3 introduces the Systematic Layout Planning procedure that we can use to generate alternative layouts. Section 2.4 reviews the general process layouts available. Section 2.5 describes a methodology to move to a production cell layout. In Section 2.6, an optimization technique for existing assembly lines is presented. Lastly, Section 2.7 introduces simulation to evaluate the proposed layout alternatives.

2.1 Research Background

We conduct our research in the field of facilities planning, capacity planning & line balancing and production management as introduced in the problem cluster in Figure 5.

2.1.1 Facilities Planning

A facility is something that is built, installed or established to serve a specific purpose. Facilities planning in this sense refers to the process by which a facility management organization envisions its future by linking its purpose to the strategy of the overall organization and by developing goals, objectives and action plans to achieve that future, according to the International Facility Management Association (International Facility Management Association, 2009). Facilities planning covers several aspects that should be taken into consideration to obtain a functional and complete facility. An overview of the facilities planning research area is provided in Figure 10.

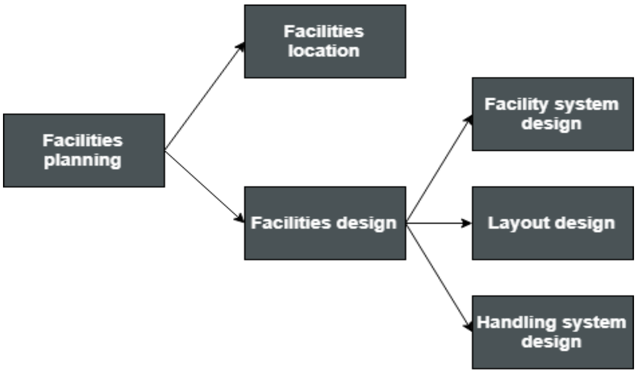

Figure 10 - Facilities planning hierarchy (Tompkins, 2010)

Facilities planning can be split up in determining the facilities location and determining the facilities design. Where facilities locations is concerned with the placement of the facility in its external environment, facilities design focusses on the internal design of the facility. Facilities location problems are often solved using integer programming formulations such as the capacitated or incapacitated facility allocation formulations. The facilities design exists out of a system design, a layout design and a handling system design. Whereas the system design refers to the (IT) systems that support the facility in its operations, the layout design is associated with the location of resources within the facility with respect to each other. The handling system design specifically focusses on the transportation of goods between resources within a facility.

Considering our research and the given situation at PostNL, we will focus on only some of these aspects. Our research focus will be on the layout design and the handling system design. The location of the fulfilment centre in Houten is fixed and there are no problems that suggest a redesign of the system design of the facility. We will, however, assess the impact of our interventions on the facility system design.

2.1.2 Capacity Planning

Capacity planning and control is the task of setting the effective capacity of the operation so that it can respond to the demands placed upon it. This usually means deciding how the operation should react to fluctuations in demand (Slack et al, 2015).

According to Slack et al (2015), capacity planning focusses on several aspects of performance:

- Costs, costs are mainly affected by the balance between demand and capacity.
- Revenues, the revenue of an operation is a direct consequence of both costs and demand.
- Working capital, the working capital is strongly related to the build-up of finished goods inventory. The build-up of this inventory requires investments.
- Quality, quality is related to capacity planning since instable production requires temporary employees that is not yet experienced and may therefore cause the overall quality of the produced goods to drop.
- Speed, speed refers to the amount of time required to respond to demand. In other words, it refers to the throughput time of a system and thus the time required to produce a product or service.
- Dependability, dependability refers to how close demand levels are to capacity. The balance between demand and capacity has a strong effect on the ability to cope with demand. If the two are close to each other, the system is less capable of coping with unexpected changes in demand.
- Flexibility, flexibility is the extent to which a system or organization can follow fluctuations in demand. It is strongly affected by the amount of over capacity available and is the main cause for dependability.

In our research, we focus strongly on the cost and flexibility aspects of capacity planning and to a lesser extent on speed and dependability by finding the right number of employees for every system setting. We focus on optimizing the AutoStore order processing line in order to reduce the costs per order (the costs aspect) while we pay special attention to the ability to cope with future demand levels (flexibility). Furthermore, the improvements that we propose must assure that the demand that arises every day can be fulfilled with certainty. Not meeting demand is often not acceptable for the customers of PostNL (speed and dependability).

2.1.3 Production management

Production management is the process, which combines and transforms various resources used in the production/operations subsystem of the organization into value added product/services in a controlled manner as per the policies of the organization. Therefore, it is that part of an organization, which is concerned with the transformation of a range of inputs into the required (products/services) having the requisite quality level (Kumar & Suresh,2006).

In our research, we analyse which activities add value to the processing line process. Activities that do not add value and cost time should generally be removed from a process. We also critically evaluate the current policies that apply to the processing line. For example, PostNL currently processes all order types on a single processing line. In the coming chapters of this thesis, we will investigate whether multiple processing lines for specific product groups allow for more efficient processing of orders.

2.2 Positioning our Research: An Overview of Common Techniques Used

Now that we described the background of our research, we provide a literature review matrix that displays the articles found during our systematic literature review on layout planning and design. This way, we evaluate commonly used methods and practices in our research field that might me relevant for our own research. Details on the search procedure itself can be found in Appendix 1. In the literature review matrix, we present relevant articles and their core content in keywords to be able to position our own research with respect to existing research. We differentiate between articles covering facility layout planning, simulation or production cell grouping. We also identify the optimization objective, being either Travel Distance minimization (TDM), Other objective minimization (OOM) or No optimization (NO). The resulting matrix is displayed in Table 1.

Article title (author)	**Facility layout planning**	**Simulation**	**Production cell grouping**	**TDM**	**OOM**
Research on warehouse design and performance evaluation: A comprehensive review (Gu, Goetschalckx & McGinnis, 2010)	✓			✓	
Facility layout problems: A survey (Drira, Pierreval & Hajri-Gabouj, 2007)	✓				✓
An improved algorithm for layout design in cellular manufacturing systems (Ariafar & Ismail, 2009)			✓	✓	
An integrated approach to the facilities and material handling system design (Aiello, Enea & Galante, 2002)	✓			✓	
Design of flexible plant layouts (Benjaafar, & Sheikhzadeh, 2000)	✓		✓	✓	
Congestion-aware dynamic routing in automated material handling systems (Bartlett, Lee, Ahmed, Nemhauser, Sokol & Na 2014)		✓			✓
Design of Material Flow Networks in Manufacturing Facilities (Herrmann, Loannou, Minis, Nagi & Proth 1995)	✓			✓	
Facility layout optimization using simulation and genetic algorithms (Azadivar & Wang 2000)		✓			✓
Layout optimization considering production uncertainty and routing flexibility (Kulturel-Konak, Smith & Norman 2004).	✓			✓	
Materials flow improvement in a lean assembly line: a case study (Domingo, Alvarez, Melodía Peña & Calvo, 2007)	✓				✓
Modeling and Analysis of Congestion in the Design of Facility Layouts (Benjaafar, 2002)					✓
Robust optimization of internal transports at a parcel sorting centre operated by Deutsche Post World Net (Werners & Wülfing 2010)	✓			✓	

Solving a group layout design model of a dynamic cellular manufacturing system with alternative process routings, lot splitting and flexible reconfiguration by simulated annealing (Kia, Baboli, Javadian, Tavakkoli-Moghaddam, Kazemi & Khorrami 2012)	✓			✓	
The cellular manufacturing layout problem (Salum, 2000)	✓		✓	✓	✓
The Facility Layout Problem: Recent and Emerging Trends and Perspectives (Meller & Gau, 1996)	✓			✓	
Count:	11	2	3	10	6

Table 1 – Literature concept matrix

As can be seen in Table 1, most articles focus on minimizing travel distance or, using another formulation, material handling costs. The algorithms that go with these procedures are often only limited by the space required by machines and building characteristics, such as pillars and walking areas. In the general approach towards the design of a manufacturing system, the capacity and thus the required number of machines is generally only determined after the design has been set. We question whether this approach is suitable for the specific situation at hand at PostNL due to the relatively small portion of travelling time compared to the processing time. Several authors already suggest that only considering travelling distance may not yield optimal solutions (Azadivar & Wang, 2000 and Manzini,2004).

We propose to use a layout design procedure that already considers *station* loading (i.e., a group of machines) at the layout design phase as well as travelling distance. We will use both the traditional and proposed hybrid approach to generate alternative layouts and evaluate the results of the procedures using a simulation model. The simulation model can then provide feedback on the performance of a layout expressed in more than just handling costs. Using a simulation model, we can also evaluate multiple KPIs such as throughput, utilization and waiting times.

2.3 Alternative Layout Design Procedure

In order to create redesigns of the AutoStore order processing line, we need a structured approach that we can use to create layout plans. No matter the optimization criterion, we should use the same structured approach in each case. Several procedures are available such as Apple's plant layout procedure or Reed's plant layout procedure (Chien, T. K. ,2004). However, in many case studies we found that Muther's Systematic Layout Planning (SLP) procedure was used (Muther, R., & Hales, L. 2015). Furthermore, Muther's procedure fits well in the methodology introduced in the previous chapter since both methods have several research phases in common such as the alternative generation phase and the alternative evaluation phase. We therefore now introduce the Systematic Layout Planning procedure.

2.3.1 Systematic Layout Planning

Systematic Layout Planning is a procedure that is aimed at helping facility planners to create layout alternatives. The procedure starts out from a decent data analysis in which the relationship and roles between activities are investigated. The relationships are displayed using a from-to chart and an activity relationship chart. The two charts can be found using a material flow analysis and a relationship analysis respectively. A from-to chart displays the material flows between activities. An activity relationship diagram displays the importance of placing activities next to each other using a letter-coding table. In Table 2 the importance is assigned to the respective letters:

Letter	Importance
A	Absolutely necessary
E	Especially important
I	Important and core
O	Ordinary
U	Unimportant
X	Undesirable

Table 2 - Dependency classification

The SLP procedure now uses both the space available and the space requirements as an input to convert the relationship diagram into a space relationship diagram. This diagram displays relative placing of activities and their size with respect to each other. The resulting layout plan should be changed according to practical limitations and modifying considerations to obtain several layout alternatives. To complete the SLP procedure, the alternatives should then be evaluated in terms of their performance.

An overview of the steps in the SLP procedure is displayed in Figure 11.

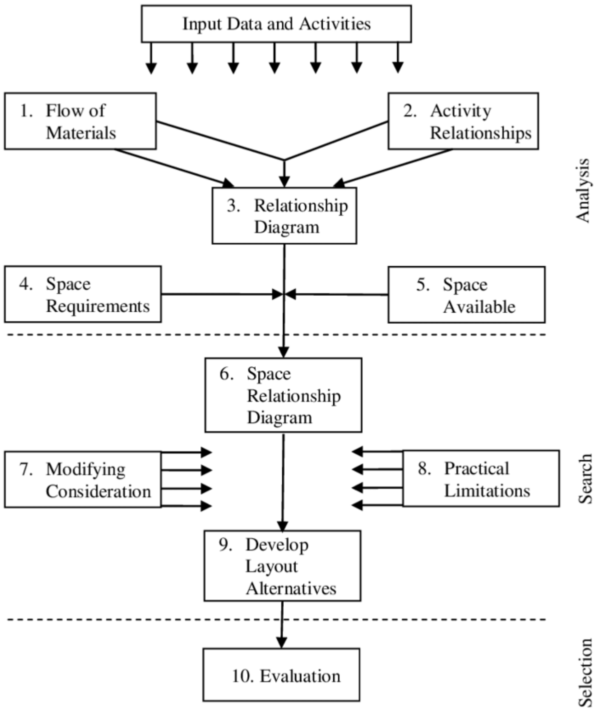

Figure 11 - An overview of the systematic layout planning procedure (Tompkins, 2010)

Step 9 of the systematic layout planning procedure relates to the development of layout alternatives. In Section 2.2, we already identified that most approaches available in literature use a material handling cost minimization objective to obtain layout alternatives. The material handling costs are often directly related to the travel distance between stations. The general formulation used to minimize material handling costs for multi-floor facilities is as follows (Meller & Gau, 1996):

$$min \sum_{i=1}^{N} \sum_{j=1}^{N} (c_{ij}^{H} d_{ij}^{H} + c_{ij}^{V} d_{ij}^{V}) f_{ij}$$

Where c_{ij}^H denotes the horizontal material handling costs per meter and d_{ij}^H denotes the horizontal distance between station i and station j. The same definition holds for c_{ij}^V and d_{ij}^V for costs and distances in vertical direction respectively. f_{ij} denotes the flow between station i and station j.

Often, several layout options are presented resulting from practical implications that are than assessed based on their implied material handling costs.

2.4 Process Layouts

In the SLP introduced in the previous section, phase nine is called "Develop Layout Alternatives". We provided the distance minimization formulation that is often used to get to these alternatives. We stated that practical implications are often considered to obtain several layout alternatives. Several considerations can play a role in this phase. An important consideration is the choice of process layout, as it defines the further construction of the processing line and a good facility layout can reduce operating expenses up to 50 % (Tompkins, 2010). The choice for a specific process layout should also be considered earlier in the SLP process as it also influences the space requirements.

2.4.1 Definition

The process layout is defined as:

The process layout determines how the process' transforming resources are positioned relative to each other and how its various tasks are allocated to these transforming resources (Slack, Brandon-Jones, Johnston, & Betts, 2015).

The process layout is a fundamental decision in the design of a processing line and therefore can cause significant problems if the layout turns out to be wrong. Changing the layout later is often time consuming and causing delays for daily operations (Slack et al, 2015). This stresses the importance of conducting extensive research before changing the setup of the AutoStore order processing line.

2.4.2 Available Production Layout Types

In choosing a production layout, it is important to first consider the available options to choose from. Generally, it can be concluded that most layouts are based on one of the following four layouts (Greene, & Sadowski,1984):

Fixed-position layout
In the fixed-position layout, the product is fixed at a location in the facility. Instead of moving the product itself through the facility, resources move towards the product when the resources are desired. A fixed-position layout is often used for project-based manufacturing at low volumes. Due to the inapplicability of this layout type for our research, we will not elaborate further on this layout type.

Functional layout
In a functional layout, resources or processes that perform alike actions are grouped together. The grouping of similar activities generally allows for improved utilization of the grouped processes or machines. A disadvantage of a functional layout is that the flow through a facility becomes more complicated. Products must travel to the grouped activities causing flow intersections and many flow paths (Slack et al, 2015). A common example of a facility that uses a functional layout is a hospital. Here, departments group similar activities and patients visit the departments they need.

Cell layout
In a facility that is designed according to a cell layout, the layout is formed using the physical division of the functional job shop's manufacturing machinery into production cells (Greene, 1984). In such a production cell, a part family is produced. That is, parts with the same characteristics and the same required processes are processed in the same cell. According to Greene (1984), a cell layout brings several advantages such as reduced material handling, reduced in-process inventory, reduced part make span, reduced set-up times and reduced tooling. The cell layout implementation does however generally come with an increased capital investment and lower machine utilization.

In order to be able to implement a cell layout in a facility, the said product families should be formed. This process is called group technology (Burbidge, 1975). To form such product families a production flow analysis (Slack et al, 2015) or the direct clustering algorithm (Tompkins, 2010) can be used. For implementations with larger numbers of products, simulated annealing, neural networks and mathematical programming can be used to form cells (Singh, & Rajamani, 1996).

Product line layout

The fourth production layout type is the product line layout. In this layout type, all required machines and processes are placed in a line, following each other in the sequence required by the specific product. As one can conclude, this approach is suitable for one specific product that only contains minor variations in its production requirements. Product line layouts are typically used in the automotive industry (Slack et al, 2015).

2.4.3 Choice of Production Layout Type

The choice for a specific layout type is often made with respect to both variability in the product being processed and the quantity of products to be produced. The overall aim of designing a facility layout often has many conflicting objectives such as minimizing the material handling cost, minimizing overall production time, minimizing investment in equipment and flexibility for rearrangement and operations (Yaman & Balibek, 1999).

The objective that applies to a specific situation or facility is dependent on the goals of the involved management and other stakeholders of the facility and should be determined for each instance of the facility layout problem separately.

As a general guideline, we can use the variety and volume of a production process to get an indication of what production layout might fit our instance of the facility layout problem. As displayed in Figure 12, the range of deployment situations ranges from fixed positions layouts that are used in low volume, high variety situations to product layouts that are typically used in low variety, high volume situations.

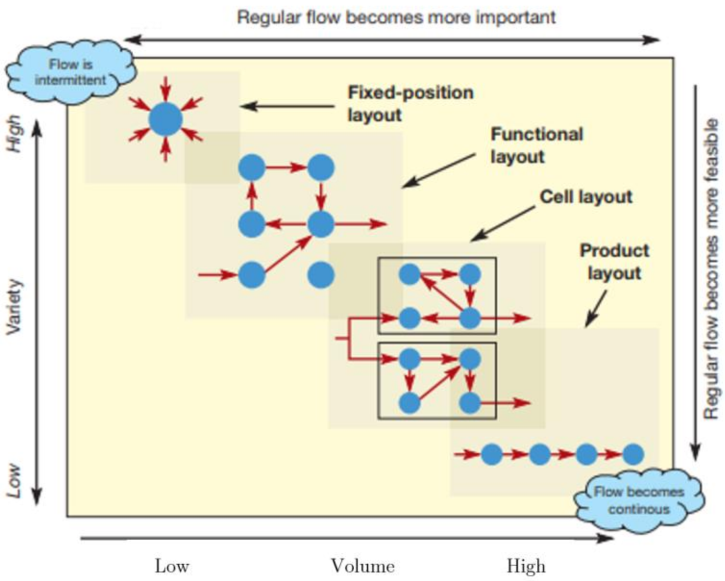

Figure 12 - An overview of the application areas of layout types (Slack et al, 2015)

We can use the production process characteristics (variability and volume) of the AutoStore order processing line to determine the applicable production layout. This will be the starting point of developing new layouts that can be adopted in the redesign.

2.5 Product Grouping

In section 2.4, we introduced the different layout types that can be applied in manufacturing system design. One of the layouts introduced is the cell layout. With our research at PostNL in mind, we introduce the steps that must be taken to move from a product layout towards a cellular layout.

2.5.1 Part-Machine Matrix

To identify possible product groups that could be processed within a machine cell, one must first identify the processing needs for each product group in terms of the machines needed. Such an analysis can be conducted using a Part-Machine matrix. This matrix displays the machines required for each product group.

$$a_{ij} \ = \ 1 \ if \ product \ i \ requires \ an \ operation \ at \ machine \ j \ , 0 \ otherwise$$

An example of a Part-Machine matrix is displayed in Table 3.

	Machine (j)				
		1	2	3	4
Part (i)	1	1	0	1	1
	2	0	1	0	0
	3	0	0	1	1

Table 3 – Part-Machine matrix

(Tompkins, 2010)

2.5.2 Similarity Index

Using the Part-Machine matrix, a similarity index can be calculated for both machines and parts. This similarity index represents the degree of commonality between two parts or two machines in terms of the number of machines visited. The similarity index for machines is defined as:

$$S_{ij}^{m} = \frac{\sum_{k=1}^{p} a_{ik} a_{jk}}{\sum_{k=1}^{p} (a_{ik} + a_{jk} - a_{ik} a_{jk})} \text{ (McAuley, 1972).}$$

Where S_{ij}^{m} is the similarity coefficient between machines i and j, p is the total number of parts, a_{ik} is the element of the ith row and the kth column in the Part-Machine matrix. The same formula can also be used for parts:

$$S_{ij}^{p} = \frac{\sum_{k=1}^{m} a_{ki} a_{kj}}{\sum_{k=1}^{m} (a_{ki} + a_{kj} - a_{ki} a_{kj})} \text{ (Carrie, 1973)}$$

In creating production cells, we generally want to maximize the similarity between products that are being processed by one machine cell as well as the similarity between machines in one production cell. Products with a low similarity index require different machines and are thus not likely to be classified in the same production cell.

2.5.3 P-median Model

Now that the similarity between products and between machines has been identified, a structured approach for creating the product groups is presented, the so-called part-family formation.

A P-median model can be used to perform the part-family formation. The P-median model is a zero-one integer linear programming problem that can be relatively easily solved with almost all solvers. The P-median model is formulated as follows (Kusiak, 1987):

$$Maximize \sum_{i=1}^{p} \sum_{j=1}^{p} S_{ij}^{p} x_{ij}$$

subject to:

$$\sum_{j=1}^{p} x_{ij} = 1, \quad i = 1,2, \dots, p \tag{1}$$

$$\sum_{j=1}^{p} x_{jj} = n, \tag{2}$$

$$x_{ij} \leq x_{jj}, \quad i,j = 1,2, \dots, p, \tag{3}$$

$$x_{ij} \in \{0,1\}, i,j = 1,2, \dots, p, \tag{4}$$

Where S_{ij}^{p} denotes the similarity coefficient between parts i and j. $x_{ij}$is the decision variable (binary) defined as $x_{ij} = 1$ if part I is assigned to the family in which part j is the median or $x_{ij} = 0$ otherwise. n is the desired number of families. This formulation contains p^2 binary decision variables and $p^2 + p + 1$ linear constraints. Constraint (1) assures that each part belongs to exactly one part family. Constraint (2) specifies the required number of part families. Constraint (3) defines that part I belongs to family j only when part j is a group representative.

Running the P-median model results in the formation of n part-families. These part families can be served by a separate production cell.

2.6 Line Balancing

Assembly lines can be split into the workstations they consist of. The workstations are typically located along a transportation system such as a conveyor belt. The products assembled on the assembly line move along the consecutive workstations in sequence. As a result of the existence of various workstations, the work itself is also partitioned in tasks that can be performed at their respective workstations. Often, precedence relations exist between the tasks that must be performed. The assembly line balancing problem (ALBP) represents the objective to find a line balance that respects the precedence relationships next to other operational constraints. When this balance is achieved, the cumulated task time for a station (station time) is roughly equal for all stations.

2.6.1 Notation

To describe an assembly line system, standardized notation is used. The notation describes the jobs, workstations, tasks and processing times that occur in an assembly line system. To be able to clearly describe assembly line systems, we will introduce a selection of the notations available that is relevant for the problem at hand:

$$Work\ stations\ k\ =\ 1, \ldots, m$$

$$Task\ set\ V\ =\ \{1 \ldots n\}$$

$$Total\ workload\ for\ assembling\ one\ workpiece\ =\ t_{sum}$$

$$Set\ of\ tasks\ assigned\ to\ workstation\ k\ =\ Sk\ (k = 1, \ldots, m)$$

$$Station\ time\ =\ T(Sk)\ =\ \sum\nolimits_{j \epsilon S_k} t_j$$

(Boysen et al., 2008).

2.6.2 Assembly line classification

Several types of assembly lines exist. The types of assembly lines can be distinguished between based on some key characteristics of the assembly line. To start with, we can distinguish a single model and mixed model assembly line. In mixed-model assembly lines, set-up times can be reduced to the extent that they can be ignored. Therefore, intermixed sequences of models can be assembled on the same line (Boysen et al., 2008). Consequently, in single model assembly lines, only one type of model is assembled and thus no set-up times are required at all.

Another characteristic of an assembly line is the synchronicity. In a synchronous assembly line, all stations transfer their workpiece (i.e. order) at the same point in time. That is, all workpieces being processed are transferred to the next station only when the slowest station has finished its operations. In an asynchronous assembly line, workpieces are simply being transferred to the next station as soon as all operations at its current workstation have been finished, independent of other workstations.

In the case of a synchronous assembly line, we distinguish between paced and unpaced assembly lines. In paced assembly lines, all stations comply to a given cycle-time that cannot be exceeded. This type of system is often implemented using a continuously advancing transportation system like a conveyor belt.

The AutoStore order processing line is an unpaced, asynchronous mixed-model assembly line. Orders with different characteristics are processed on the same processing line and released by every station once the operations at that station have been completed.

2.6.3 Line balancing in unpaced, asynchronous, mixed model assembly lines

Now that we identified the type of assembly line at the fulfilment centre, we can identify the relevant line balancing technique for this type of assembly line. As mentioned earlier, the starting point for line balancing is the aim to achieve similar workloads at each station. A simple formulation of this objective would be:

$$Min \sum_{x} \sum_{y} |T(S_x) - T(S_y)|$$

Where $T(S_x) = \sum_{j \epsilon S_x} t_j$

And $T(S_y) = \sum_{j \epsilon S_y} t_j$

This formulation assures that the difference between the station time of all possible combinations of stations in an assembly line is minimized. In practice, we see that line balancing is also dependent of sequencing procedures. If several work intensive models follow each other shortly after another, the aimed cycle time might be exceeded at some workstations and a so-called overload occurs. This overload must be solved using an intervention such as line stoppage, off-line repair or higher local production speed (Wild, 1972). These overloads can be avoided if a sequence of models is found where those models which cause high station times alternate with less work-intensive ones at each station. This leads to a short-term sequencing problem that must be solved to prevent large buffers in the assembly line. This sequencing problem must be incorporated in the line balancing problem.

Moreover, buffer storage allocation must also be incorporated. Lastly, the effect of varying processing times introduces another complicating factor. Although this variation can be captured in a probability distribution, the combination of all named complicating factors results in the fact that most of the research performed in this field focuses on the optimization of only part of the named factors. A simulation approach can incorporate all effects in one model (Boysen et al., 2008). Simulation will be further introduced in Section 2.7.

2.7 Simulation

In order to evaluate the layout alternatives in such a way that all variables and future scenarios can be considered, we suggest using simulation. Simulation is a time-consuming evaluation method. However, it provides reliable results that can be tested against several scenarios. Moreover, simulation is often used to evaluate the benefits and performance of several layouts (Aleisa & Lin, 2005). Simulation therefore seems to be a suitable method for evaluating the layouts that we propose in our research.

2.7.1 Definition

To start with, we provide a formal definition of simulation:

> *"Simulation is the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behavior of the system and /or evaluating various strategies for the operation of the system" (Shannon, 1998)*

From this definition, we conclude that a simulation model is meant to assess the behavior of a system with respect to experiments. The system refers to the process or facility under investigation in this context. If the system under investigation is simple enough, it is preferred to use mathematical models instead of simulation as a result of the time-consuming nature of a simulation study. Moreover, as opposed to a mathematical exact model, simulation evaluates a system numerically and thus an estimate of the system performance is obtained (Law, 2015).

2.7.2 Simulation Types

Law (2015) introduces three dimensions that can be used to distinguish between simulation types:

- Static vs. dynamic simulation models. A static model represents a system at a given time or in a situation where time is not relevant and dynamic simulations represents a system that evolves over time.
- Deterministic vs. stochastic simulation models. Deterministic simulation does not incorporate any uncertainty (i.e., probabilistic components). A deterministic simulation is a set of differential equations that determine an output once provided with an input. The transformation of inputs to outputs is pre-specified and does not depend on varying factors. In stochastic simulation models, output is random. That is, the transformation from input to output is stochastic and dependent on (semi)random factors. As a result, the output itself is random as well.
- Continuous vs. discrete simulation models. In a continuous simulation, state variables change instantaneously at specific points in time, where a state refers to all variables required to describe a system at a particular time. In a discrete simulation model, state changes are triggered by events. For example, an arrival of a product or customer in the system causes the initiation of another event, say, the processing of the customer at an entrance desk.

As a result of the fact that the order processing line at PostNL contains several queues and stochastic processing and arrival times, we use a dynamic, stochastic and discrete simulation model. A so-called discrete-event simulation model (Law, 2015).

2.7.3 Simulation Experiments

When a simulation model is constructed, we conduct experiments with the simulation model. Several aspects play an important role in conducting an experiment. We now go through the important ingredients of a simulation experiment.

Warmup

Simulation models typically need some runtime to fill the system such that it represents "normal" operations of the system being simulated. Depending on the nature of the simulated system (terminating or non-terminating system), the warmup period varies from days to hours typically. There are also systems in which we do not want to mitigate the warmup period as this period occurs in reality as well. For example, a supermarket opens and closes every day. This behaviour should also be included in the simulation study. In other cases, we do not want to include the warmup period in the simulation results, typically in continuous operations without shutdowns.

Replications and run length

Another ingredient for a simulation experiment is the number of replications. The number of replications should be discussed together with the run length as these two factors together determine the amount of data being created. The run length determines how long the simulation should run. The number of replications determine how often this period should be repeated.

The data should be enough to establish a precise enough confidence interval for the output factors being measured. A confidence interval is a numerical interval that represents the system performance with a certain percentage of certainty. To make sure that the interval width and the accompanying certainty percentage match the requirements, we can increase both the run length and the number of replications. Doing so will decrease the confidence interval width. On the other hand, decreasing either the number of replications or the run length analogously increases the confidence interval width.

Experiment design

To conduct an experiment with a simulation model, we must determine the setup of the variables in various scenarios. These scenarios are the scenarios that we want to test the performance of. The setup of variables is a combination of settings for the system. In most simulation studies there are many possible combinations to test. Testing all possibilities often requires many computations and hence, a lot of time. Instead of testing all possible combinations (i.e., a full factorial experiment), researchers often try to reduce computation time by intelligently selecting some experiments that cover the range of experiments that is interesting for the system at hand.

Although there are more techniques to reduce the computation time, we will now introduce, next to the full factorial experiment, the 2^k- factorial and simulation-based optimization. In a 2^k- factorial approach, we can investigate the effect of one factor by performing one simulation run at a high level and one run at a low level. We then perform this for all factors and thus have an indication of the effects of all factors on the system. Conducting the experiments for each factor separately is called a one-factor-at-a-time approach (OFAT). Note that as a result of the OFAT approach, the interaction between several factors is not known. In a typical 2^k- factorial design, we test several combinations of factor settings (either high or low) such that the interaction effects can also be determined (Law, 2015).

In simulation-based optimization, more advanced programming is used to "seek" optimal settings of the system. We do not predetermine the setups to run. Instead, intelligent logic determines the next settings to run based upon previous results such that we finally arrive at a (near) optimal solution.

2.7.4 Simulation Results

Results of a simulation study must be validated and verified to assure the correctness of the model and to be able to use the results as proof for a new proposed layout.
Validation and verification are important to establish the credibility of the conclusions that are drawn based on the simulation model. This section introduces both validation and verification.

Validation

Validation refers to testing of the resemblance of the simulation model compared to reality. We here check whether the simulation model performance is in line with the system we are trying to model. Validation is often performed by running some real-life scenarios in the simulation model. If the performance of the simulation model matches reality, the model is said to be valid.

Verification

Verification refers to testing the simulation results and performance with respect to the modelled version of reality. We here only look at the resemblance of the simulation model compared to the paper model that was created based on reality. The question to be answered is: are we still in line with our planned simulation model?

In our research, we will both validate and verify our model to assure the correctness and the credibility of our approach.

A representation of the relation between reality, the simulation model and the paper model is displayed in Figure 13.

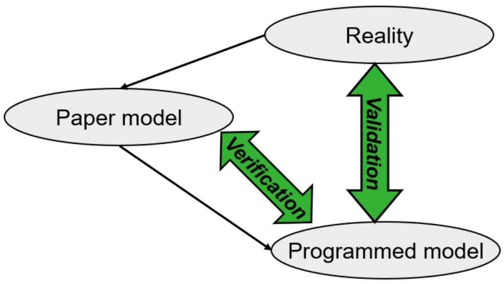

Figure 13 - Visualization of validation and verification (Mes, 2018)

2.8 Conclusion on the Literature Review

In this chapter we provided a review of relevant literature for our research. We started with an introduction of the research field in Section 2.1. The present research operates in the field of facilities design, capacity planning and production management. These three dimensions form the fundaments of our research. The methods and ideas that we use originate from these dimensions.
In section 2.2, we positioned our research with respect to existing research. In doing so, we answered our second research question:

How should an order processing line be designed according to existing literature?

We found that scientific literature that deals with comparable problems often uses a distance minimization approach. In this approach the material handling costs are minimized by minimizing the distance to be travelled. We question this approach and propose to also take into consideration other performance indicators in the early phases of the design of a production system.

Next to the objective in designing a production line, we also evaluated the available procedures for creating alternative layouts. In Section 2.3, we introduced the systematic layout planning procedure as a procedure that can be used to develop alternative layouts for the AutoStore order processing line. We use this procedure to structure our approach in finding new layout alternatives.

In Section 2.4, we compare several processing layout options that can be used as a foundation for these alternative layouts. We described four of the most used processing layout options being fixed position layout, functional layout, cell layout and a product layout. PostNL currently uses a product layout for the AutoStore order processing line. A cell layout seems to be more applicable for the product mix at hand. As a result, we investigated the transition form a product layout to a cell layout.

In Section 2.5 we introduced a procedure that can be used to move towards a production cell layout using an IP formulation of the processing steps required for the orders. A similarity index is then used to identify product groups that follow similar production paths. As a final step in this procedure,

In Section 2.6, we introduced an optimization approach for existing processing lines. Line balancing was defined and the specific procedure for the processing line at PostNL was identified.
Lastly, we introduced simulation as an evaluation method of the layouts we come up with in Section 2.7.

3. Current Situation Analysis

In this chapter, we provide a detailed process analysis of the current AutoStore order processing line and its operating environment. We do so by first providing an overview of the entire process and layout in Section 3.1. In this section, we also address every station in the order processing line separately in more detail by assessing the processing times and actions performed at the station. In Section 3.2, we describe the problems that we observe during our observation of the AutoStore order processing line and quantify these problems. Section 3.3 contains a comprehensive data analysis of the processing line, resulting in order characteristics, customer characteristics and performance measures. Section 3.4 introduces the IT-systems that support the operations of the AutoStore order processing line. In Section 3.5 we introduce the current selection procedure for suitable customers for the Autostore. Lastly, in Section 3.6, all stakeholders of the AutoStore order processing line at PostNL are identified.

3.1 Process Overview

To start with, we introduce the overall AutoStore process. The AutoStore and its processing line are in the so-called AutoStore competence centre, one of the departments within the PostNL Fulfilment site in Houten. The AutoStore process consists of several stations. These include, in consecutive sequence, the items receive, AutoStore, pickports, consolidation, automatic order reject, order control and the expedition area. An overview of the AutoStore competence centre is provide in Figure 14. Recall from our introduction to the research in Chapter 1 that we only consider the processing line in our research.

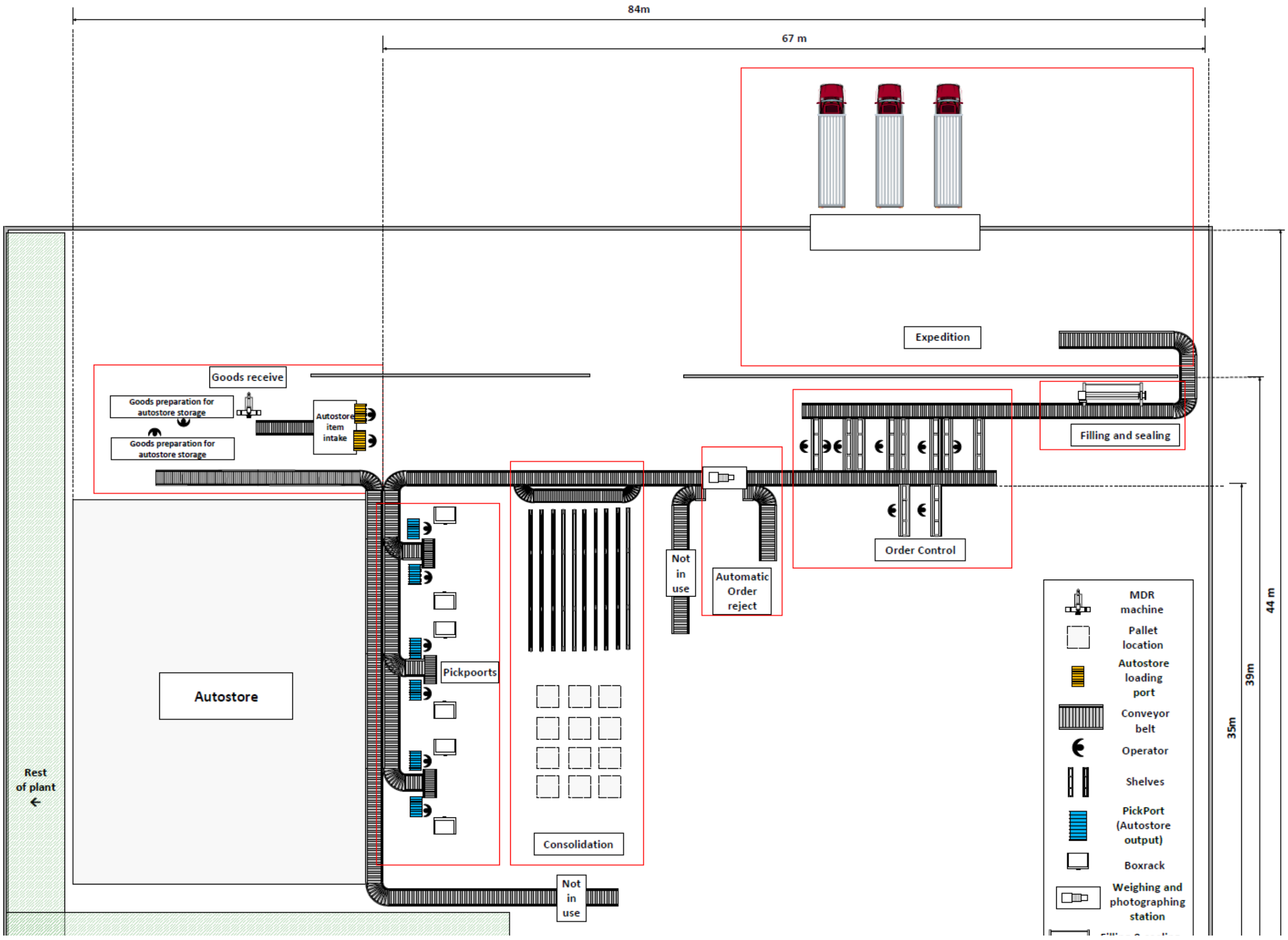

Figure 14 - Plant overview

The AutoStore itself and the items receive area will not be considered other than the AutoStore being the generator of orders for the processing line.

The current AutoStore order processing line is a typical product line layout. All machines are placed in sequence allowing for only minor variation in the parcels being handled. We observe that in practice, there is more variation between orders than the processing line can efficiently process. We observe many order specific processes that are all incorporated in the single product line layout. As a result, all orders pass station or processing steps that might not be relevant for that specific order. This induces increased overall leadtime for the orders being processed by the processing line. This observation will be elaborated further on in chapter 5. For now, we will discuss each station present in the current process layout. The processing times presented have been partially established using the work of a previous graduation project by Westra (2019). We validated all measurements and adjusted the measurements where we observed a misfit. We measured actual processing times and compared the sample measurement results with the processing times documented by Westra (2019). Misfits were found for the consolidation station and the illing and sealing station. The misfit was mainly caused by a changed order profile and changes in the working procedures that have been implemented after Westra's research. For the named two stations, we performed new processing times measurements. We thus discarded the available measurements by Westra for these stations.

3.1.1 Goods Receive

Products enter the competence centre via the goods receive station. A photo is taken of every product and the product is weighted on the MDR machine. The dimensions of the product are now known and stored in a database. These dimensions are used to suggest a shipping box type and size later in the process. Next, the products are loaded into crates that are then stored in the AutoStore.

3.1.2 Pickports

When a new order is being processed, it is first picked at the pickports. Products are presented in crates to the pickers. The pickers pick the right number of items until the order is filled. The items are then packed in a box in case of a parcel or transferred into a crate in case of a mailbox order (an order that fits in a mailbox). Either way, orders are labelled using a "Collo-ID", an internal reference that helps to identify the order later on in the process. The crates are filled until they contain around five orders and then put on the conveyor belt. A parcel is immediately put on the conveyor belt. The conveyor belt now transports the orders to the consolidation area. The typical processing times of the actions performed at the pickports are displayed in Table 4. The upper bound and lower bound provided in the table refer to the bounds of the 95% confidence interval describing the measurements.

Pickport				
Action	**Required processing time(s)**	**Upper bound(s)**	**Lower bound(s)**	**St. dev(s)**
AutoStore orderline pick time	0.7	1.5	0	4.7
Set-up Autolock box	5.6	6.5	4.7	2.9
Set-up A03-A10 box	20.0	23.3	16.7	9.7
Set-up container	10.5	11.6	9.4	3.2
Scanning & attaching Collo-ID	4.8	5.0	4.6	0.9

Table 4 - Processing times of the pickport station

The first and last activity are performed for every order. Dependent on the type of order, either an Autolock box, A03-A10 box or a container is used.

3.1.3 Consolidation

In the consolidation area, items that are not suited for storage in the AutoStore are manually added to the already partially filled shipping boxes of orders (i.e., consolidated). The partially filled shipping boxes contain the items in an order that can be stored in the AutoStore. As a result, these items have already been added to the shipping box at the pickports. The consolidation items are either too large or too heavy for AutoStore storage and are thus stored outside of the AutoStore. Note that consolidation only takes place for a limited number of orders, most orders can be picked form AutoStore storage directly. The manual adding of items to an order in the consolidation area is often costly and takes a relatively long time as compared to the picking process at the pickports. The processing time of consolidating an order is provided in Table 5. The upper bound and lower bound provided in the table refer to the bounds of the 95% confidence interval describing the measurements.

Consolidation				
Action	**Required processing time(s)**	**Upper bound(s)**	**Lower bound(s)**	**St. dev(s)**
Pick and consolidate order	65,3	85,1	45,5	20.1

Table 5 - Processing times of the consolidation station

3.1.4 Order Reject

After the optional consolidation, orders are transported to the automatic order reject system. This system is designed to check the weight of an order. The system compares the theoretical weight of an order with the actual weight of the shipping box containing the order items. The theoretical weight is determined based on the weights of the items in the order that were stored in the database at the goods receive station. Therefore, the automatic weight check can only be performed for items that have been stored in the AutoStore. If an order turns out to be out of the acceptable weight range, it is automatically rejected and put aside on a separate conveyor.

The order reject station is currently not in use due to its malfunctioning in practice. A large percentage of orders was rejected due to wrong data entries at the goods receive station and due to the relatively small weight of the orders being handled. The latter causes small deviations in the actual weight to cause the order to be rejected while the order is actually correctly picked. In other words, a lot of false negatives occurred. Next to the weighing machine, a camera is installed that can be used to take a picture of the content of a box or crate. This picture can be sent to customers and can consequently be used to prove correct picking or to inform consumers about the state of their order. The camera is also not used in practice as there was no priority to implement the integration of photos in the order-follow system.

3.1.5 Order Control

At the next station, the order control station, orders are checked manually by scanning the picked items to make sure the right items and the right quantity of items have been picked. The mailbox order that have been transported in crates up until now are also packed in the correct packaging material. For these small items this is either an envelope or a small shipping box. At the order control stations, inserts, delivery notes and receipts can also be inserted into the shipping box or envelope containing the order. When all actions have been completed at the order control table, the order is transferred to another conveyor at the other side of the table. This conveyor transports the orders to the filling and taping section of the process. The processing times for the Order Control station are provided in Table 6. The upper bound and lower bound provided in the table refer to the bounds of the 95% confidence interval describing the measurements.

Order Control				
Action	**Required processing time(s)**	**Upper bound(s)**	**Lower bound(s)**	**St. dev(s)**
Set-up	4.3	4.7	4	1.5
Order check	11.3	14.7	7.9	18.3
Place inserts	4.7	5.3	4	1.3
Shipping label	6.5	7	6	2.5
Delivery note	8.2	9.3	7	4.4
Transfer to conveyor or trolley	11.0	12.7	9.3	5.7

Table 6 - Processing times of the order control station

Set-up time is required for all orders, order checks are only conducted for those orders that require an extra order check. Only some orders require an insert while all orders require a shipping label. Just like the inserts, delivery notes are added to a portion of the total order volume. Lastly, all orders are transferred to either the trolley or the conveyor. The percentages of orders that require order checks, inserts or delivery notes are introduced later on in this chapter.

At the order control station, either single orders that arrive in a shipping box or a crate containing 4 to 5 orders is handled depending on the aggregation applied at the picking station. Note that the processing times provided in Table 6 are referring to the processing times of one order. In case of a crate, five orders are handled at once. Set up times are equivalent to single order handling, however, transfer time of a crate to the conveyor is equivalent to the transfer time of single order transfers.

3.1.6 Filling and Sealing

At the filling and sealing station, extra filling material is added to the shipping boxes to protect the items from potential damage during transportation. Finally, the filled boxes are sealed using a sealing machine. Smaller boxes are taken from the conveyor and put on a trolley to be transported to the expedition area while the other boxes are transported to the expedition area using the conveyor. The processing time required for filling and sealing an order is provided in Table 7. The upper bound and lower bound provided in the table refer to the bounds of the 95% confidence interval describing the measurements.

Filling & Sealing				
Action	**Required processing time(s)**	**Upper bound(s)**	**Lower bound(s)**	**St. dev(s)**
Filling & sealing	8,4	9,3	7,5	3,2

Table 7 - Processing times of the Filling & Sealing station34.1.7 Expedition

In the expedition area, all sealed shipping boxes are prepared for transportation in the sense that they are packed on trolleys and moved to the dock area. A redesign of the expedition area itself is not in scope of our research project. However, the flow of orders towards the expedition area using conveyors is considered in our models.

3.1.7 Material Flow

Now that all stations in the Autostore order processing line have been introduced, we identify the input flows for each station. We created a Sankey diagram that displays both order and material flow for the AutoStore order processing line. The order flow between stations is represented by orange lanes, input materials required for the operations at each station are represented by grey lanes in Figure 15.

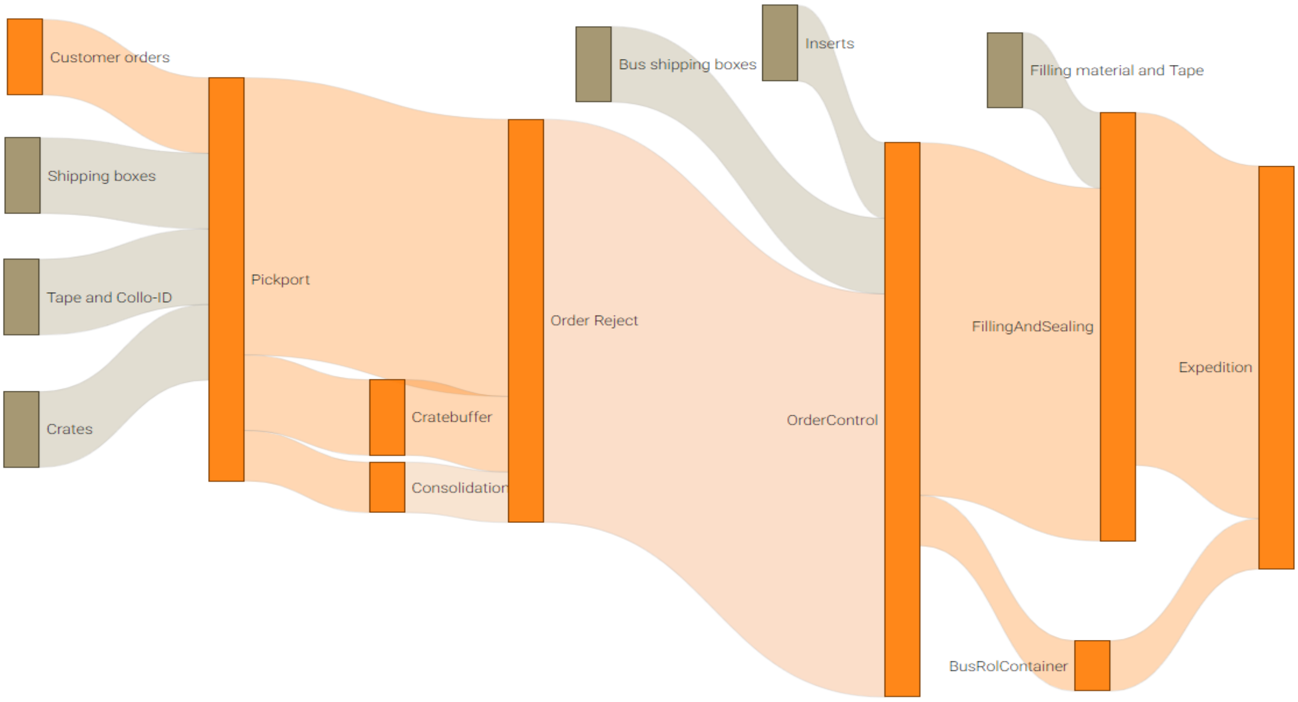

Figure 15- Sankey diagram of material flows

The supply of the materials required at each station require specific attention in the redesign of the processing line layout such that efficient and easy supply of the materials is enabled by the design. For example, inserts should be stored near the order control stations and filling material for the filling machines at the filling and sealing station should also be available in close proximity of the station. Resupplying these items over large distances during shifts costs a significant amount of time.

In Section 3.5, we identify the bottleneck processing station in the current processing line based on an analysis of the current utilization of the processing stations.

Impressions of the processing line stations can be found in Appendix 5.

3.2 Observed Problems

During the observation period of the AutoStore process, we noted several inefficiencies. Moreover, at PostNL a list of known inefficiencies was available as a result of previous research (Westra, 2019) and operator experiences.

3.2.1 Bottleneck Stations

Currently, only 3 to 4 pickports are used at the AutoStore. Despite the relatively low utilization of the AutoStore itself, jams occur at the order control tables. Operators tend to push orders forward on the automatic conveyor belt to create more buffer space. From a theoretical point of view, this is a highly undesirable action since this is in fact only treating the symptoms of a larger problem, namely the lacking balance in the processing line. In a (paced) assembly line, buffers or intermediate stock are generally to be evaded.

In practice, the assembly line is currently used as intermediate storage locations for orders that are being processed. Operators switch from working station to try to balance the line when large queues occur. An impression of the order queue on the conveyor belt is displayed in Figure 16 and Figure 17.

Figure 16 - Jam formation upstream

Figure 17 - Jam formation downstream

The bottleneck effect that we observed during the shifts can also be observed in the simulation model that will be introduced in Chapter 4. The utilization of all workstations generated using this simulation model is provided in Figure 18. Note that we used the system settings that are currently used in practice, resulting in three pickports (PP1, PP2 and PP3) and three order control stations (OC1, OC2 and OC3).

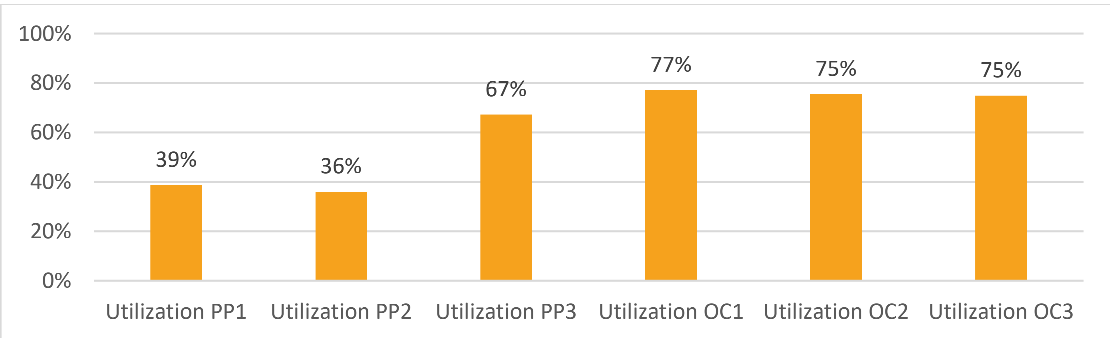

Figure 18 - Simulated utilization of the active workstations

From Figure 18, we can conclude that the order control workstations have a significantly higher utilization compared to the pickports and the filling and sealing station. A so-called overload in comparison to the other stations occurs. Especially pickport one and two, which are located closer to the order control tables suffer from the queue formation up to the pickports. The exact utilizations

3.2.2 Other Observations

Next to the easily observable queueing problems at the order control station, we identified several other undesirable process characteristics that should be prevented in a new layout.

- Unnecessary rejects. As mentioned earlier in this report, the reject station is currently not used. However, when a Collo-ID cannot be read, orders are still rejected and thus automatically taken off the conveyor. In the current setup, this rejection is not used. That is, orders that are rejected are put back on the conveyor belt by the operator without further consideration.
- Lacking overview. In the current setup, the order processing line cannot be observed from one position. Storage locations for pallets and racks obstruct the view. This causes operators to be forced to call each other while working on the same process. Moreover, the foreman (supervisor) of the AutoStore order processing line is not able to spot irregularities quickly. Instead, the foreman continuously walks around to try and assist the operators.
- Disjoint production stations. As a result of the previous observation, the stations as identified earlier in this report function disjointly. That is, operators at the pickports do not have any information about the activities at the order control station. Each station is operating on its own.
- Shipping boxes unavailable. At the pickports, shipping boxes are folded and then packed with the items in an order. Missing shipping box types are sometimes not available causing either the use of a larger shipping box type that thus causes inefficient transportation later on in the process or an interruption of the process when the operator has to obtain the right shipping box type himself. Although improvements have been made to make sure enough shipping boxes are available during a shift, the supply of shipping boxes could be more systematic and should at least be embedded in a new system design.
- Inefficient consolidation. Currently, consolidation of orders as explained in Section 3.1.3 is a time-consuming process. Items that are not suitable for the AutoStore are picked and consolidated with the other items in an order manually. Although this procedure takes far more time compared to the standard AutoStore picking, it is not being compensated for from a financial point of view by the customers. Reconsidering whether or not to offer consolidation services to customers is an important aspect of the redesign of the processing line.

Although it is not the main focus of this research project to solve all the above-mentioned problems occurring in the current setup, we do strive to incorporate solutions for the problems in our newly proposed design as much as possible.

3.3 Data Analysis

The customers together form the order portfolio that should be supported by the AutoStore order processing line. Therefore, we provide insight in the customers and the orders that are currently being served by the AutoStore competence centre. The profile that can be deduced from this data serves as input for the simulation model. We used Astro (the warehouse management system) data to analyse the order profiles. Astro only stores historic data for 3 months. However, by exporting the data at several moments in time during our research, we succeeded in collecting data that represents an evaluation period from 15-10-2018 till 11-02-2019. The data that contains a large number of rows was consequently analyzed using QlikSense, a business intelligence tool.

3.3.1 Customers

The PostNL Fulfilment site in Houten serves a range of customers. The AutoStore competence centre serves a selection of the customers that are served at the site. This selection currently consists of 35 customers, ranging from nutrition products to switchgear. The spread of customers and their respective cumulative order count in the evaluation period is displayed in Figure 19.

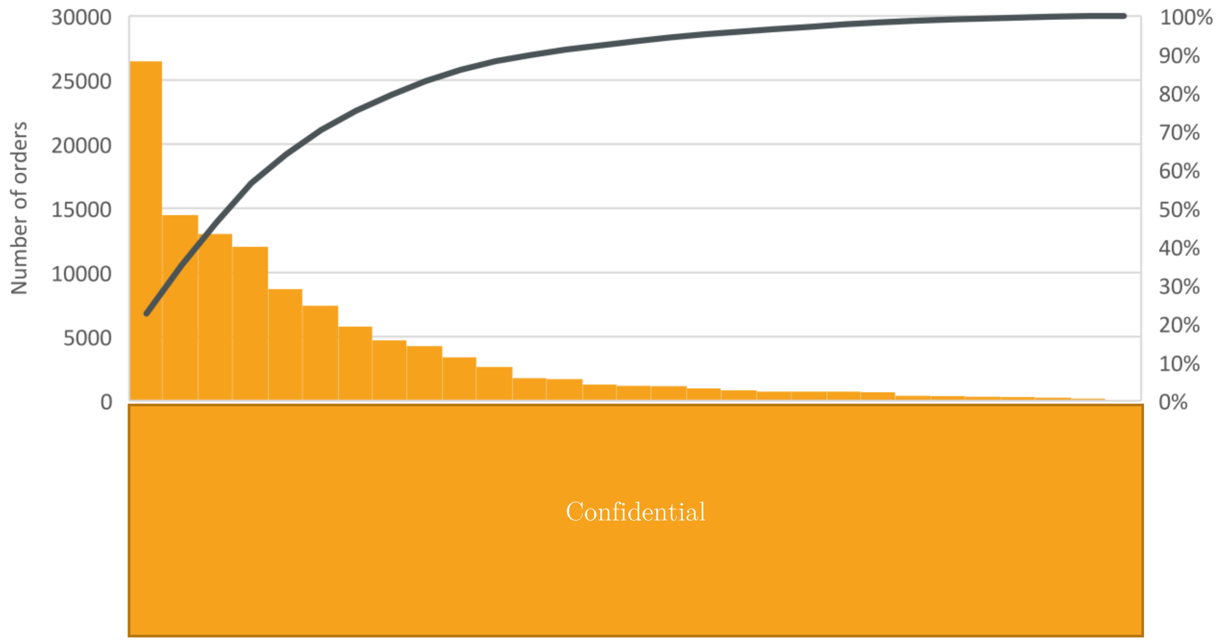

Figure 19 - Customer profile

From Figure 19, we can conclude that a few customers cause a large share of the orders. In fact, the five largest customers are responsible for 64% of the orders in the evaluation period. During our research, several new customers were moved to or introduced in the AutoStore competence centre. Handling times in the order processing line are customer dependent due to variety in the use of possibilities such as including inserts, delivery notes or consolidation. Therefore, we decided to base our research on an evaluation period, we do not consider changes that occurred after the evaluation period. We did monitor customer development to assure that the customer profile remains representative. The largest customer is responsible for most of the consolidation orders. This information is of importance to determine the importance of the different process steps. If, for example, only one small customer requires a customer specific process, this process does not have priority in our designs. We focus on the requirements for the 5 largest customers. However, the processing steps required for this selection of customers also covers the processing requirements of all other customers. We thus cannot remove processing steps based on limited demand for these processing steps.

3.3.2 Orders

At PostNL, customers typically place orders that consists of one or several orderliness, which in turn exist out of one or several items. An orderline is a Shop Keeping Unit (SKU). In one order, several SKUs can be ordered. Also, several instances (items) of the same SKU can be included in an order.

An order of two pairs of socks, three T-shirts and a pair of glasses thus consists out of one order, three orderlines (three different SKUs) and six items. This example order structure is displayed in Figure 20.

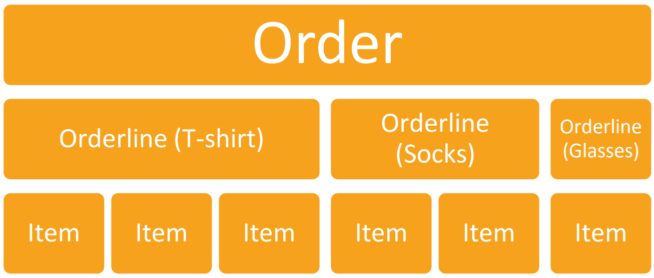

Figure 20 - Order decomposition

Using historical data from the Astro WMS system, we identified the order profiles that are processed by the AutoStore order processing lines. Evaluation of the data representing the evaluation period provides us with the order characteristics that function as input for our simulation model. The order characteristics are displayed in Table 8. The percentage of shipping boxes used per type is displayed in Figure 21, ranging from the smallest boxtype (A01) to the largest boxtype (A10). Boxtypes A65 and A62 are special boxtypes. For example, boxtype A65 is a so called “Speedbox”, a box that can be easily folded and has pre-attached tape mounted for faster sealing.

Characteristic	Value
Average number of orderliness in an order	2.08
Average number of items in an order	4.32
% of Bel orders, deliver as parcels	75.1%
% of Bus orders, delivered by the post network	24.9%
Consolidation %	1.4%
% of orders with an insert	39%
% orders with direct packing at OC	14.5%
% orders with scan check at pickport	13.6%
% orders with delivery note	39%
% of orders with Giro	3%

Table 8 - Order characteristics

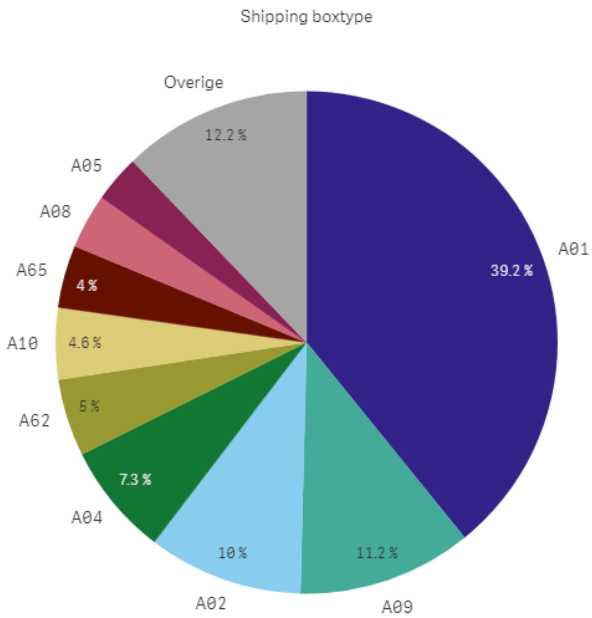

Figure 21 - Shipping box use

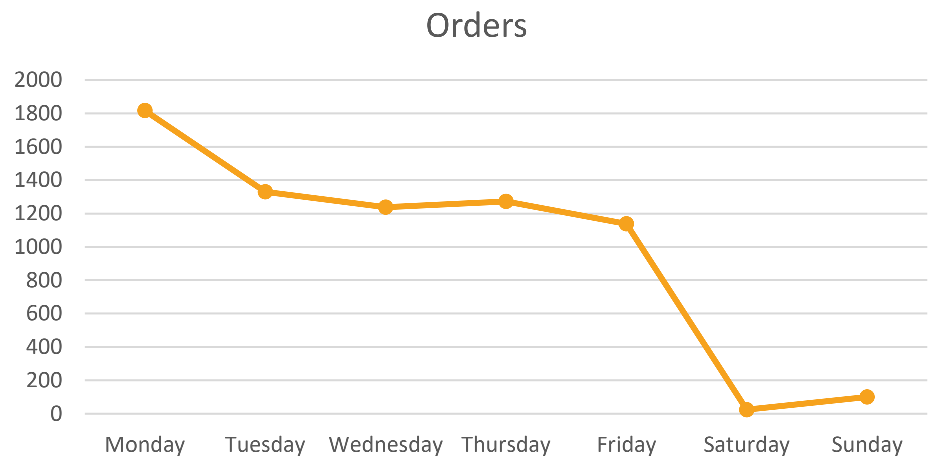

Figure 22 – The average number of orders per weekday

As can be seen in Figure 22, the number of orders in the evaluation period during the weekend is negligible.

During the weekend, only a few customers are being processed. In the future, PostNL would like to feed its weekend parcel delivery network using, amongst others, its fulfilment services. For now, weekend operations are loss-making. These operations are considered to be an initialization of future business and thus weekend operations are continued despite their negative results. We focus on the achieved productivity during business days (Monday up to and including Friday) as the productivity achieved during these days is most representative of the system performance when it is loaded.

To finalize our order analysis, we investigated the order arrival at PostNL. During the day, customers (i.e., web shop owners) send orders received in their web shop to the integrator (as defined in Section 3.2.1). These orders are then transferred towards Astro. We analysed the arrival of orders in Astro to create an order inflow profile that defines the load on the AutoStore order processing line. The resulting order inflow figure is displayed in Figure 23.

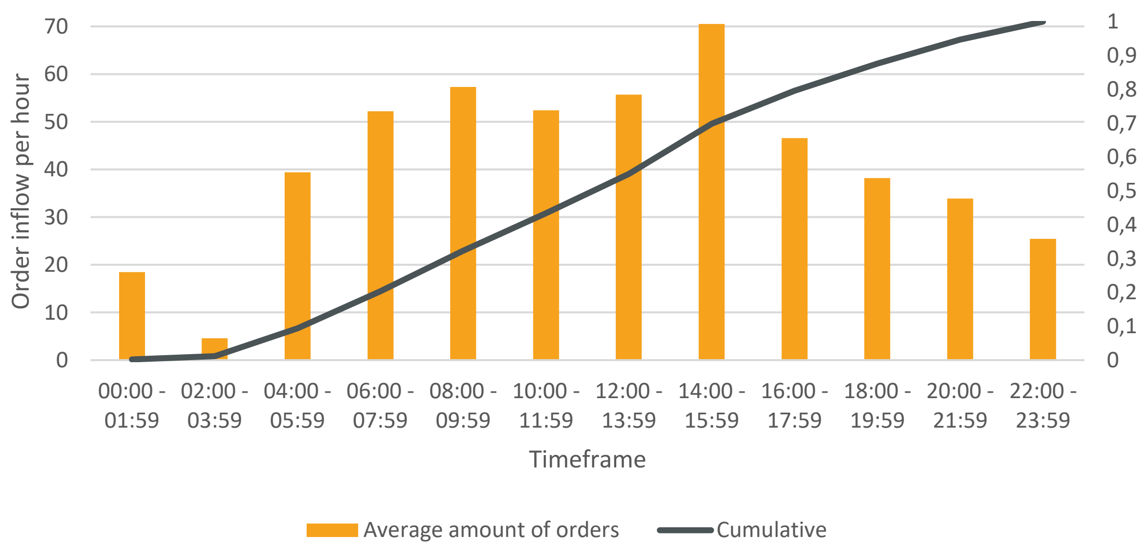

Figure 23 - Order inflow

From Figure 23, we observe that at the start of a shift (at 16.00 o'clock), roughly 70% of all orders for the day have been received. From here on, orders are released for picking and processing.

The foreman releases all available orders at the start of the shift to allow the AutoStore to optimize the picking sequence. We can thus conclude that there are enough orders available at the start of a shift for the operators to operate the processing line at full capacity. There is no need to wait for orders to arrive. It is only during the last hour of the shift that there might be a lack of orders to process if the number of orders differs significantly from the amount expected. In this case, operators are sent home early or provided with another task to make sure productivity is secured.

3.3.3 Shifts

Operators at the AutoStore order processing line typically work from 16.00 o'clock until 00.00 o'clock. During a shift, operators have one break of half an hour and two breaks of a quarter of an hour. All operators have their breaks at the same time to minimize the process downtime. During a shift, a kick-off is organized as well. This kick-off takes place at 18.00 o'clock. The kick-off is planned to take 15 minutes. During our evaluation period, we noted that the kick-off time frame adherence is improving as a result of the research conducted by Westra (2019) that highlighted adherence to be a relatively easy "quick-win".

3.3.4 Key Performance Indicators

PostNL uses "Productivity" as its Key Performance Indicator (KPI) for the all the competence centres. Productivity is a KPI that can be applied to all competence centres and even to parts of the competence centres easily. Efficiency at PostNL is defined as:

$$Efficiency = \frac{Number\ of\ orders\ processed}{Number\ of\ operator\ hours\ deployed}$$

We note that the key performance indicator that PostNL uses as efficiency is referred to as productivity in scientific literature (Coelli et al., 2005). More generally, productivity is defined as the output of a process divided by the input of the process. The productivity PostNL uses to assess its processes is a productivity indicator that uses the employee hours as its input measure and the number of processed orders as its output measure. Productivity is referred to in literature as a percentage of optimal performance. For example, if a machine is able to produce 100 products an hour while the industry standard for this type of machines is 200 products per hour, the productivity of the machine is 50%.

We already used the correct expression productivity throughout this report to make sure our terminology is in line with the generally accepted scientific terminology.

Although the productivity gives a good indication of the overall performance of a competence centre, it provides no leads to where problems occur or to what problem causes might be. Therefore, we introduce two other KPI's that can be used to assess the performance of the AutoStore order processing line in more detail. To start with, the utilization of each workstation can be used to identify bottleneck stations in the processing line. Note that we already used utilization as a means of finding the bottleneck station in the current processing line in Section 3.2.

Next to the utilization we can use the number of unfinished orders as an indicator of the capacity of the processing line. If the capacity of the processing line suffices, the number of unfinished orders will be close to zero. If the processing line is not able to cope with demand, the number of unfinished orders is significantly larger.

The proposed KPIs will be used in the further assessment of new layout alternatives, as they are currently not recorded centrally by PostNL we will continue this data analysis using the productivity KPI. To provide a baseline measurement, we investigated the productivity trends over the past four representative months. The data used ranges from 15-10-2018 till 11-02-2019. We display the average weekly productivity and the productivity per weekday in Figure 24 and Figure 25 respectively.

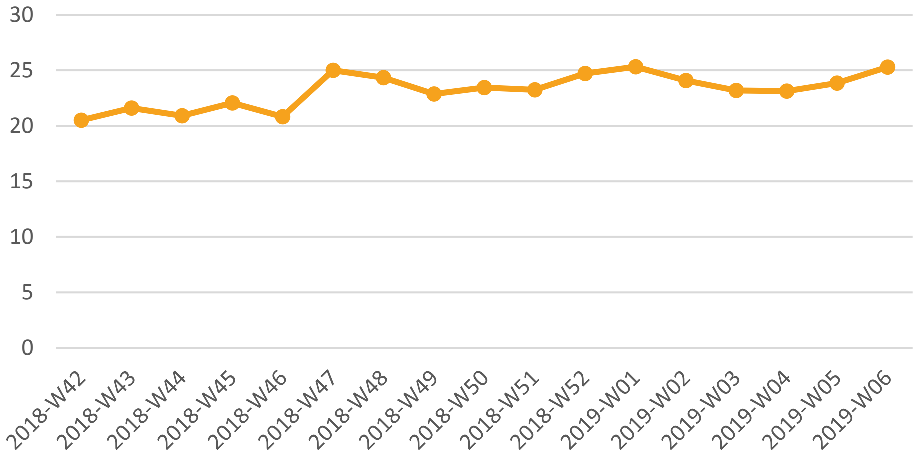

Figure 24 - Productivity per week

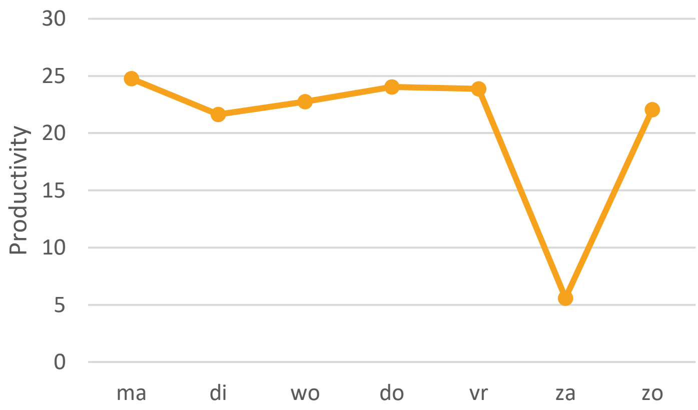

Figure 25 - Productivity per weekday

As we can conclude from the weekly productivity trend displayed in Figure 24, improvements have been made in the evaluation period. This observation is in line with the actions taken by PostNL. Several "Quick wins" have been implemented to improve the performance of the current order processing line. Examples of these quick wins are:

- Scanning items at the pickport to check the right quantity for some suitable customers
- Use more "Autolock" shipping boxes that can be folded faster.

The quick wins are short term solutions that result in relatively small productivity improvements. For our redesign project we use the baseline measurement as a reference for the improvement potential of new scenarios. We conclude that an productivity of 25 is seldomly achieved on a weekly basis in the current setup. Normally, productivity scores between 20 and 30 are common. During the weekend, lower productivity scores are achieved due to the low volume of orders being processed.

3.4 IT-System Overview

This section introduces the structure of the systems that support the operations of the AutoStore and the order processing line. The IT structure is an important aspect of this redesign project since changing the physical layout has significant consequences for the accompanying IT systems. For example, splitting parcel streams requires the IT systems to distinguish between product groups, which in turn requires correct data management.

Considering the IT systems in this phase of the redesign project increases the feasibility and the probability of implementation significantly as providing clear instructions for the changes required in the IT systems lowers the burden of starting an implementation trajectory.

To be able to provide such instructions, we now introduce the current IT infrastructure, explain the components and their main function. We distinguish three main components being the integrator, the Astro Warehouse Management System (Astro WMS) and LogiCS. Next to these three core components, the PostNL Application Programming Interface (API) is connected to Astro WMS to obtain parcel labels and to announce parcels for transportation at PostNL parcel services or the Cargo network. We will now discuss the three core components of the IT-system in more detail.

3.4.1 Integrator

The integrator is the link between PostNL E-commerce services and its customers. The integrator is a Mendix based platform that can be used to announce customer orders and to view the status of these orders. Mendix is a platform that offers businesses the opportunity to create webapps with limited coding effort. Replenishments for the AutoStore storage can also be announced here, when a customer delivers new stock. All information concerning stock levels, storage location and returns can be found in the integrator. Customers are connected to the integrator using an Enterprise Service Bus (ESB), this connector translates messages from the customers' webshop to a format that can be used by the integrator. Implementing the connection between the Integrator and the webshop system of a customer often causes a considerable share of the implementation time of new customers.

3.4.2 Astro WMS

Astro is the Warehouse Management System at several PostNL locations. This system was chosen as a result of the possibility to personalize the system to a large extent. Astro is connected to the integrator using another ESB. Just like the integrator ESB, this ESB assures that incoming messages are transferred towards a compatible format. Astro covers all onsite orders and item tracking and issues new instructions to other subsystems. Astro itself is also linked to the database of the site where it stores all historic and current actions. To be able to print correct parcel labels at the fulfilment site, Astro is also connected to the PostNL Parcel API (SAM).

3.4.3 LogiCS

LogiCS is the software that comes with the AutoStore. LogiCS issues pick-commands to the robots in the AutoStore and determines storage locations within the AutoStore. LogiCS is intelligent software in the sense that it applies storage optimization automatically. For example, frequently used items are at the highest storage layers such that they can be picked relatively quickly. LogiCS also drives the conveyors and conveyor logic such as routing and timing of orders.

3.4.4 Landscape Overview

To further illustrate the interaction between the processing station in the AutoStore order processing line and the IT systems that support the operations, we now provide a matrix that displays the actions performed by the two systems involved for each processing station.

Station	Logics	Astro
Picking	LogiCS receives order from Astro and calculates the most efficient picksequence. LogiCS presents the picktask to the picker and functions as a feedback interface for incorrect data in Astro (e.g. stock corrections).	Astro is used to release orders for picking and to store the relation between an order and a Collo-ID.
Consolidation	Logics identifies orders that require consolidation and transfers these orders to the consolidation area.	
Order Reject	Logics sends a request for validation of a scanned Collo-ID to Astro. In case of an unreadable or unknown Collo-ID the order is rejected and transferred to the reject area.	A Collo-ID check is performed with the Collo-ID database in Astro
Order control	The required inserts are presented to the operator using a Pick-to-Light system.	Astro is used to check the items in an order using a hand scanner. Delivery notes, giros and shipping labels are printed if present in Astro.
Filling & sealing		
Expedition		

Table 9 - Interaction between the processing station and the IT systems

An overview of the discussed IT landscape is provided Figure 26. A legend for all elements in the landscape is provided in the figure. Direct relations are represented using arrows.

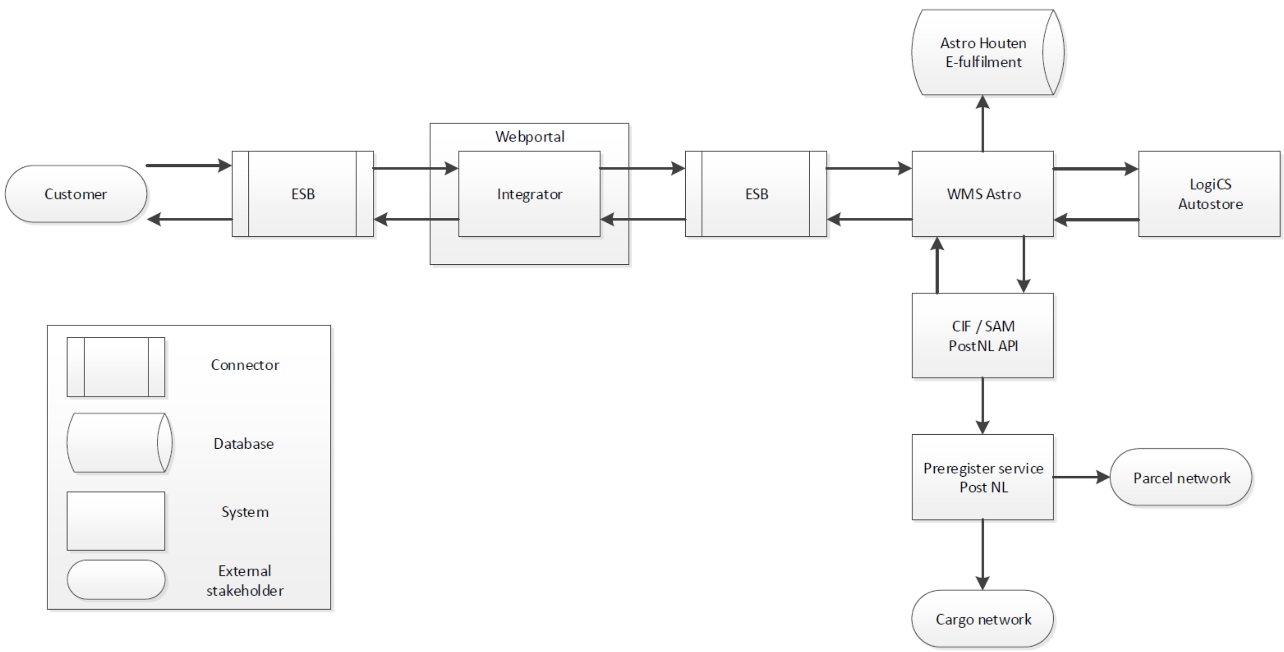

Figure 26 - IT landscape

3.5 Current Assignment of AutoStore Space

In Section 1.3.1 we addressed the various competence centres present in the PostNL fulfilment site in Houten. Customers are divided among these competence centres based on their characteristics. The suitability requirements that should be complied with for a customer to be suitable for the AutoStore competence centre are displayed in Table 10.

Variable	AutoStore suitable	Not suitable
Pallet replenishments	<monthly	>= monthly
Weight: >30kg per container	<5%	>=5%
Size	>95% larger than 5/60x40x30cm	>5% larger than 60x40x20cm
Delivery notes	Black & white or not	Colour or double-sided
Specific packing requirements	None	Fragile/present/extra
Distributor	PostNL track&trace	mail/UPS/other
Value (Theft-likeliness)	< €250	>= €250
#containers pick storage required	<4.000	>4.000
# ne SKU/day	<10	>=10
# SKU ADR (dangerous materials)	0	>=5%
# orders/hour outside AS	<25	>30
% single line	<80%	>90%
Large batches of 1 SKU	None	Yes
Customer specific packaging	None	Yes

Table 10 - AutoStore suitability requirements

Changing the layout of the AutoStore order processing line will have an impact on the required conditions presented in Table 10. For example, by creating separate processing lines for specific product groups, the process can be more suitable for more single line orders or a separate line for customer specific packaging can be used to also include these items in the AutoStore competence centre.

3.6 Stakeholders

Several stakeholders are involved in the redesign of the AutoStore order processing line. We now identify each of the stakeholders shortly and introduce their relation to the AutoStore order processing line.

- PostNL. PostNL itself as a company directly benefits from more efficient operations at the fulfilment site in Houten. As mentioned in the introduction chapter of this report, PostNL identified E-commerce as its most important market in terms of growth potential. Therefore, the company is specifically benefiting from improved E-commerce services as this will strengthen PostNLs position in this competitive market and help assure a sustainable infeed to its parcel network.
- Site Management. Site management is held responsible for the investment in the AutoStore, its returns and the performance of the site as a whole. Improving the AutoStore order processing line will allow for optimal use of the AutoStore itself and thus unlock the potential that was presented in the business case for the AutoStore. Overall performance improvement of the AutoStore competence centre will yield a higher profit per order and thus improved financial results for the fulfilment site.
- Operators. Operators are involved physically in a new order processing line. Operators will have to adjust to the new setup that should be an improvement to the current working environment. However, changing to a new system requires operators to learn new procedures and get used to a new way of working. As in most change processes, this requires a significant effort. Change management with good guidance is therefore an important aspect of successful implementation of the new system layout. Without good guidance, any new layout will not achieve its expected performance levels.
- Teamleader. The team leader is the leader of both the operators and the foreman. The teamleader is responsible for the team as a whole and for the performance of the AutoStore competence centre. The teamleader is employed with both planning operator capacity, improvement projects and the well-being of the team. As a result, the teamleader has an important voice in a redesign of the processing line. In addition, the teamleader is an important translator between theory and practice and should therefore be closely involved in improvement projects.
- Process coordinator. The process coordinator is the overarching responsible person for the processes taking place in the entire plant. The process coordinator has an operational orientated function and is involved in the redesign of the AutoStore order processing line to a lesser extent.
- Operations support. The operations support department deals with all operational issues that also affect customers. The operational support department is the bridge between customers and PostNL and is responsible for the support to all processes. Operations support exists out of FSO (IT support), finance, capacity planning, customer management, technical support and inventory management. Although all operations support employees will benefit from a more efficient processing line in the sense that they will have to solve less errors or late deliveries the support team will be particularly involved in implementing the new redesign of the processing line. Among other aspects, the IT systems, the capacity assignment and technical design of the processing line components will all have to be reconsidered. The workload for a redesign will therefore mainly be carried by the operations support department.

All stakeholders introduced in this section play a role in the redesign of the AutoStore order processing line. Careful considerations of the involved stakeholders is of vital importance for successful implementation of the new design. The stakeholders also form the primary data and experience input for the redesign itself.

3.7 Conclusion on the Current Situation Analysis

In this chapter, we provided an in-depth analysis of the current process layout of the AutoStore order processing line. As a result, we can answer our first research question:

What is the current design layout of the Autostore order processing line and what is the current performance of the layout?

In Section 3.1, we provided an overview of all the stations in the AutoStore order processing line. These include the pickports, the consolidation area, the order reject station, and the filling and sealing station ordered in the sequence of product flow. We also validated the processing times initially measured by Westra (2019) and define all processing steps conducted at the processing stations, providing an overview of the current order processing line.

In Section 3.2, we analysed the problems occurring in the current processing line layout. We found that the order control station is the bottleneck station in the order processing line using the system settings that are currently being used. Moreover, we identified several other problems that we observed during working shifts such as the lack of overview and the availability of shipping boxes.

In Section 3.3, the results of a detailed data analysis were presented. In our analysis of the customer profile we found that the 5 largest customers are responsible for 64% of all orders. As a result, we focus on the processing steps required for these customers in our proposed redesigns of the processing line. We provided insight in the current order profile per weekday and investigated the order characteristics of the orders that are currently processed. We also described the efficiency performance indicator that PostNL uses. This KPI is commonly referred to as productivity in scientific literature. We also suggested the use of utilization and the number of unfinished orders as KPIs.

In Section 3.4, an overview of the IT landscape was provided that exists out of three main systems. Astro is the warehouse management system, LogiCS is the AutoStore software and the Integrator is the platform that connects PostNL to its customers.

Lastly, in Section 3.5, we described the current selection procedure for customers of the AutoStore and in Section 3.6 we provided an overview of the involved stakeholders.

4. Model Design

In this chapter, we introduce the simulation model that we use to evaluate improvements and redesigns for the current AutoStore order processing line. In Section 4.1, we describe the simulation model conceptually by addressing the input and output of the model and by describing the assumptions and simplifications that apply to the simulation model. From heron, we move towards the technical implementation of the model in Technomatix Plant Simulation by Siemens. We first introduce the simulation model using screenshots and introduce the logic used in the model using process and logic flows. We also address how processing times and downtime were included in the model. Lastly, in Section 4.3, we address the credibility of the model using a comparison between actual performance data of the system and simulation model output data.

4.1 Conceptual Model

In this section, we introduce the conceptual model that we use to answer our research questions. The conceptual model describes the functioning of the model and is implemented in simulation software subsequently. We describe the model itself, the input used by the model and the generated output. We also define the assumptions and simplifications that we used to model the system and introduce some of the logic used in the model.

4.1.1 General Model Description

The simulation model represents the AutoStore order processing line as close as possible both functionally and visually. That is, the visualizations used should be easy to recognize for PostNL. This way, the model can be used for its primary use: evaluating interventions and providing indications of the effects of interventions but also for visual explanations for the Management Team, teamleaders and operators.

The conceptual model represents the main building blocks that the processing line consists of. These building blocks are directly related to the processing stations that we identified in Section 3.1. The blocks are displayed in Figure 27. The building blocks are connected using a transportations system. In our technical implementation described in Section 4.2, we also use these building blocks to construct our simulation model. Structuring a model in this object-oriented way eases later adjustments, relocation and duplication of parts of the processing line.

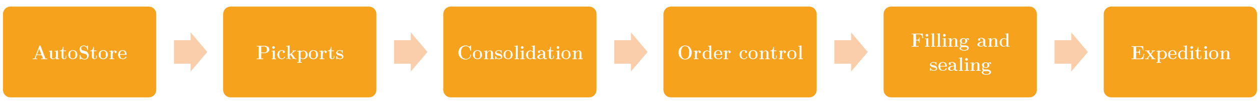

Figure 27 – The building blocks of the conceptual model

Recall that the processing line in focus of this research starts at the pickports of the AutoStore and ends at the expedition area. Although the AutoStore itself is not in scope of this research, it is included in the model to generate orders and their characteristics. The AutoStore order release logic and processing time can thus be adjusted. The specific order pick logic of the AutoStore is not included in the model. When the orders leave the AutoStore via the pickports, the stations that have been defined in Section 3.1 are also visited in the simulation model. Transportation takes place using conveyors that can also mimic the queueing behaviour observed in the actual processing line including the blocking of new orders once the conveyor is full.

Employees are included in the model. Every station in the processing line except the automatic reject station requires an employee to finish its jobs. Employees can travel between the processing stations using footpaths. The number of employees per shift can be set using a shift calendar.

The model tracks statistics of all orders when a simulation run is conducted. That is, the processing times, lead time and waiting time are stored for every order as well as the specific order characteristics of each order.

4.1.2 Model Input

The input for the simulation model can be divided into the categories workers, system and orders. We now provide the used inputs for each category and describe how we obtain the input for our simulation model.

Workers

- Shift times. The working hours for the AutoStore order processing line vary per day. Three shift types exist. At Mondays, a dayshift is used from 9.00 am until 4.00 pm in addition to the regular evening shift starting at 4.00 pm and ending around midnight. During the weekend, a weekend shift is used due to the relatively low order intake.
- Number of workers. the number of workers deployed at the processing line is determined using a deployment model that calculates the required number of employees with respect to the forecasted number of orders. In the current situation, this model generally prescribes six employees for the evening shifts and two employees for the day shift and weekend shift.

Orders

- Demand data. Historical demand data is used to determine the order inflow for the processing line. We elaborated on the data in the analysis conducted in Section 3.3. We determined both the amount of orders per day and the order arrival rate per hour. Based on this analysis, we find the parameters for a theoretical distribution. We used a poison arrival process to mimic the arrival of orders resulting in exponentially distributed interarrival times. The parameter beta (β) represents the time between arrivals. This parameter can be found using historical data. We specify beta for every hour and adjust the arrival rate accordingly.
- Boxtypes. In Section 3.2.2, we introduced the existing boxtypes referring to the different sizes of boxes available. The boxtypes used were also determined using historical data. The boxtypes influence the processing time of orders and can be used to differentiate between product groups. Using boxtypes in the simulation also allows for getting insight in the number of boxes used per type. We create an empirical distribution based on historical data to allow for boxtype sampling in our simulation model.
- Number of items per order. The number of items per order has a strong influence on the processing time of the order at the pickport and the order control station. The number of items in an order is also determined using historical data. Similar to the boxtype sampling, we obtain the relative frequency of occurrence of all possible number of items in an order. We then randomly sample form this empirical distribution to generate the number of items for a specific order.
- Other order characteristics. Several other boolean order characteristics are used that determine whether an action should be performed for a specific order. These include whether an order has a giro, a delivery note, inserts, consolidation items and whether the order is being scanned at the pickport instead of the order control station. For all the Boolean characteristics of orders, we create a simple uniform distribution that we than sample from using a random number that

we draw from the range of the uniform distribution. This way, we are able to randomly mimic the order characteristics that we observe in reality.

System

- Facility dimensions and space available. The facility dimensions have been obtained from CAD drawings of the plant that have been used during the construction of the AutoStore.
- Processing time per station. The processing times per processing station have been measured in detail by Westra, C (2019). We used the summary data of these measurements to fit distributions to all processing steps at each station. Note that we also include setup time in these processing times if applicable for the station. Because of the order dependent processing times, we construct the total processing time at a station out of several distributions that each represent a processing step at the station. This way, the total processing time at a station is the sum of all the sub distributions used for the processing steps.
- Number of servers per station. The number of workplaces per station is determined by observing the current setup and by checking whether the workplaces are operational. Currently, only a small portion of the workplaces is used. Generally, only three order control stations and three pickports are used while six pickports and seven order control tables are available.
- Conveyor speed. The conveyor speed has been obtained from the technical documentation supplied by the supplier of the processing line. Although freeflow conveyor speeds are only rarely achieved during a shift as a result of the queues, we need the information on the conveyor speed for new setups as we aim to reduce the queueing in these setups. The conveyor speed is determined to be 0.32 m/s.
- Conveyor capacity. Conveyor capacity is an important characteristic of the AutoStore order processing line. The conveyor functions as a buffer in the current setup. We determined the capacity of the conveyor during a shift. Although in practice the operators pack the conveyor by pushing all boxes forward and by repositioning boxes to fill all available space,

4.1.3 Model Output

Once a simulation run has been conducted, statistics are being stored to be able to evaluate the simulation run. Recall that the aim of this research is to improve the productivity of the AutoStore order processing line. Therefore, our evaluation will take place based on at least the productivity of the processing line. We therefore keep track of both the number of orders processed during a day and the total number of employee hours spent during that same day. Productivity can then be calculated by the dividing the number of orders by the number of employee hours used. We calculate the weekly productivity based on the weekday Monday up to and including Friday. We exclude Saturday and Sunday, as the productivity is generally not representative at these days due to the high number of employees that must be present for safety reasons.

However, productivity is a general performance measure that does not define *where* improvements should be made in the processing line, it only defines the overall performance of the processing line. To be able to propose a redesign for the processing line, we need more detailed information on the performance of the various components that together make up the entire processing line. We therefore also store the utilization for each workplace in each station in the processing line. The utilization of a processing station is determined as the portion of working time compared to the available time in a shift. As a result, the fact that the system is not used during the night or during the day does not have an effect on the achieved utilization. The leadtime of an order in the system is also stored which can, in combination with the processing times at each station be used to determine the transportation and waiting time per order as well.

In general, we store all order specific characteristics once the order has been finished and it leaves the processing line through either the expedition area for Bel parcels or when the order has been stored in the trolley near the filling and sealing station for Bus parcels.

Next to the KPIs that we measure for orders and working days, we also keep track of some variables that we use for the validation of the simulation such as the number or orders at the start of the evening shift, the total number of orders created, the total number of unfinished orders at a day, the number of orders in buffer, the current number of employees and the current order arrival rate.

To summarize, all output data collected in the simulation model is displayed in Table 11. We provide a short description and the update frequency for every variable.

Output	Description
Finished orders	The number of orders that leave the fulfilment centre each day
Number of working hours	The number of employees multiplied by the hours in a shift
Productivity	The number of finished orders divided by the used working hours for the weekdays Monday to Friday.
Number of unfinished orders	The number of orders that have to be processed on the next day
Orders in buffer	The number of orders present in the AutoStore buffer
Number of employees	The number of employees currently active at the processing line
Utilization per workplace in a station	The portion of time at which the workstation was processing orders, measured only from the start of shift up until the end of a shift.
Leadtime	The total time orders spent on the processing line
Transportation & Waiting time	The difference between the leadtime and the sum of the processing times
Order arrival rate	The order inflow rate per hour into the AutoStore order buffer that is used to generate order inflow form each day.

Table 11 - Model output

4.1.4 Assumptions and Simplifications

In designing the simulation model, several details that do not affect or hardly affect the system performance have been excluded. Most of these details are related to order characteristics that have a low frequency of occurrence.

- **Autostore simplification** - The AutoStore system itself as well as the intake of goods in the AutoStore is modelled as a "black box" that generates orders in the simulation model. Although processing logic is created for the AutoStore, reproducing the performance of the AutoStore in more detail is not included in the model.

- **Packing units** - In our simulation model, we do not model the highly unlikely event of an order being shipped using multiple packing units. In practice, it might be decided that an order cannot be shipped in one shipment order due to its size or due to stockouts for specific items in an order. In that case, several shipments are used to fulfil an order. The occurrence of this event is highly unlikely and its effect on the performance of the order processing line is estimated to be negligible.

- **Consolidation** - The consolidation area is represented by a simple processing unit although in practice it contains a relatively large shelve space that is used for the storage and retrieval of consolidation goods. Consolidation orders only make up 1.4 % of the total order amount and this share is expected to decline even further since the largest consolidation customer is leaving PostNL ECS. Due to the small percentage of orders and the expected further decrease of the percentage of consolidation orders, we only include the simplified processing unit that represents the entire consolidation process.

- **Serial Number Scan** - For some items, PostNL is currently implementing serial number scans to identify objects. This is another way of identifying items that is required for serial number dependent products such as gift cards that have a unique serial number. As a result of using the already present serial number of a product, no temporary barcode (Collo-ID) must be attached to the product which saves a small amount of time during the picking and packing process. The number of products that is currently identified using serial number scans is limited to a few percent of the entire order volume. Therefore, the effect of the decreased processing time is negligible and is not incorporated in our simulation model.

- **Deviation from scheduled breaks** - In our simulation, we assume that operators comply with their scheduled breaks. In practice, break times deviate from the planned breaks resulting in reduced operational time. The effect of the, in comparison to the entire shift, marginal deviations are not included in the simulation as the deviations would occur in every proposed setup and the effect on performance comparison is thus negligible.

- **Breakdowns -** Breakdowns are not being recorded by PostNL. In case a system failure occurs, this is often related to the IT systems. In that case, orders cannot be released for processing and the processing line is thus stopped. Partial failures at specific processing stations occur only incidentally and can often be solved easily by using another workplace at the station. The effects of failures at workstations is therefore minimal and we do not include this type of breakdowns. Instead, we include the more common AutoStore breakdowns in our simulation model, as will be discussed in Section 4.2.5.

- **Operator productivity -** We assume equal operator productivity. Although in practice some operators outperform other operators, the measured processing times used in our simulation are average processing times. PostNL is not interested in individual performance tracking at this point in time. Moreover, we assume that every employee is able to operate every station in the AutoStore order processing line. In practice, PostNL is currently training its employees to be able to work at all stations. Since this will be the situation in the near future, we base our model on this future situation.

- **Weekend shift -** Weekend shifts are simplified as they are exceptional shifts with significant overcapacity due to safety regulations. These regulations enforce at least two employees per shift while less employees are needed to process the available amount of orders. In practice, orders are processed between 19:00 pm and 22:00 pm on Saturdays. On Sundays, processing takes place between 17:00 pm and 22:00 pm in the evening. In our model, we use a regular evening shift starting at 16:00 pm and ending at 0:30 am. This is a simplification that allows us to use the same order generating procedure in weekends such that orders are generated up until midnight. If we would follow the actual situation, the shift would already have ended at 22:00 pm, the small order inflow created after 22:00 pm, adding up to 5% of the daily order inflow, could not be processed in this case.

- **Downscaling at the end of a shift -** When the amount of orders turns out to be less than expected during a shift, some of the operators are employed with other tasks in the fulfilment centre in Houten. This is often only a limited amount of time that is used to compensate for deficiencies between the planned order intake and the actual order intake. In our simulation model, we incorporate downscaling. We assume that 25% of the workforce can be employed elsewhere or sent home early. The overcapacity that exceeds 25 % of the workforce cannot be sent home early or deployed elsewhere. The planned employment hours of these employees will therefore be recorder as working hours although these employees cannot effectively work during these hours.

- **Order reject station -** The order reject station is not in use in practice. However, orders are being identified at this station using their barcode. If barcodes cannot be scanned, an order is taken off the line automatically (i.e. rejected). Orders that are rejected are generally returned to the line manually since there is often no reason for rejecting the order other than an incorrectly attached barcode. This entire procedure, the scanning of barcodes, rejects of some orders and manually placing them back on the line is simplified as one processor with a small processing time (3 seconds) in our simulation model that represents the scanning time of a barcode. Order rejects only occur a few times per shift and have no impact on the overall system performance. Rejects are therefore not included in the simulation model.

4.2 Technical implementation

For the technical implementation of the model, we used Siemens Tecnomatix Plant simulation, a discrete-event simulation software package. We now provide an impression of the model, a high-level explanation of the structure of the model and our considerations in choosing probability distributions for the modelled processes. Detailed explanations on the implementation of the model in Tecnomatix Plant Simulation are provided in Appendix 2

4.2.1 Model impressions

The simulation model exists out of two main frames, the control panel and the processing line. An impression of both frames is provided in Figure 28 and Figure 29 respectively. Whereas the control panel can be used to access the settings of the simulation and the experiment results, the processing line is the actual representation of the AutoStore order processing line.

Figure 28 – Control panel

The control panel is divided into six boxes. The boxes mainly contain tables, variables and methods. Variables are used to store certain values. Tables are used to store larger data collections. Methods are used to program system logic.

In the EventControl box, everything related to timekeeping and experimentation can be found. The experiment manager can be used to vary input variables of the simulation model. The Eventcontroller itself can be used to start a custom simulation run.

The "Input & Variables" frame contains system settings that are fixed and variables that are used by the system itself. These variables are mainly used to mimic the order inflow pattern. SeedValues for all random processes are also stored in the table "SeedValues".

The "Settings" box contains all system settings that can be adjusted. These settings include all order characteristic settings, personnel settings, the number of active workplaces for both the pickport station and the order control station and shift settings that define the working hours. Although the function of all settings can be easily recognised by their name, the demandfactor setting may require some additional explanation. The demandfactor can be used to increase or decrease the demand inflow in the system. If we use a demand factor of two, the demand will be doubled. However, the original inflow distribution over the day is still respected.

The “Indicators & KPIs” box contains variables that display the current state of the system. This box can be used to check the functioning of the system and to relate it to reality. We also used these indicators for validation, which we will cover in more detail later.

We store all the measured data in the box “Statistics Tracking”. The table “OrderStatistics” contains all relevant information related to the orders that have been processed at the current day. At the end of a day, the order statistics are removed once they have been used to calculate the day statistics. The DayStatistics table contains these daystatistics. These include the deployed hours, the utilization of all stations and their workplaces and order data aggregated on a day level.

In the “Model” box, the user can navigate to the ProcessingLine frame displayed in Figure 29. The ProcessingLine frame provides an overview of the AutoStore order processing line. This frame is created in such a way that it looks exactly like the processing line overview provided in Section 3.1. In comparison to that overview, only the footpaths that are used by the operators to get to a processing station are added next to some methods and a workerpool (the origin of the operators in the simulation). Once a simulation run is started, animations are visible at the ProcessingLine frame. The queueing behaviour occurring in the processing line in Houten is visible here as well.

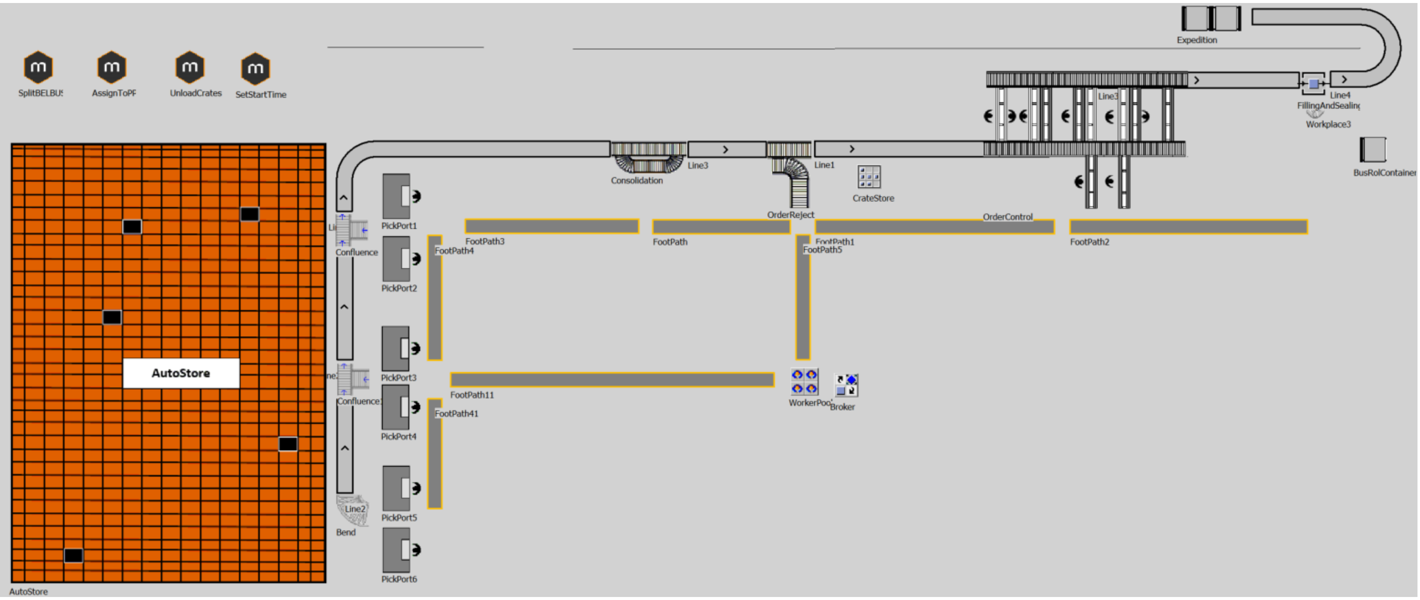

Figure 29 – The simulation model frame of the order processing line

5.2.2 Other Frames

Within the two main frames presented in the previous section, several other frames exist. All processing stations except for the order reject station have been modelled as separate frames. This way, the concept of inheritance can be optimally used and adjustments concerning for example the pickports can be made instantly for all pickports by adjusting the parent frame. Frames have been used for the AutoStore, the pickports, the consolidation station, expedition and the order control station. We also used frames for merges in the conveyor. The content of these frames is discussed in Appendix 2. the frame structure, new processing line setups can be easily configured with the frames functioning as building blocks.

4.2.3 Flowcharts and methods

The proces flow of our simulation model is displayed in Figure 30. The processflow shows the logic of the processing line per station represented by the horizontal lanes. The methods used to to model the system logic are also displayed in the process flow diagram in yellow. Although more methods are used in the simulation model, the methods displayed in Figure 30 are directly related to the orderflow.

For every method used in the simulation model, we provide a logic flow chart in Appendix 3. The logic flow charts provide more details on the logic incorporated in the model by a specific method. Therefore, the logic flows can be used to represent the system in other programming languages.

Confidential

Figure 30 - Process flow including methods

4.2.4 Distribution fit

To be able to generate representative processing times for each station in the order processing lines, we fit a probability distribution to the measured processing times. Processing times have been measured in detail by Westra, C (2019). Unfortunately, the raw measurements have been deleted after her graduation. Instead, only summary data is available on the measured processing times. To be able to fit a distribution to the summary data, we re-measured the processing times at one of the processing stations of the AutoStore order processing line. We then assume that the processing times at other stations follow a same distribution type with the parameters that can be determined using the available summary data. By measuring the processing times at the Filling and Sealing station, we were able to obtain a representative dataset that is based on jobs performed by both humans and machines.

In fitting a probability distribution to the obtained data, we first fitted several distributions and performed a visual inspection of the fit between the measured data and the proposed probability distribution equivalent. Once several distributions had been judged, the gamma distribution showed the best fit to the measured data. More details on the fitting procedure can be found in Appendix 4. The parameters of this distribution have been determined using the following formula's:

$$\alpha = \left(\frac{\mu}{s}\right)^2 \ and \ \beta = \frac{s^2}{\mu}$$

Where μ represents the sample mean, s represents the sample standard deviation and s^2 represents the sample variance.

Calculating the alpha and beta for the dataset measured at the filling and sealing station results in an alpha of 8.095 and a beta of 1.305. The resulting fit is displayed in Figure 31.

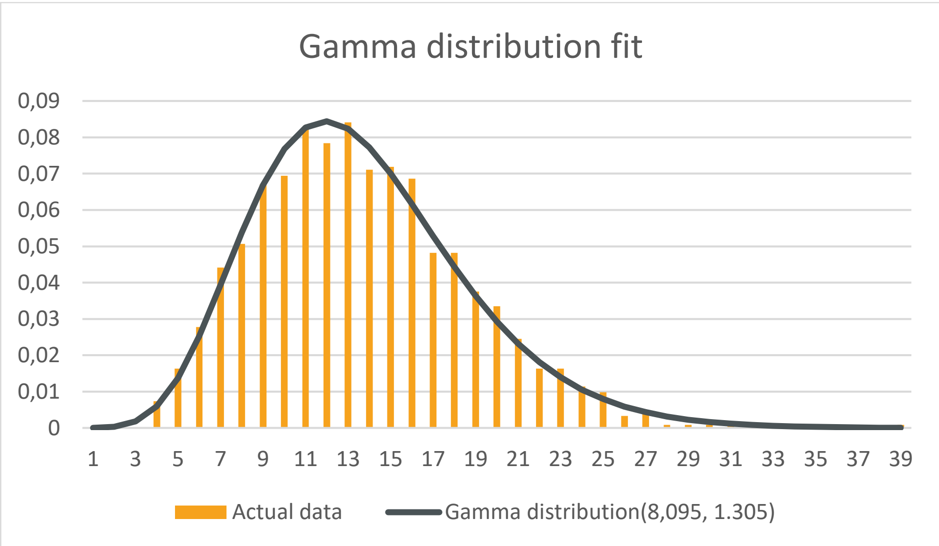

Figure 31 - Gamma distribution fit

Although choosing the gamma distribution seems to result in a good fit visually, we perform several statistical tests to check the fit between the probability distribution and the measured processing times. To start with, we conducted a chi-square goodness-of-fit test. The chi-square test tests whether the measured values differ significantly from the expected values based on the chosen probability distribution. As a result of performing the goodness-of-fit test, we can conclude that there is no significant difference between the observed and expected values with a significance of 0.05. We chose this level of significance as it is a common value used in the field.

Next to the goodness-of-fit test, we also used a QQ-plot and a PP-plot to judge the fit between the empirical data and the expected data. Both plots can be found in Appendix 4. As described in Section 4.1.2, we assume that all other processing stations in the processing line follow the same distribution type with their own respective parameters defined by the formulas provided at the start of this section.

4.2.5 Downtime

Downtime of machines in the AutoStore order processing line is not recorded. Due to the lack of data available, we must use estimations provided by the machine operators. When a failure occurs, this is often related to the robots of the AutoStore or the software of the AutoStore (Logics). In either case, a downtime causes the entire processing line to be halted because the inflow of goods via the AutoStore is stopped. As a result of multiple identical workplaces per processing station, the processing line itself hardly causes downtime. If one workplace is not functioning properly, operators generally switch to another workplace.

The foreman of the AutoStore team estimates the downtime due to the AutoStore to occur once a month and to last between half an hour to an hour. Assuming a month consists of four weeks and combining this assumption with the observation that a week consists of 55 operational hours, we determine the monthly operational hours to be 220 hours. Of these 220 hours, the estimated downtime is one hour.

The availability of the AutoStore order processing line is thus $\frac{219}{220} = 0.995$. We set the Mean Time To Repair (MTTR) at one hour, following the estimation provided by the foreman of the AutoStore team. The MTTR and the availability are used in our simulation model to simulate exponentially distributed breakdowns with the Mean Time To Failure (MTTF) as its parameter (λ). Lambda can be calculated directly from the availability and MTTR using the formula displayed below.

$$Availability = \frac{MTTF}{MTTF+MTTR} \qquad \text{(Birolini, 2013)}$$

Filling out the formula for the named parameters results in a MTTF of 199 hours. Using the MTTR, MTTF and availability, the failure behaviour can now be simulated.

4.3 Model Credibility

To establish model credibility, we must validate and verify the correctness of the model. We introduced the concepts of verification and validation in Section 2.7.4. Next to verification and validation, including the management and the operators at the fulfilment site in Houten in the development process leads to a better understanding of the model and consequently a better credibility of the model.

During the entire development process of the simulation model, we informed both the operators and the involved supervisors of the progress made. During kick-offs of the shifts of the AutoStore order processing line team, we presented our model in various stages of development. This led to feedback and further improvement of the simulation model.

4.3.1 Verification

During the development of the simulation model, we verified that the simulation model complied with the "paper" model. The object-oriented nature of Plant Simulation allows us to build the model in a modular fashion. We could therefore build one workstation at a time. After having built a workstation we have checked its functionality in detail using the debugger in Plant Simulation. The debugger allows the user to run the code line by line to see the effects of every line of code.

Next to close inspection of the programmed code, we also performed visual checks by following an order along its way through the order processing line. This way, we could check whether all required processing steps were completed and whether the order characteristics correctly determined the processing time at each station.

4.3.2 Validation

Whereas verification assures the fit between the "paper" model and our simulation model, validation assures the fit between the simulation model and reality. In the end, we want our simulation model to mimic the system it represents to be able to draw credible conclusions out of the model.

Validation of our simulation model is performed in two ways. First, we validate the actual performance of the current processing line layout with the modelled version of the processing line. We do so by comparing the capacity of the system, the productivity of the system and the number of unfinished number of orders at the end of a day. Secondly, we validate one of our interventions using a test setup at the fulfilment site in Houten and compare the simulation performance and the measured performance of the test setup. The two validation methods will be elaborated further on in this section.

To start with, the productivity of the simulated AutoStore order processing line should match the productivity achieved in practice. Productivity was earlier introduced in Section 3.3.4. In validating the productivity of the simulation model, we compare simulated productivity data with the actual performance of the system in the past ten weeks, a more up-to-date sample compared to the larger dataset used in Chapter 3. This way, we assure that the model matches the current state of the system. Earlier in this report, it was stated that weekend shifts are not representative measures for the performance of the system due to the overstaffing of the system as a result of safety regulations. We therefore focus on the weekdays ranging from Monday to Friday to assess the fit between the simulation model and the actual system.

Table 12 provides a comparison of the productivity results achieved in both the simulation model and the actual system. The values provided are averages taken over calendar week eight up until week ten for the actual performance. The values provided for the simulation model performance are averages taken over a sample run of one year. Table 12 illustrates that the simulation model closely resembles the actual performance of the system. The average weekly productivity closely resembles the actual performance of the system.

WeekDay	Actual performance (orders per manhour)	Simulation model performance (orders per manhour)	Deviation
Monday	26,6	26,8	0,2
Tuesday	25,4	27,0	1,6
Wednesday	26,2	25,4	-0,8
Thursday	26,2	25,9	-0,3
Friday	25,0	24,0	-1
Average	**25,9**	**25,8**	**-0,1**

Table 12 - Productivity comparison between the actual system and the simulation model

The largest performance deviation is observed on Tuesdays, further investigation lead to the conclusion that this is due to the high frequency of occurrence of unfinished work at Mondays. This work is then moved to Tuesdays and therefore contributes to the number of finished orders at Tuesday, thereby boosting the productivity achieved at Tuesday. The second largest deviation occurs at Fridays. At Fridays, the lowest number of orders is processed. This means that in practice, the number of employees is scaled down more compared to Mondays or Tuesdays. In our simulation model, we scale down employees using the same procedure for every weekday. That is, 25% of the employees can be sent home early in case of overcapacity. We observe that in practice, higher productivity scores are achieved on Fridays (with the same amount of orders), so less employees are used. We can thus conclude that in practice, more that 25% of the overcapacity can be sent home or deployed elsewhere. As a result, the processing line is slightly overstaffed at Fridays in our simulation model, resulting in the observed deviation.

The existing deviations in productivity are thus mainly caused by the moving of workload between days and dynamic staffing of the processing line and the stochasticity of the model. In our evaluation of interventions, we focus on the average weekly productivity scores that do not include weekends, the relatively small deviations in performance on a weekday level have therefore been determined to be acceptable in consultation with the management of PostNL Fulfilment in Houten.

Next to the validation of the productivity of the processing line, we also validate the capacity of the system. The capacity of the current system can be evaluated best using the day in the week that processes most orders, being Monday. At Monday, the system operates at its highest capacity in the current setup. In practice, it is not uncommon that orders for customers with lower priority are postponed to Tuesday in case of unfinished work. In our simulation model, we also see this postponement of orders to the next day, mainly on Mondays.

For our simulation run with a duration of one year, the average number of unfinished orders per day is displayed in Table 13.

Weekday	AverageOrdersUnfinished
Monday	37,6
Tuesday	-36,0
Wednesday	-0,4
Friday	0,1
Saturday	-0,1
Sunday	-0,1

Table 13 - Backlog of orders

Although PostNL does not possess any data on the number of backorders per day that we can use to compare our simulation output, we do observe a backlog behaviour that is comparable to the behaviour of the actual AutoStore order processing line. From Table 13, we conclude that backlogging of orders generally occurs at Mondays and that the backlog is processed on Tuesday, resulting in a negative backlog on that day. The negative values in the table result from the fact that the order intake is smaller than order outflow as a result of the processing of backlog orders from the previous day. On the other weekdays, incidents (e.g. breakdowns) occasionally cause a backlog of an order though there is no structural shortage of capacity which is in line with our observations at PostNL.

We also validated whether the order profiles generated in the simulation model match with the order profiles that we measured and discussed in Section 3.3. Although we carefully set the characteristics and empirical distributions that generate the order characteristics, checking the actual output of orders assures that these modelling steps have been completed successfully. We checked the order characteristics for delivery notes, inserts, giros, consolidation, boxtype and number of items in an order by comparing the frequency of occurrence of all values for each setting in the order output of our model in a dayrun. The observed frequencies for all characteristic values are within 2% of the measured frequencies provided in our data analysis. The results of the validation procedure are displayed in Table 14 and Table 15 for the boxtypes and other order characteristics respectively.

Boxtype	Simulation model (%)	Data analysis (%)
A00	1%	1%
A01	38%	39%
A02	9%	10%
A04	7%	7%
A05	3%	3%
A06	1%	1%
A07	3%	2%
A08	3%	4%
A09	12%	11%
A10	5%	5%
A20	1%	1%
A21	2%	2%
A22	4%	3%
A60	0%	0%
A61	1%	1%
A62	5%	5%
A65	4%	4%

Table 14 - Validation of boxtype generation

Characteristic	Simulation model (%)	Data analysis (%)
Consolidation	2%	1,4%
Delivery Note	40%	39%
Giro	4%	3%
Inserts	39%	39%

Table 15 - Validation of Characteristic generation

Introducing new layout alternatives consequently also introduces significant changes for the employees of the AutoStore order processing line. Although we can estimate the effect of changes well with the use of our simulation model, we want to assure ourselves of a good fit between the outcome of our model and reality for the new layouts. Working at another place, in another sequence might cause unexpected effects that cannot be predicted. Therefore, we used an onsite experimentation setup to validate the processing times of processing stations with new job allocations in the new layout alternatives. Processing times in this new setup have been measured and validated with the outcome of our simulation model.

In our test-setup, we measured the processing time of the available Bus orders using one operator. This operator used 52 minutes and 31 seconds to process 55 orders. The measured hourly throughput rate thus results in 55/52,5 * 60 = 63 orders per man hour. In this test setup, barcodes were still attached to each order and temporary conveyors and an imitation of the pick-to-light system was used. The actual performance of the specialized order processing line is expected to perform better. An impression of the test setup existing out of a pickport (marked in red), a small conveyor (marked in blue) and an order control table (marked in green) is provided in Figure 32. This specialized processing line for Bus orders is part of the cellular layout intervention that will be introduced in Section 5.2.3.

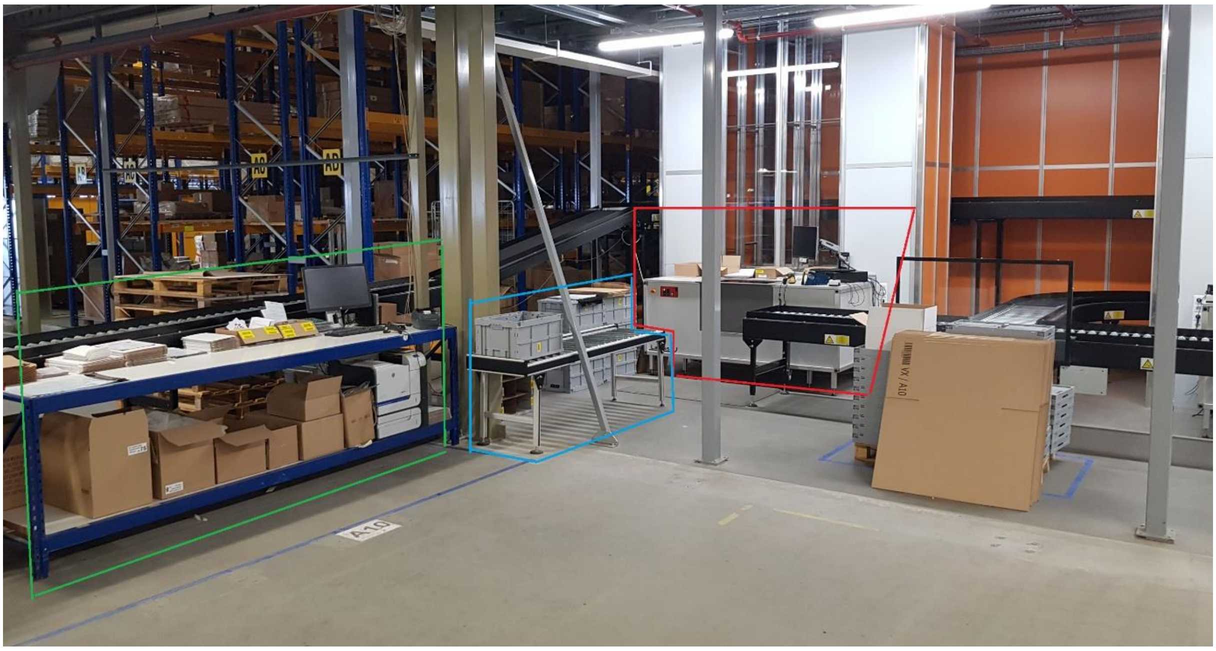

Figure 32 - An impression of the test setup

In our simulation model, the Bus order processing line reaches a throughput rate of 65 orders per hour using a single operator. This value is close to the measured throughput rate. The measurement thus validates our simulation model. Note that attaching new bar codes to every order is not included in the processing time of our simulation model. We expect the actual throughput rate of the specialized processing line to be higher than the simulated value if the application of barcodes to every order is not performed in the test setting.

4.4 Conclusion on the Model Design

In this chapter, we presented the model used for our research from both a conceptual and a technical point of view. Section 4.1 defined the model input and output and defined the assumptions and simplifications used. These simplifications and assumptions allow us to model the system efficiently. The assumptions and simplifications should however not influence the performance measures and representativeness of the model significantly. We therefore also elaborated on the implications of each simplification, assuring the effect on our experiments and conclusions to be negligible.

Using this conceptual description of the intended model, we then moved towards the technical implementation of the model. Section 4.2 elaborates on the steps that we took to create the technical implementation of the model in Tecnomatix Plant Simulation. We elaborated on the structure of the model and presented our probability distribution fitting procedure resulting in a gamma distribution for the order processing times at the workstations. The gamma distribution was fitted to each processing step performed at a station separately using the parameters suitable for that specific processing step. We also introduced downtime in the model that results from AutoStore failures, occurring on average once a month. Although no data is recorded concerning the downtime, we used interviews and thus operator experience to determine a representative setting for our simulation model.

In the last section of this chapter, we established model credibility by explaining our verification procedure and by validating the model based on its performance fit in terms of productivity and the generated order characteristics. We also validated the capacity of the system by comparing the number of unfinished orders per week with the pattern we observe in reality. Both the technical validation of the model and the involvement of both management and operators in the development of our model assures that these stakeholders trust the model and the conclusions that we find based upon it.

Lastly, we also introduced the validation of one of our interventions using an onsite experimentation setup. The performance measured on this on-site setup confirmed the performance observed in our simulation model. The discrepancy between the simulation model and the onsite test is most probably a result of the fact that barcodes still had to be applied to every order in the test-setting, whereas this processing step is not included in the simulation model. Based on the entire validation procedure, we can thus state that the performance displayed in our simulation model corresponds with reality.

5. Solution and Experiment design

In this chapter, we elaborate on the process of creating new layout alternatives for the AutoStore order processing line. First, we provide design requirements for a new layout design in Section 5.1. We then introduce the interventions that we propose in Section 5.2. We chose to develop five interventions in the current layout. The first four interventions result in four new system designs. Whereas the first intervention is an optimization of the current processing line layout, interventions two and three propose a new layout based on a "greenfield" situation. That is, these layout alternatives have been developed from scratch and do not consider the current layout. The last intervention, intervention four, proposes a system redesign that is entirely based upon future demand levels. With growing demand, new opportunities arise in terms of investments in automation. The last intervention that we introduce is an online line-balancing procedure that can be used to further optimize the systems resulting from the other interventions. Section 5.3 introduces our experimental design, covering the indicators, variables, scenarios and settings of our experiments. We also introduce the sensitivity analysis that we conduct.

5.1 Requirements for New Designs

For all interventions, some basic requirements must be incorporated in the designs. These requirements have been identified during interviews with operators, team leaders and the management team. Next to these interviews, we also base the requirements for new designs on observations made during production shifts that we observed and joined. The following requirements have been defined.

- Shipping box supply. In a new layout design, the supply of shipping boxes to the pickports must be incorporated. To be able to supply pickports with shipping boxes, a shipping box stock is to be located near the pickports in such a way that the stock is accessible for pallet movers. In the current layout, the supply of shipping boxes is hard due to limited space available around the pickports. As a result, the box stock is located further away from the pickports.
- Storage space for insert stock. The so called "grab stock" for inserts should be located close to the order control tables. Currently, this stock is located along the conveyor belts of the processing line. As a result, operators have to walk away from their work to get new inserts once they have all been used.
- Consolidation space. A consolidation space should be reserved for items that cannot be stored in the Auto Store. It should be noted that the number of consolidation items will decrease significantly due to fact that the largest consolidation customer will leave PostNL soon. The consolidation area should be located in such a way that is does not obstruct paths or the overview of the foreman, which is a common complaint in the current setup.
- Kick-off area. The operator team uses a small gathering space for kick-offs and performance updates during a shift. This area is already present in the current layout.
- Accessibility of operator workspace. All workspaces should be easily accessible via safe and clear walking areas. Currently, order control tables are harder to reach as most of them are located behind a conveyor belt. To access the workspaces, one must first pass the conveyor belt using one of the foldable sections in the conveyor belt system.
- Operator workspace size. The workspaces should be allocated in such a way that enough space is available for an ergonomic and spacious way of working. Currently, working spaces are large enough. However, the size of the working spaces has been a problem in the past.

The named requirements will be incorporated in the interventions that we propose. Especially in the interventions that change the layout of the AutoStore order processing line, we assure ourselves of complying with these design requirements.

5.2 Proposed Interventions

In this section, we use several approaches to generate alternative layouts. Each approach is formulated as an intervention. Whereas some interventions only influence the logic or content of processing stations in the current setup, other interventions change the entire setup of the processing line by rearranging processing stations and the workload of these workstations. We also introduce an intervention that proposes a smart order sequencing procedure to actively balance workload during operations.

5.2.1 Intervention 1: Finetuning the current layout

In our first intervention, we optimize the current processing line layout. We introduce several small interventions to the processing line that improve its performance. This way, we can evaluate the maximum capacity and productivity that is feasible in the current setup in its optimized form.

To optimize the current layout, we adjust the processing line in several ways. To start with, we remove process steps that are not being used. We then apply the concept of line balancing to level the workload on each workstation and thus improve throughput.

Unnecessary process steps

The current processing line consists of stations that are not being used. These stations do require processing time and can be removed from the layout. Although these stations are no bottleneck stations, non-value adding processing steps should be removed to reduce the overall required processing time. Processing steps that will be removed from the current layout are the automatic reject based on order weight and the camera for taking photos of delivery box content. Although both processing steps can potentially be used in the future, they currently do not add any value.

Line balancing

To assure optimal utilization of the available resources, the workload in the processing line should be equally divided among the workstations. In the current layout, workload division is unbalanced. This can be concluded both from real-time observations as well as from our simulation model. Overloading of the order control station is occurring in both the model and the actual processing line. For determining desired shifts in workload, we use our simulation model as main input as it provides more detailed information on utilization of each station.

As mentioned in Section 2.6 in our literature study, line balancing can be achieved by minimizing the difference in workload between each workstation. To do so, we first determine the current workload at each station based on the utilization of the workstations. These utilization rates have been obtained from our simulation model by running the simulation for one year in its current configuration. Note that in the current setup, only three pickports and three order control tables are used. The utilization is therefore only displayed for these pickports and order control tables. We also differentiate between utilization rate including weekends and excluding weekends. Weekend shifts are short and special shifts in the sense that they are operated by two operators and only process a limited number of orders (only 4-5% of the order amount on Monday). The number of operators is determined by safety regulations (at least two operators) and not by capacity requirements. Therefore, weekend shifts do not provide valuable information on system performance.

We aim to equalize the utilizations of all stations and therefore should try to shift jobs being processed at the order control tables towards either the pickports or the filling and sealing station.

In Section 3.1, we already identified the jobs that are being completed at the order control station. We now identify which jobs can be moved to another station and which jobs require to be performed at the order control station.

Order Control			
Action	**Required time(s)**	**Fixed at Order Control?**	**Possible other stations**
Set-up	4.3	Yes	
Order check	11.3	No	PickPort
Place inserts	4.7	No	Pickport Filling and Sealing
Shipping label	6.5	Yes	
Delivery note	8.2	Yes	
Transfer to conveyor or trolley	11.0	Yes	

Table 16 - Jobs suitable for a transfer to the pickports

The utilization of the pickport station is significantly lower as we found out in Section 3.2.1. We thus aim to shift workload to the pickports. As can be seen in Table 16, both the order check and placing inserts can be transferred to the pickports. Inserts can also be added to the parcel boxes at the filling and sealing station. These and other jobs cannot be transferred to other stations due to precedence constraints or due to the IT system design. Moreover, set-up and the transfer times to the conveyor or trolley are station specific.

PostNL already started order checking at pickports. However, this is gradually introduced for those customers that experience relatively few picking errors. Orders for these customers do not require the order control anymore. We can use both the movement of placing inserts and the remainder of the order checks to the pickports to level the workload between the pickports and the order control tables.

Although the performance of the systems that result from moving workload between stations will be assessed in Chapter 6 together with the other interventions, we will now determine what workload should be moved based on some simple simulation runs with the new workload configurations.

To start with, we estimate the effects of moving the inserts to the pickports. If we run the system with the settings that we also used for obtaining the utilization of all stations in Figure 18 in Section 3.2.1, using three pickports and three order control tables, we obtain the utilizations presented in Figure 33.

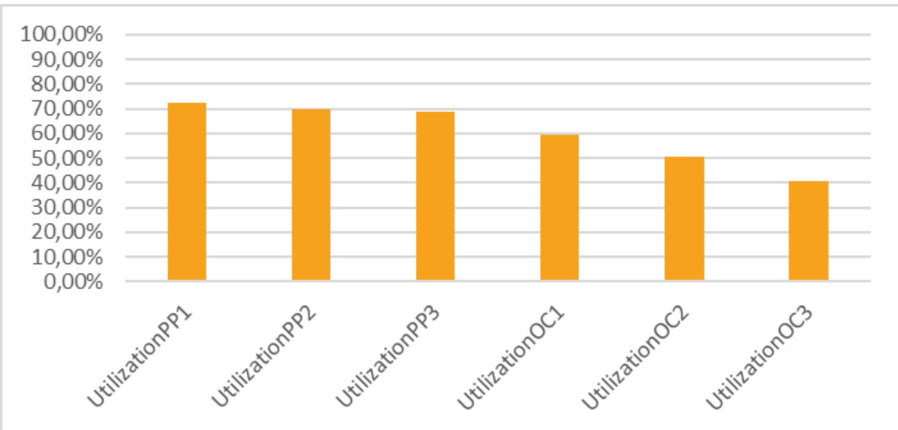

Figure 33 - Station utilizations with inserts at the pickports

Figure 33 shows that moving the inserts to the pickports is a measure that overcompensates for the workload difference. We see that the pickports are now overloaded compared to the workload of the order control tables. However, as utilization now decreases the further, we move down the processing line, queues do not appear. Note that the pickports receive their orders directly from the AutoStore system, so the output rate of the AutoStore system can easily be adjusted to the processing rate of the processing line without queue formation in front of the pickports. As a result, demand can grow until the pickports reach their capacity without further consequences for the processing line.

As another intervention in shifting workload between workstations, we proposed to increase the percentage of orders that we scan at the pickport. Evaluation of this adjustment leads to the utilizations presented in Figure 34. We observe that the effect of moving the scanning procedure to the pickport is considerably smaller compared to moving the inserts to the pickport.

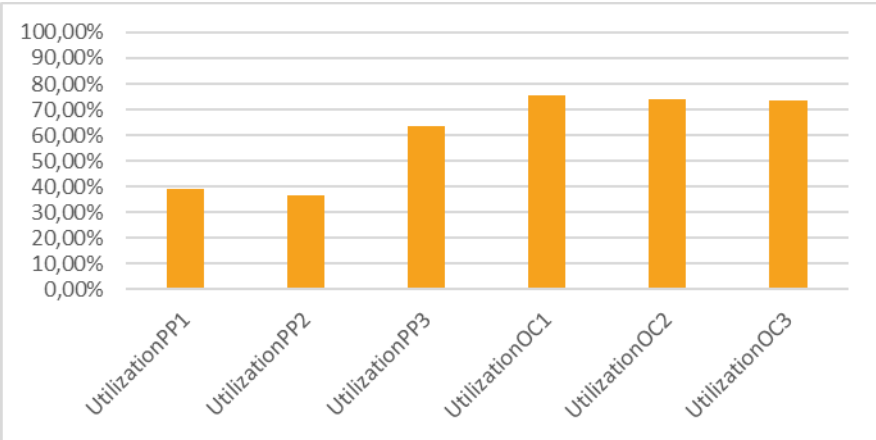

Figure 34 - Station utilizations with scanning at the pickports

Based on the explorative experimentation with the movement of workload to other stations, we further investigate the performance of the optimized current situation with inserts at the pickports and removed order reject and photo station. The resulting system will be tested as “intervention 1” in Chapter 6 as well as the other interventions proposed in this chapter.

5.2.2 Intervention 2: Distance Minimization

In the literature review chapter, we highlighted the general trend in the available literature to minimize the material handling costs in designing a production line. Following most of the papers read, we also apply this methodology in one of our interventions. This intervention minimizes the conveyor distance to be travelled. As a result, the material handling costs are also minimized. Moreover, the unused station order reject station is removed from the line, just like in the intervention presented in the previous paragraph.

The general formulation for distance minimization introduced in the literature review in Section 2.3 is as follows (Meller & Gau, 1996):

$$min \sum_{i=1}^{N} \sum_{j=1}^{N} (c_{ij}^{H} d_{ij}^{H} + c_{ij}^{V} d_{ij}^{V}) f_{ij}$$

For our single floor facility, we do not have to distinguish between the vertical and horizontal component of the formula. The formulation consequently can be reduced to:

$$min \sum_{i=1}^{N} \sum_{j=1}^{N} (c_{ij} d_{ij}) f_{ij}$$

We repeat that f_{ij} denotes the flow between station i and station j, c_{ij} denotes the material handling cost per meter between station i and station j and d_{ij} denotes the distance between station i and station j.

For us to be able to apply this formulation to the AutoStore order processing line, we require input for all three variables. However, we noted earlier that the processing line uses a typical product line layout in which all products pass all stations. Moreover, the means of transportation between each station is similar, namely using a conveyor. Therefore, both variables c_{ij} and f_{ij} are fixed in our situation. Minimizing the material handling costs formulation consequently boils down to minimizing d_{ij}.

With this assumption in mind and the observation that processing stations are spread out over the available floor space in the current layout of the AutoStore order processing line, we suggest to relocate the stations of the AutoStore order processing line in such a way that the travel distance between the stations is minimized. In other words, we compress the current layout to reduce the distance to be travelled by reducing the conveyor length.

Note that by doing so, we also reduce the available buffer space and thus may require additional servers at a station to compensate for the reduction in buffer availability. In principle, adding an additional server is an undesirable action since the achieved productivity will decrease (recall that productivity is defined as the amount of orders processed divided by the total number of employee hours spent to do so). However, if the processing end-time reduces significantly, the extra hours spent by the additional server can be regained by a reduced shift length. Applying the line balancing proposed in intervention one can also be beneficial for reducing the effects of the smaller buffer spaces as queues will not form downstream the processing line.

Reducing the conveyor length as much as possible results in the layout displayed in Figure 35.

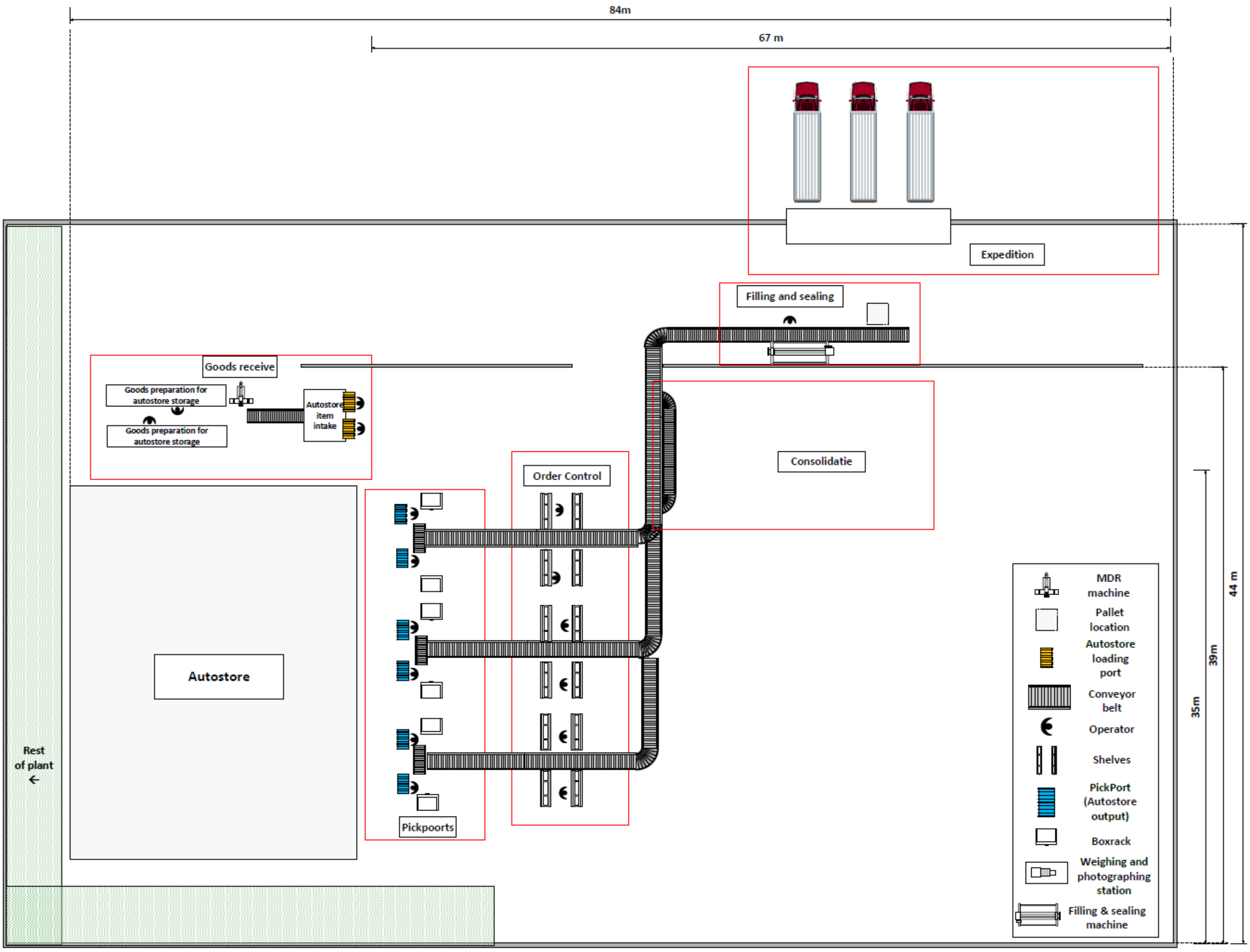

Figure 35 - Distance minimization intervention layout

Note that, to be able to minimize the travel distance as proposed in Figure 35, we swapped the sequence of the order control and the consolidation station. Earlier in this report, we drew the conclusion that consolidation order account for a small percentage of the overall order intake. Creating a consolidation area that serves all three pickports before the order control station would result in a significant travel distance increase for all orders. We therefore chose to position the consolidation station near the end of the processing line, implying that the consolidated items are not checked at the order control station. Therefore, an additional order control action is performed at the consolidation station itself for the small number of consolidation orders. This intervention is technically feasible, though the change in sequence requires additional IT related adjustments to the current system.

5.2.3 Intervention 3: Cellular Layout

The third intervention is a redesign of the processing line starting from a greenfield situation. Whereas we followed a distance minimization approach in the previous intervention, we now do not necessarily consider material handling costs. Instead we focus on creating a cellular layout. We do so by identifying order groups that have the same processing requirements using the following procedure:

1. Identify all possible order groups based on order characteristics
2. Calculate a similarity index for all the found order groups that indicates whether the processing paths of these groups are alike
3. Use a P-median model to cluster order groups with a high similarity index into two groups
4. Create a processing line layout that exists out of separate processing lines for the found order groups

The cellular layout design approach originates from the observation that many orders do not require all stations in the current processing line layout. However, all orders visit all stations in the processing line. To clarify the range of product types that is being processed, we identify the processing needs per product group. Product groups are formed through combinations of the order characteristics identified in Section *3.3.2.*

We identify five main characteristics of the orders being processed. These include whether the order is a Bel or Bus order and whether the order has Consolidation, Inserts, Giros or a Delivery Note. All characteristics can have only two values. For example, an order can be either a Bus or a Bel order. The total amount of characteristic combinations would thus add up to 2^5 =35. However, some combinations are not possible in practice. Bus orders, for example, are relatively small. Consolidation therefore does not occur for this type order per definition as consolidation is the process of manually adding items to orders that are too large for the AutoStore. These large items do not fit in the small Bus orders. After removal of all impossible combinations, 24 combinations are left. For these 24 combinations, the required resources for completing the required processing steps are displayed in the product-machine matrix in Table 17.

#	Characteristic combination:	Probability of occurrence	Pickport	Crate	Consolidation	Insert	Giro printer	Delivery Note printer	Filling & Sealing
			Required resources						
1	Bel-Consolidation-Inserts-Giro-DeliveryNote	0,00%	1	0	1	1	1	1	1
2	Bel-Consolidation-Inserts-Giro-NoDeliveryNote	0,01%	1	0	1	1	1	0	1
3	Bel-Consolidation-Inserts-NoGiro-DeliveryNote	0,16%	1	0	1	1	0	1	1
4	Bel-Consolidation-Inserts-NoGiro-NoDeliveryNote	0,24%	1	0	1	1	0	0	1
5	Bel-Consolidation-NoInserts-Giro-DeliveryNote	0,01%	1	0	1	0	1	1	1
6	Bel-Consolidation-NoInserts-Giro-NoDeliveryNote	0,01%	1	0	1	0	1	0	1
7	Bel-Consolidation-NoInserts-NoGiro-DeliveryNote	0,24%	1	0	1	0	0	1	1
8	Bel-Consolidation-NoInserts-NoGiro-NoDeliveryNote	0,38%	1	0	1	0	0	0	1
9	Bel-NoConsolidation-Inserts-Giro-DeliveryNote	0,34%	1	0	0	1	1	1	1
10	Bel-NoConsolidation-Inserts-Giro-NoDeliveryNote	0,53%	1	0	0	1	1	0	1
11	Bel-NoConsolidation-Inserts-NoGiro-DeliveryNote	10,92%	1	0	0	1	0	1	1
12	Bel-NoConsolidation-Inserts-NoGiro-NoDeliveryNote	17,09%	1	0	0	1	0	0	1
13	Bel-NoConsolidation-NoInserts-Giro-DeliveryNote	0,53%	1	0	0	0	1	1	1
14	Bel-NoConsolidation-NoInserts-Giro-NoDeliveryNote	0,83%	1	0	0	0	1	0	1
15	Bel-NoConsolidation-NoInserts-NoGiro-DeliveryNote	17,09%	1	0	0	0	0	1	1
16	Bel-NoConsolidation-NoInserts-NoGiro-NoDeliveryNote	26,73%	1	0	0	0	0	0	1
17	Bus-NoConsolidation-Inserts-Giro-DeliveryNote	0,11%	1	1	0	1	1	1	0
18	Bus-NoConsolidation-Inserts-Giro-NoDeliveryNote	0,18%	1	1	0	1	1	0	0
19	Bus-NoConsolidation-Inserts-NoGiro-DeliveryNote	3,62%	1	1	0	1	0	1	0
20	Bus-NoConsolidation-Inserts-NoGiro-NoDeliveryNote	5,67%	1	1	0	1	0	0	0
21	Bus-NoConsolidation-NoInserts-Giro-DeliveryNote	0,18%	1	1	0	0	1	1	0
22	Bus-NoConsolidation-NoInserts-Giro-NoDeliveryNote	0,27%	1	1	0	0	1	0	0
23	Bus-NoConsolidation-NoInserts-NoGiro-DeliveryNote	5,67%	1	1	0	0	0	1	0
24	Bus-NoConsolidation-NoInserts-NoGiro-NoDeliveryNote	8,86%	1	1	0	0	0	0	0

Table 17 – Product-Machine matrix

Now that we identified the product groups and their required resources, we can calculate the similarity index of the product groups based on the resources they require. The similarity index was introduced in Section 2.5.2 as:

$$S_{ij}^{m} = \frac{\sum_{k=1}^{p} a_{ik}a_{jk}}{\sum_{k=1}^{p}(a_{ik}+a_{jk}-a_{ik}a_{jk})} \text{ (McAuley, 1972)}$$

Where S_{ij}^{m} is the similarity coefficient between machines i and j, p is the total number of parts, a_{ik} is the element of the ith row and the kth column in the Part-Machine matrix.

Calculating the similarity index between each product group results in a matrix that displays commonality between the product groups as displayed in Table 18.

ParcelType (i) \ Parceltype (j)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	1,0	0,8	0,1	0,8	0,4	0,3	0,3	0,3	0,7	0,3	0,8	0,7	0,7	0,5	0,8	0,7	0,7	0,5	0,7	0,5	0,5	0,6	0,4	0,4
2	0,8	1,0	0,2	0,7	0,3	0,1	0,4	0,3	0,8	0,3	0,7	0,8	0,5	0,6	0,7	0,8	0,5	0,6	0,5	0,6	0,3	0,4	0,5	0,3
3	0,1	0,2	1,0	0,2	0,5	0,7	0,3	0,7	0,2	0,7	0,2	0,2	0,2	0,3	0,2	0,2	0,2	0,3	0,2	0,3	0,3	0,4	0,5	0,5
4	0,8	0,7	0,2	1,0	0,5	0,3	0,4	0,1	0,8	0,3	0,7	0,5	0,8	0,6	0,7	0,5	0,8	0,6	0,5	0,3	0,6	0,4	0,3	0,3
5	0,4	0,3	0,5	0,5	1,0	0,8	0,2	0,4	0,3	0,8	0,3	0,1	0,3	0,2	0,5	0,3	0,6	0,4	0,3	0,2	0,4	0,8	0,6	0,6
6	0,3	0,1	0,7	0,3	0,8	1,0	0,3	0,5	0,2	0,5	0,3	0,2	0,4	0,2	0,3	0,2	0,4	0,2	0,4	0,2	0,5	0,6	0,4	0,8
7	0,3	0,4	0,3	0,4	0,2	0,3	1,0	0,3	0,5	0,3	0,4	0,5	0,5	0,7	0,4	0,5	0,5	0,7	0,5	0,7	0,7	0,2	0,2	0,2
8	0,3	0,3	0,7	0,1	0,4	0,5	0,3	1,0	0,2	0,5	0,3	0,4	0,2	0,2	0,3	0,4	0,2	0,2	0,4	0,5	0,2	0,6	0,8	0,8
9	0,7	0,8	0,2	0,8	0,3	0,2	0,5	0,2	1,0	0,4	0,5	0,6	0,6	0,8	0,5	0,6	0,6	0,8	0,3	0,4	0,4	0,3	0,3	0,1
10	0,3	0,3	0,7	0,3	0,8	0,5	0,3	0,5	0,4	1,0	0,1	0,2	0,2	0,2	0,3	0,4	0,4	0,5	0,2	0,2	0,2	0,6	0,8	0,4
11	0,8	0,7	0,2	0,7	0,3	0,3	0,4	0,3	0,5	0,1	1,0	0,8	0,8	0,6	0,7	0,5	0,5	0,3	0,8	0,6	0,6	0,4	0,3	0,5
12	0,7	0,8	0,2	0,5	0,1	0,2	0,5	0,4	0,6	0,2	0,8	1,0	0,6	0,8	0,5	0,6	0,3	0,4	0,6	0,8	0,4	0,3	0,3	0,3
13	0,7	0,5	0,2	0,8	0,3	0,4	0,5	0,2	0,6	0,2	0,8	0,6	1,0	0,8	0,5	0,3	0,6	0,4	0,6	0,4	0,8	0,3	0,1	0,3
14	0,5	0,6	0,3	0,6	0,2	0,2	0,7	0,2	0,8	0,2	0,6	0,8	0,8	1,0	0,3	0,4	0,4	0,5	0,4	0,5	0,5	0,1	0,2	0,2
15	0,8	0,7	0,2	0,7	0,5	0,3	0,4	0,3	0,5	0,3	0,7	0,5	0,5	0,3	1,0	0,8	0,8	0,6	0,8	0,6	0,6	0,7	0,5	0,5
16	0,7	0,8	0,2	0,5	0,3	0,2	0,5	0,4	0,6	0,4	0,5	0,6	0,3	0,4	0,8	1,0	0,6	0,8	0,6	0,8	0,4	0,5	0,6	0,3
17	0,7	0,5	0,2	0,8	0,6	0,4	0,5	0,2	0,6	0,4	0,5	0,3	0,6	0,4	0,8	0,6	1,0	0,8	0,6	0,4	0,8	0,5	0,3	0,3
18	0,5	0,6	0,3	0,6	0,4	0,2	0,7	0,2	0,8	0,5	0,3	0,4	0,4	0,5	0,6	0,8	0,8	1,0	0,4	0,5	0,5	0,3	0,4	0,2
19	0,7	0,5	0,2	0,5	0,3	0,4	0,5	0,4	0,3	0,2	0,8	0,6	0,6	0,4	0,8	0,6	0,6	0,4	1,0	0,8	0,8	0,5	0,3	0,6
20	0,5	0,6	0,3	0,3	0,2	0,2	0,7	0,5	0,4	0,2	0,6	0,8	0,4	0,5	0,6	0,8	0,4	0,5	0,8	1,0	0,5	0,3	0,4	0,4
21	0,5	0,3	0,3	0,6	0,4	0,5	0,7	0,2	0,4	0,2	0,6	0,4	0,8	0,5	0,6	0,4	0,8	0,5	0,8	0,5	1,0	0,3	0,2	0,4
22	0,6	0,4	0,4	0,4	0,8	0,6	0,2	0,6	0,3	0,6	0,4	0,3	0,3	0,1	0,7	0,5	0,5	0,3	0,5	0,3	0,3	1,0	0,8	0,8
23	0,4	0,5	0,5	0,3	0,6	0,4	0,2	0,8	0,3	0,8	0,3	0,3	0,1	0,2	0,5	0,6	0,3	0,4	0,3	0,4	0,2	0,8	1,0	0,6
24	0,4	0,3	0,5	0,3	0,6	0,8	0,2	0,8	0,1	0,4	0,5	0,3	0,3	0,2	0,5	0,3	0,3	0,2	0,6	0,4	0,4	0,8	0,6	1,0

Table 18 – Similarity Index matrix

In the similarity index matrix, we already observe a clear spread of orders that fit together well (dark green colour) and orders that show almost no similarity in the processing paths that they use (dark red colour). Note that the matrix is, per definition, symmetric. Using the similarity indexes between products, we can form groups of products that share a large portion of their processing requirements. To do so, we apply the P-median model introduced in Section 2.5.3. The P-median model identifies a prescribed amount of product groups in such a way that the achieved similarity between products in the same group is maximized.

Applying the P-Median model for the instance represented by the similarity index matrix in Table 18 results in the product groups {1,2,4,7,9,11,12,13,14,15,16,17,18,19,20,21} and {2,5,6,8,10,22,23,24} with product group seeds 1 and 22 respectively. The result of running the P-median model is displayed in Table 19.

Product group (j)	Product group (i)																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
9	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
11	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0

Table 19 – Outcome of the P-median model

The formed product groups are Bel parcels and Bus parcels with a share in total relative order quantity of 75.1% and 24.9% respectively. For the formed product groups, specialized processing lines can now be designed. As a result of the relative order quantities of both groups, we chose to dedicate two of the six available pickports to Bus parcels. Note that this is equal to 1/3 of the available pickports which is more than the required 24.9%. This decision was made in cooperation with the PostNL management with the expected Bus parcel growth in mind.

For the two specialized processing line types, we tailor the processing stations and minimize the processing steps required. For the Bus parcel line this means, no consolidation and no filling and sealing station is required. Moreover, because of the small size of the parcels, we can use pre-produced crates to store the orders in without having to use new Collo-IDs every time a new order is picked. Lastly, orders that have passed the order control can be directly transferred to the Bus parcel trolley, further reducing the time required to process an order.

The proposed new production cell layout is presented in Figure 36. The upper two processing lines are processing lines for Bel orders. Note that consolidation orders can only be processed by the middle processing line. This way, orders without consolidation items do not have to pass the consolidation station. The lower processing line is a processing line especially designed to process Bus orders. As can be seen in the layout, this processing line ends in a Bus parcel trolley, no filling and sealing station is required.

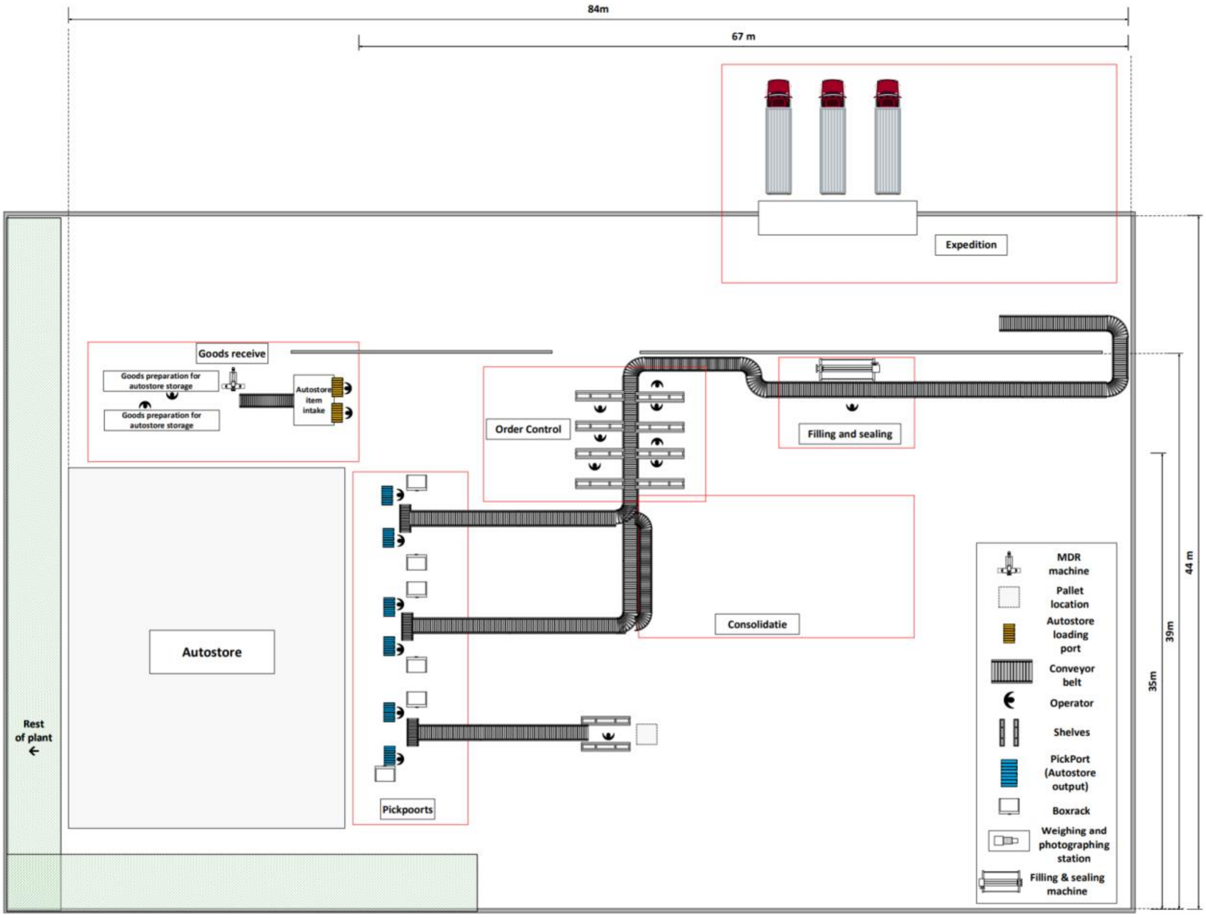

Figure 36 – Proposed new production cell layout

Note that we incorporated the design requirements mentioned in Section 5.1. For example, delivery boxes can be easily supplied to the pickports through the lane between the AutoStore and the pickports themselves. There is enough space for a kick-off area and insert stock can be stored between the order control and goods receive area. An additional advantage of the proposed layout is that the consolidation area size can easily be adjusted to store more consolidation items in case of more consolidation orders as a result of the free space available around the consolidation area.

The performance of the new production cell layout will be assessed in Chapter 6, where we will compare this layout with the other interventions. Note that we validated the simulated performance of the specialized Bus order processing line in Section 4.3.2.

5.2.4 Intervention 4: Online Pro-active Line Balancing.

In intervention 1, we applied basic line-balancing to the existing AutoStore order processing line. This basic line-balancing is an offline option. That is, we try to minimize the difference in workload as good as possible by dividing tasks among the workstations prior to the operation of the order processing line. However, we deal with a stochastic process in which processing times vary strongly. Especially due to the rich variety in orders being processed. This may result in an imbalance in the workload during a shift, while the theoretical workload of each station is balanced. A local imbalance in workload can cause queues in the system, which may in turn affect the ability to process orders for other stations. For example, if the conveyor is entirely filled with orders, the pickports will not be able to process orders as there is no space for the finished orders.

In traditional approaches, varying processing times should be accounted for using buffers in a typical assembly line. During a shift, we cannot predict where imbalances will take place. Therefore, queues resulting from unexpected delays can be stored in buffers. The queue should then be compensated for by, for example, adding additional capacity to the queue-causing station.

Although we cannot prevent local imbalances from taking place in the processing line due to stochasticity, we can compensate for the resulting queues active line balancing. We can actively balance the workload by transferring workload from busy stations to other stations. In our first intervention in Section 5.2.1, we saw that transferring the inserts to the pickports was a measure that resulted in a workload shift that is too large. However, we can also transfer the process of adding inserts to an order partially.

Inserts are added to orders using a pick-to-light system. Installing such a system at both the pickports and the order control tables allows us to add inserts to orders at the pickports and at the order control tables simultaneously. We choose where to add the inserts depending on the current workload at both stations. If the workload at the order control tables is considered to be too high, we insert inserts at the pickports and vice versa. This way, we actively balance the workload between the two stations.

The logic required for this intervention is relatively simple. A flowchart containing the logic flow for this intervention is presented in Figure 37.

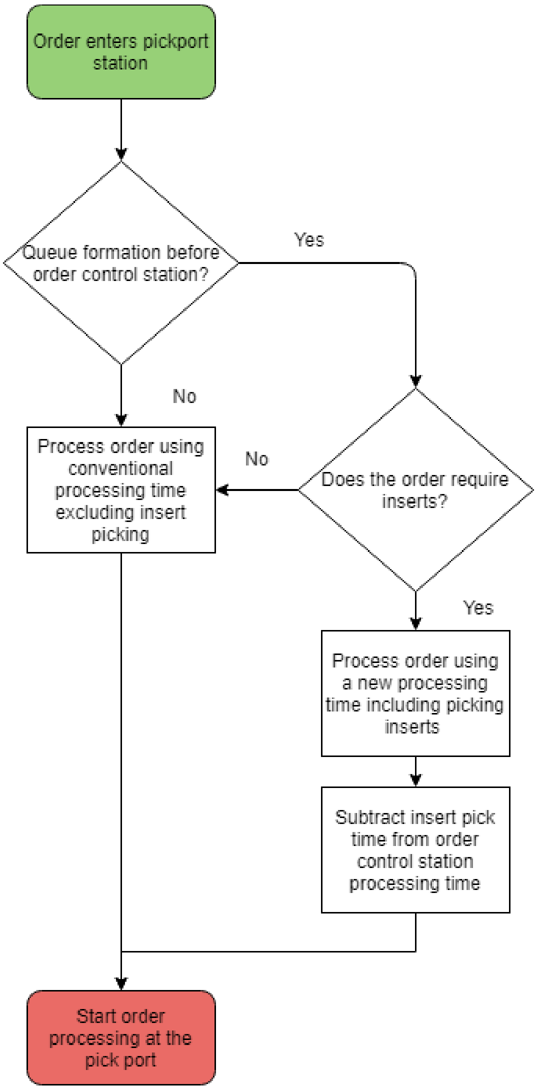

Figure 37 - Logic flow for the Dynamic pick to light intervention

To summarize, we can actively move workload to a station that is not overloaded at that moment using dynamic insert picking at either the pickports or the order control tables using two pick-to-light systems that can be alternated between based on the current queue formation in the system. This way, the workload balance between the available employees can be further optimized.

5.2.5 Intervention 5: Automated Packing with Additional Order Inflow

Our last intervention concerns changing the setup of the processing line such that it can cope with higher order amounts. In this situation, new possibilities arise in terms of automation that are too expensive for the current order quantities to be profitable. We developed an intervention together with packing specialists of PostNL that have been involved in deploying the automation possibilities in larger PostNL depots and similar environments at other companies.

In terms of automation, several options are available. These include automized delivery box folding, fully automized packing, automized shipping label application and personalized parcel box printing. For the fulfilment centre in Houten, the most interesting option for automated packing is the use of a machine that resizes boxes to the exact right height. An impression of the functioning of such a box resizer is provided in Figure 38.

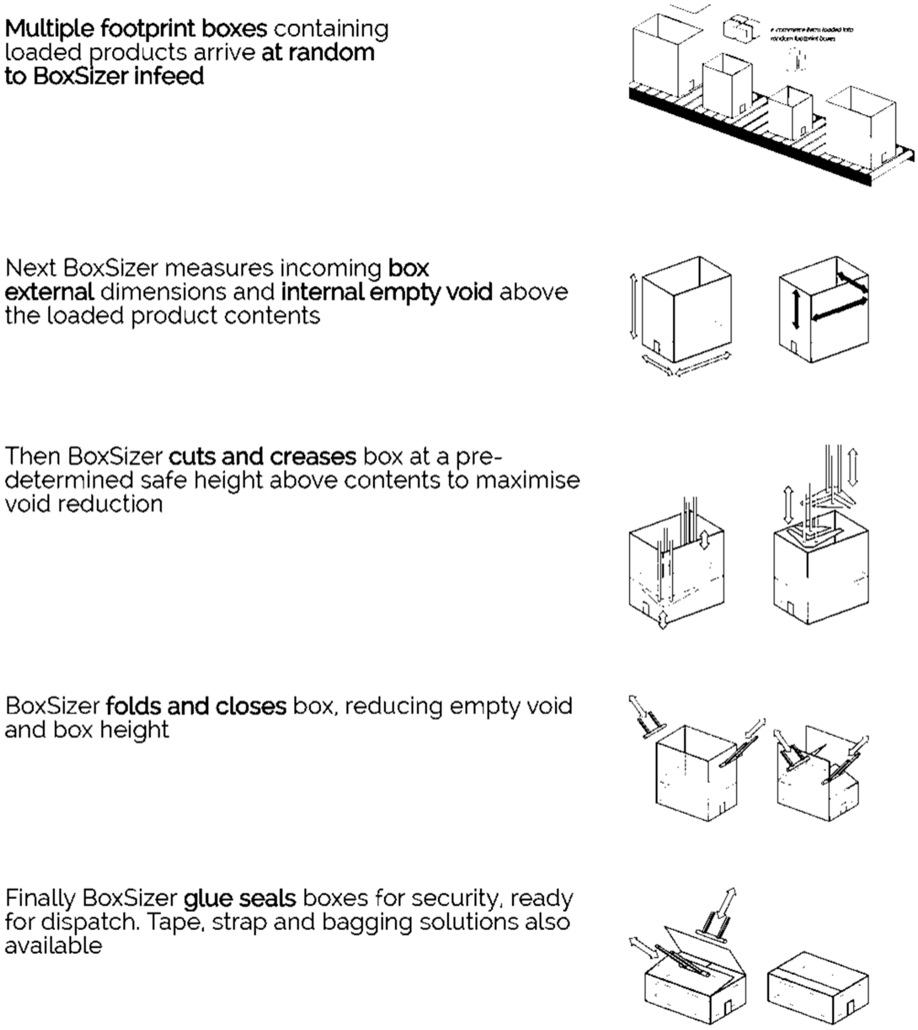

Figure 38 - The processing steps of a box resize machine (Boxsizer e-commerce packaging, 2019)

Currently, time is lost with filling and sealing of boxes. These processing steps can all be replaced by the box resize machine. The advantage of choosing for a boxresizer instead of a fully automated packing machine that wraps a carton around any product are related to the price of the machines and the space required for such a machine. Whereas a box resizer is available for around €350.000, a fully automated packing machine is available for around €1.000.000. For any of these machines to be profitable, higher volumes should be processed. We use our simulation model to determine the effects of not using an employee for the packing process.

The order amounts of the AutoStore competence centre are expected to grow continuously. However, to be able to generate the required volume, we introduce the possibility for another order inflow from other competence centres. This way, we can process an order mix from all competence centres at the site and thus reduce the threshold for investing in an automated packing machine.

The layout of the order processing line with an automated packing machine and additional order inflow from other competence centres incorporated in the design is displayed in Figure 39.

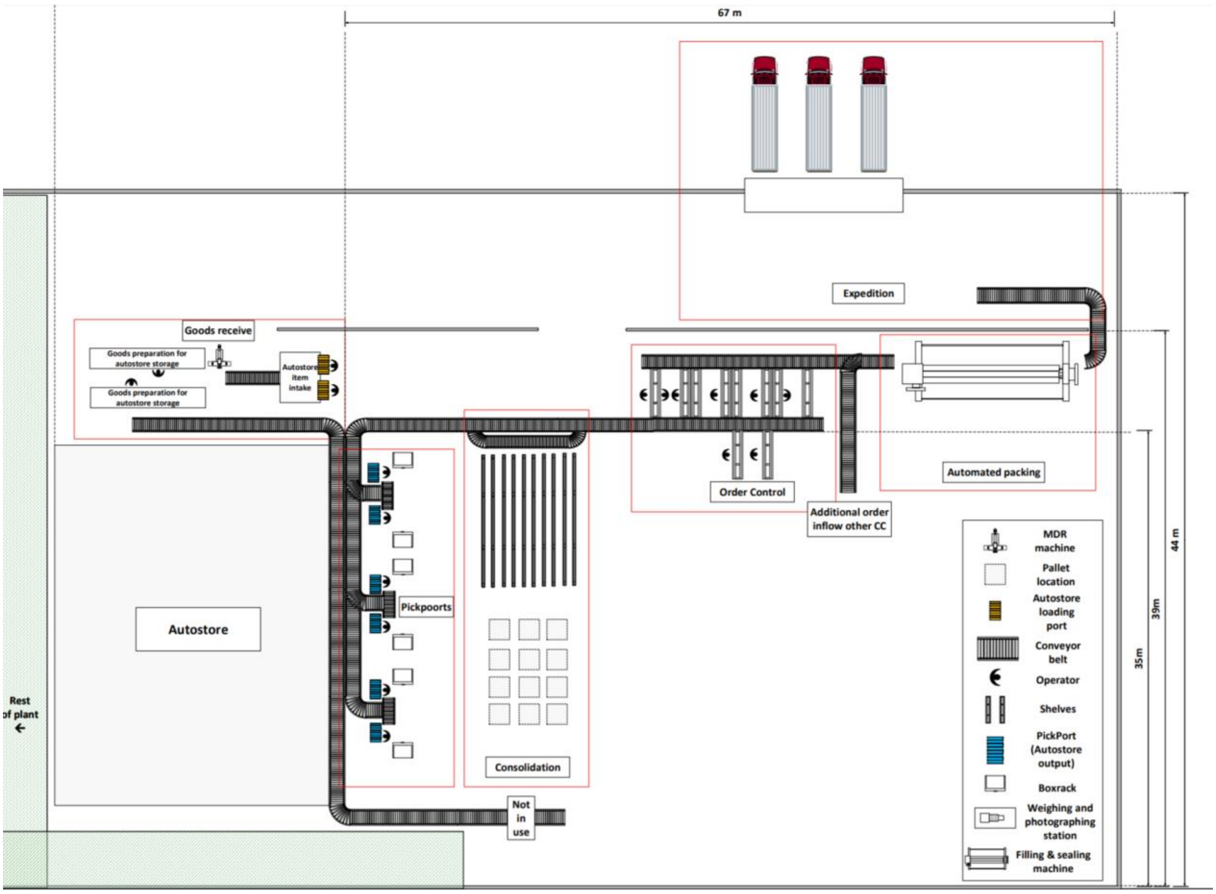

Figure 39 - Automated packing in the current layout

In Chapter 6, we will address the effects of the proposed interventions. However, the combination of several interventions will also be assessed. To be able to assess the combination of production cell grouping and automated, centralized packing, Figure 40 presents a layout in which both interventions are combined.

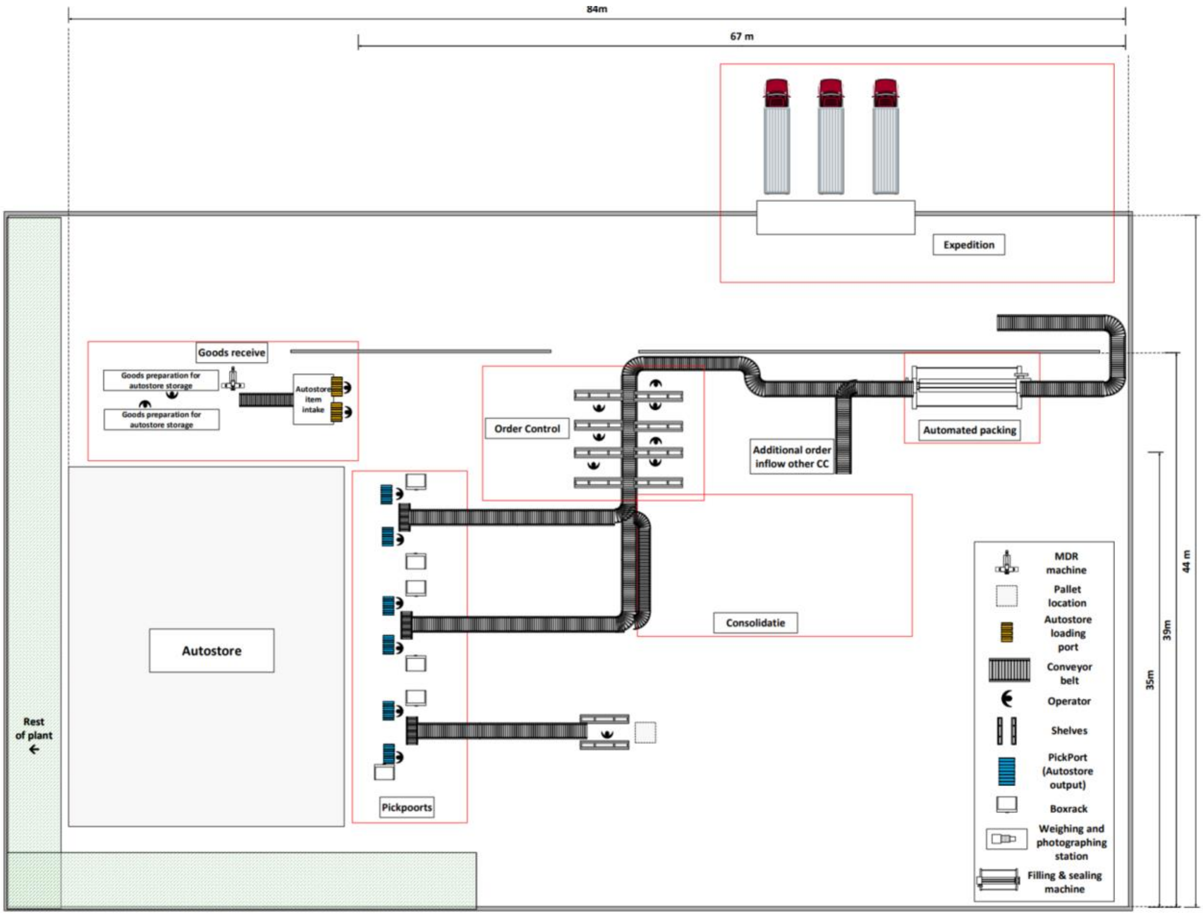

Figure 40 - Automated packing in the production cells layout

Together with the packaging specialists at PostNL, a suitable box resizer was selected. The selected machine is the Lynkx Boxsizer that has a capacity of 1020 orders per hour which is well above the order flow of the AutoStore competence centre. The output rate of the processing line does not surpass the 200 orders per hour, leaving over 80% of the capacity of the automated packing machine unused and available for other competence centres.

It should be noted that next to the potential productivity improvements of using automated packing, there are other significant advantages. PostNL is increasingly focussing on the transition towards environmentally friendly operations. In doing so, PostNL tries to reduce the amount of "air" transported through its networks such that less capacity is needed in, for example, trucks.

Buying an automated packing machine minimizes the amount of air in a parcel to a minimum. Moreover, the use of cardboard material is reduced by around 40% in alike deployment cases. Lastly, the amount of filling material is reduced by 100%, since the boxes are tailor made per order. Investing in an automated packing machine thus not only reduces processing times, it also contributes to the environmentally friendly strategy of PostNL.

5.3 Experimental Design

Now that the interventions have been described, we define the experiments that we will use to evaluate the different interventions. Evaluating the interventions will be done by experimenting with pre-defined variables and by measuring the effects of the interventions using indicators.

To start with, we summarize the proposed interventions introduced in Section 5.2. The interventions and a short description of the intervention are presented in Table 20.

Interventions	**Description**
Line balancing & minor optimizations	Removal of redundant workstations and process steps and minimization of the imbalance in workload between the workstations by moving inserts to the pickports
Distance Minimization	Reducing the overall travel distance of orders by minimizing conveyor belt length and swapping the consolidation station and the order control station sequence.
Transition to cellular production layout	Order specific order processing using three specialized processing lines. One line for Bus orders and two lines for Bel orders, with one Bel processing line suitable for consolidation orders.
Online proactive line balancing	Using the AutoStore to feed the processing lines with orders in such a way that workload is reduced temporarily at the workstations that experience a local overload and using dynamic insert placement to level the workload between the pickports and the order control stations.
Automated packing	Incorporating centralized, automated packing and additional order inflow from other competence centres in both the current processing line layout and in the cellular production layout.

Table 20 - An overview of the interventions

The interventions presented will be evaluated separately and in combination where possible. The combinations of different new layouts are not possible, for example, the distance minimization intervention results in a new layout while the transition to a cellular production layout also results in a new layout. These two interventions cannot be combined and will thus only be tested separately. However, line balancing can be applied to all layouts.

5.3.1 Indicators

In the experiments performed in the simulation model, the interventions are being evaluated based on indicators. The indicators that we use to judge whether an intervention is performing well are provided in Table 21. The indicators are in ranked sequence. That is, productivity is the most important indicator, throughput time and utilization follow upon productivity in terms of importance.

Indicators	Description
Productivity	Productivity is calculated as the number of orders processed divided by the number of employee hours deployed. Productivity is used to evaluate all processes within PostNL ECS, we therefore also want to express the performance of interventions using this indicator
Throughput time	Throughput time is an indicator that is closely related to queue formation. We want to minimize queue formation such that the processing line is balanced and free of large intermediate buffers.
Utilization	Utilization describes the portion of time that the resource is working/active. This indicator provides us with information on how we should improve a system and is to a lesser extend suitable for evaluation of the system as a whole.

Table 21 - An overview of the indicators

5.3.2 Variables

In order to achieve the best possible efficiencies of each tested system, we vary the input variables of the system. Per variable a description is provided that also addresses whether the variable can be adjusted freely or not. The overview of all variables and their description is provided in Table 22.

Variables	Description
Number of employees during the dayshift	This variable can be used to set the number of employees during the dayshift at Mondays. This variable is not fixed and can be changed to obtain the best performance of the system.
Number of employees during the evening shift	Comparable to the number of employees during the dayshift, but for the evening shifts occurring every day.
Number of employees during the weekend shift	Comparable to the number of employees during the dayshift, but for the weekend shifts at Saturday and Sunday
Number of pickports in use	This variable sets the number of pickports in use. The variable can be set between one and six. The value set for this variable can be higher or lower than the available employees.
Number of order control tables In use	This variable sets the number of order control tables in use. The variable can be set between one and seven. The value set for this variable can also be higher or lower than the available employees.
DemandFactor	The demand factor can be used to increase or decrease demand. This variable cannot be adjusted freely, instead, a few predefined settings are provided at which the system should perform as good as possible (see Section 5.4.3)
DirectPackingOC	This variable refers to the portion of orders being packed directly at the order control station. If an order is packed directly at the order control station, it automatically is scanned at the pickport to prevent picking errors.

Table 22 - An overview of the variables

5.3.3 Scenarios

All interventions and the resulting systems are tested in different use cases. These use cases should illustrate how well a system is able to cope with increased demand than can be expected in the future. Using the use cases that represent different demand scenarios, we can provide adequate advice to the management of PostNL on which system setup to use for a specific demand scenario. Management can then determine for which scenario the processing line should be designed and adjust the current layout accordingly. The demand scenarios studied in this simulation study are provided in Table 23.

Scenario
Demand growth of +25%
Demand growth of +50%
Demand growth of +100%

Table 23 - An overview of the demand growth scenarios

5.3.4 Sensitivity analysis

Next to the intentional variation of variables we also want to assure the robustness of the provided solutions. That is, the conclusions drawn based upon the simulation model should remain valid under small deviations in its input variables.

Sensitivity analysis	Description
Demand factor	The demand factor has been introduced in the previous Paragraph. In our sensitivity analysis, we vary the demand by +5% and -5% to make sure decisions made by the management based on our report also remain valid in case of unexpected new customers or unexpected leaving customers.
Processing time deviation	We adjust the overall processing times by +5% and -5% to evaluate the robustness for processing time variation.
Percentage of Bus orders	The percentage of Bus orders is expected to grow in the future, we examine the effects of this growth on our conclusions.

Table 24 - Description of the sensitivity analysis

5.3.5 Warmup and Run Length

The system represented in our simulation model is a non-terminating system. That is, when the system is loaded, orders that cannot be finished within the day they entered the system will be processed during the next day. As this transfer of work between days occurs frequently in practice, we want to incorporate this behaviour in our simulation model. During the first week of our simulation, work that was not completed during the past week is not yet available. Although cumulation of orders through the weekend is highly unlikely, this might occur in load cases that stress the system extremely. To make sure all the captured data is representative for normal operations of the system, we use a warmup period of one week. The first week of data stored during a simulation run is thus deleted and not incorporated in the results of a simulation run.

The run length of a simulation run is set to one year, as this is the timescale that we used for exploratory simulations and we observed stable outcome for this run length. Moreover, we can generate replication data that resembles year data by choosing a run length of a year, which eases the interpretation of the data. After having generated several years of data, the measures used seem to be relatively stable.

Based on the chosen run length, we determine a number of replications that, together with the run length, generates enough data to obtain confidence intervals for our output that meet our requirements. We determine the number of replications based on the average achieved productivity excluding weekends. We performed several tests runs to generate data for the determination of the number of replications of the simulation.

The data was then analysed with the requirements in mind for creating a confidence interval with the desired width. We use a significance level of 95% (α=0.05) and a relative error value (Υ) of 5%. In doing so, we choose a significance level and relative error that are commonly used in simulation studies and that provide al level of accuracy that is in line with the accuracy required by the PostNL management. In Table 25, we calculate the achieved relative error for every replication. We also provide the input values for the procedure in Table 26.

n	AvgYearlyProductivity	Mean	Variance	T-value	Relative Error	Test
1	26,52995222					
2	26,45451288	26,49223	0,002846	4,302653	0,006126	Enough
3	26,49328174	26,49258	0,001423	3,182446	0,002616	Enough
4	26,53006245	26,50195	0,0013	2,776445	0,001889	Enough
5	26,46467143	26,4945	0,001253	2,570582	0,001536	Enough
6	26,48169329	26,49236	0,00103	2,446912	0,00121	Enough
7	26,47878312	26,49042	0,000884	2,364624	0,001003	Enough
8	26,51036397	26,49292	0,000808	2,306004	0,000875	Enough
9	26,53591219	26,49769	0,000912	2,262157	0,000859	Enough
10	26,56039539	26,50396	0,001204	2,228139	0,000922	Enough

Table 25 - Determination of the number of replications

Alpha	0,05
Gamma	0,05
Gamma'	0,047619048

Table 26 - Input values for determining the number of replications

From Table 26, we conclude that the desired relative error is already achieved after two replications. We therefore use two replications and a run length of one year as the experimentation settings for our simulation model. The variance observed in the model output is relatively small, this can be explained by the fact that the average yearly productivity is an average over all weeks (52) in the year runs which is in turn an average over the first five weekdays in the week. The daily productivity itself is based on more than thousand orders. Therefore, the average yearly productivity is an extremely stable measure that is calculated as an average over 260 days of processing data.

5.4 Conclusion on Solution and Experiment Design

In this chapter, we introduced the designed solutions that were created with the aim of improving the order processing line productivity. The designed interventions answer our third research question:

How can the order processing line be (re)designed in such a way that it is able to cope with future requirements and demand growth?

The design requirements used have been introduced in Section 5.1. The design requirements assess points of attention in the design process in terms of accessibility and required space for workstations and replenishment of materials.

In Section 5.2, we introduced the proposed interventions that we will evaluate using our simulation model. The first intervention improves the current processing line while it retains the current layout of the processing line. Adjustments to workload distribution and removal of redundant workstations are the main improvements made in this intervention.

In the second intervention, we followed most of the available literature on assembly line design and minimized the travel distance by reducing the conveyor length. The resulting compressed version of the original system allows for shorter processing paths.

In the third intervention, we proposed a new layout based on the concept of production cells. This way, we introduced specialized processing lines for Bus orders and Bel orders. In the new design, two processing lines are refined for Bel orders and one processing line is refined for Bus parcels, roughly representing the percentages of the respective order types.

In the fourth intervention, we introduced an online pro-active line balancing procedure that actively balances the workload of workstations during a shift. This is achieved by releasing orders with specific characteristics that relief the overloaded station. We also proposed dynamic pick-to-light systems that can actively decide whether inserts are added to the orders at the pick stations or at the order control tables. This way, a better workload balance can be achieved compared to shifting all insert to either the pickports or the order control tables.

In our last intervention, we introduce automated packing. For automated packing to be economically feasible, we introduced the possibility to create an order inflow from other competence centres. This way, centralized packing for the entire site can be realized in the AutoStore processing line.

Lastly, in Section 5.3, the experimental design was introduced, covering the variables, indicators and interventions that we use in our simulation and the experimentation settings that we use. The experimental design provides an outline for the procedure that we will follow in conducting our experiments. In the experimental design, a sensitivity analysis and several use cases were introduced. The sensitivity analysis is used to prove the robustness of the experimental results. The use cases illustrate the different operating environments that we want to simulate with respect to the amount of demand that the processing line must cope with.

6. Solution Evaluation

In this chapter, we evaluate the interventions presented in Chapter 5 under different load cases. For each of the proposed interventions, we find an optimal system setting for specific demand levels. We thereby assess which of the systems that results from an intervention is most suitable for the demand level. We measure the performance of a resulting system in terms of productivity, the number of unfinished orders and utilization in Section 6.1. The robustness of the resulting solutions is tested in Section 6.2. The effect of making small adjustments to the system settings is examined to assure that the proposed solution and its accompanying performance is stable under a range of conditions. The impact of applying an intervention in terms of IT requirements is assessed in Section 6.3. Changes in the IT landscape account for a considerable share of the implementation time of new setups at PostNL in Houten. To give an indication of the required time for a change towards a new system, we evaluate the required adjustments and the duration thereof. In Section 6.4, the effect of interventions on the selection of customers for the AutoStore is assessed, referring to the selection procedure presented in Section 4.4.

To provide insight in the performance of the proposed interventions, we first provide general performance results for all the models with their optimal settings applied. These are the results that we obtained from the “best” simulation runs for each model. For these simulation runs, we evaluate the (cumulative) number of unfinished orders, the productivity performance and the savings that can be achieved with respect to the productivity performance increase. The evaluation procedure of experiments is as follows.

1. Select experiments that do not exceed the maximum number of cumulative unfinished orders in the simulation run
2. Order the remaining experiments based on their productivity performance
3. Select the best performing settings for each intervention and for each feasible combination of interventions
4. Test the robustness of the selected models using a sensitivity analysis that tests robustness in terms of Bel/Bus order distribution, order inflow changes and processing time changes
5. Evaluate the impact on the IT landscape of the selected interventions
6. Evaluate the effect on the requirements set for customers to be suitable for the AutoStore

The (sub)sections in this chapter each represent one step of the evaluation procedure.

6.1 Intervention Performance Evaluation

6.1.1 Unfinished Orders

To start with, we ran many configurations for each system. The first step in evaluating the simulation results is to filter the possible configurations based on the cumulative number of unfinished orders that the system configuration results in. We set the threshold for the number of unfinished orders at 3650 orders per year, equalling an average of 5 unfinished orders per day (in a simulation run of two years, equalling two replications). This threshold was decided upon based on both observations of the actual unfinished orders of the AutoStore order processing line and the behaviour of our simulation model with more than five unfinished orders per day. We observe that, in this case, the system is not able to meet demand structurally. Settings that result in less than 3650 unfinished orders per year display a more incidental occurrence of not meeting demand. The performance in terms of unfinished orders of the best performing system settings that comply with our threshold are provided in Table 27.

	Cumulative Unfinished Orders per demand level			
Configuration	100%	125%	150%	200%
Base Layout	65	75	961	698
Base Layout Balanced	4282	94	2667	1964
Base Layout Balanced Automated Packing	85	94	349	2053
Distance minimization layout	68	75	451	531
Distance minimization layout balanced	87	156	724	1255
Distance minimization layout balanced online	49	64	291	222
Cellular manufacturing layout	2077	227	160	inf
Cellular manufacturing layout balanced	2514	168	82	526
Cellular manufacturing layout balanced online	42	618	588	2366
Cellular manufacturing layout balanced online Automated Packing	765	2003	278	1321

Table 27 - Unfinished orders per configuration per demand level

From Table 27 we conclude that optimal settings in experiments that use the current demand level require less unfinished orders compared to the experiments that test the system at high demand levels (150% and 200%). Moreover, a setting for the cellular manufacturing layout without balancing that complies with our unfinished order threshold cannot be found for a demand level of 200%. The experiment with the least unfinished orders still resulted in 53888 unfinished orders during an experiment of two years. From this observation that the cell layout requires balanced workload between its processing stations to cope with larger amounts of demand.

6.1.2 Productivity performance

Now that we provided the unfinished orders for the selected system configuration experiments, we present the accompanying productivity performance scores. We divide the productivity performance results into three groups. Each group represents a system layout, being either the base layout, the distance minimization layout or the cellular manufacturing layout. For each of these groups we provide the productivity performance results of all possible intervention combinations. For example, for the base layout, we present the standard base layout, the balanced base layout and the balanced base layout with automated packing. For each of the layout-intervention combinations, we performed experiments for four demand levels as introduced in Section 5.3.3. The respective productivity performance results are displayed by four different colours. Before we introduce the productivity performance results for the first layout, we compare the three layouts with each other.

The productivity performance for the base system of each layout is provided in Figure 41.

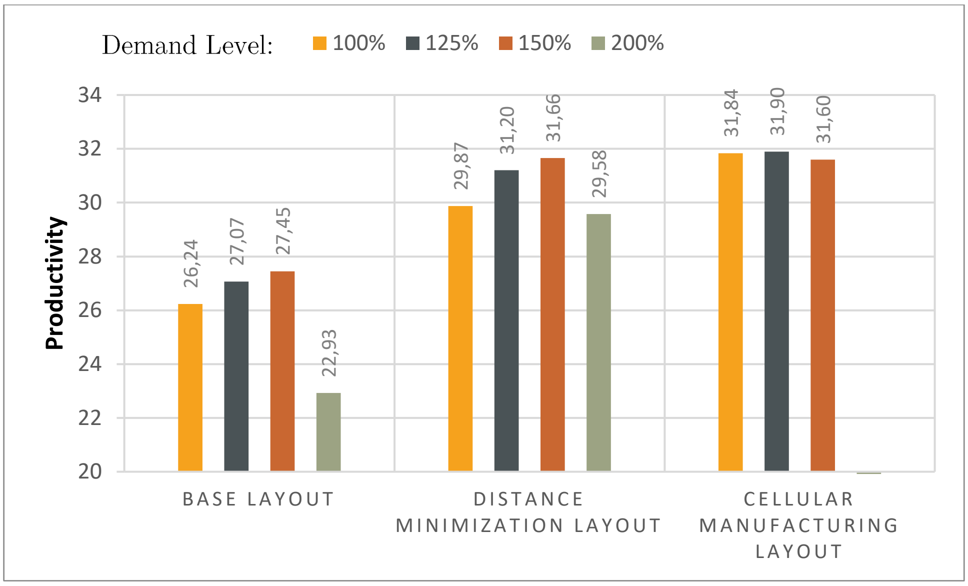

Figure 41 – Productivity performance of the three layouts

From Figure 41 we conclude that both the base layout and the distance minimization layout result in unstable performance for different demand levels. The cellular manufacturing layout is a more stable layout. The performance of the cellular manufacturing layout hardly varies with demand growth. We also observe that a measurement for the 200% demand level for the cellular manufacturing layout is missing. Out of all possible settings for this system, we have not been able to find a setting that is able to cope with the 200% demand level. That is, the tested settings all resulted in a too large number of unfinished orders as noted in the previous section. Later in this chapter, we will see that the cellular layout is suitable for higher demand levels in combination with the other proposed interventions.

With the performance of the three layouts in mind, we now introduce the performance of each layout in combination with other interventions. To start with, the productivity performance results for the base layout, the layout of the current AutoStore order processing line, are displayed in Figure 42.

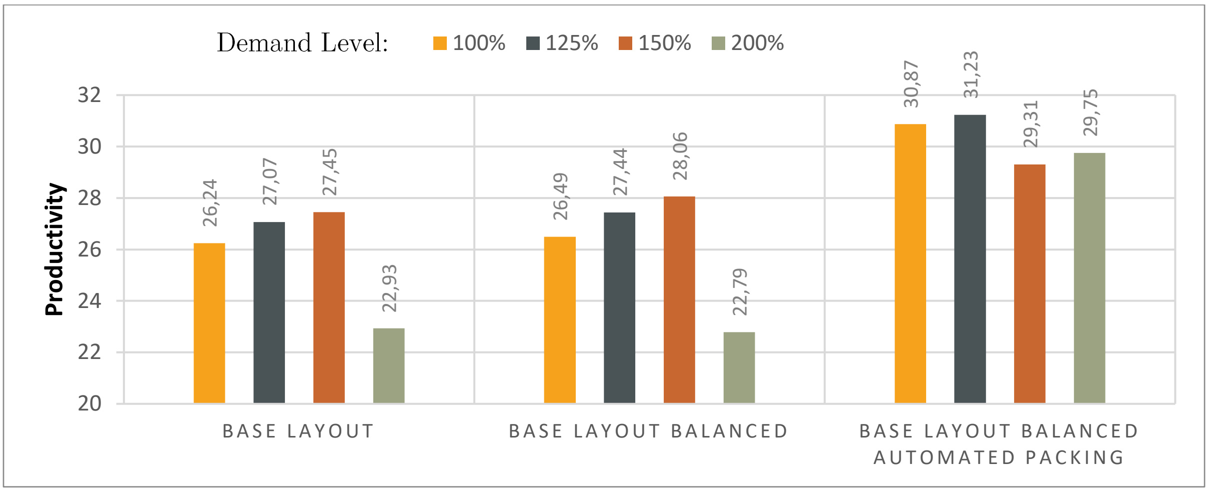

Figure 42 - Productivity performance of interventions applied to the base layout

From Figure 42, we conclude that the base layout can achieve slightly higher productivity rates at demand rates of 1.25 and 1.50 times the current demand. Once demand is increased significantly by doubling the order inflow, the productivity rate achieved drops rapidly to 22.93 orders per man hour. From this observation we conclude that the current layout is not suitable for demand rates that exceed 150% of the current demand as its performance declines once this order inflow rate has been exceeded. The reason for the sharp decrease in productivity performance at a demand level of 200% is different for the base layout, that generally has a higher utilization of its order control stations, and for the balanced base layout, that has a higher utilization for its pickports.

Another striking result is the performance of the base layout with line balancing and automated packing at a demand level of 200%. Whereas we see a sharp decrease in productivity performance for the configurations without automated packing, this trend is not observed when automated packing is used. This can probably be explained by the fact that the automated packing machine reduces the number of workplaces to be occupied by one. This way, an extra employee is available for the other workstations. This employee can be used at overloaded workstations to prevent the occurrence of queues in the system. The productivity decrease will thus occur at a higher system load as the bottleneck effects that we see at the other configurations are postponed.

The average productivity of the base layout overall demand levels equals 25.92 orders per man hour, while the balanced layout achieves an average productivity of 26.20 and the balanced layout that uses automated packing results in an average productivity score of 30.29. We thus conclude that both interventions improve the performance of the processing line. However, balancing the processing line is specifically effective at higher demand levels when the system is not yet overloaded.

The second group of intervention combinations is a group that uses the distance minimization layout as its basis. We also apply layout balancing and online layout balancing here. The performance for the three configurations of the distance minimization layout using the optimal settings is provided in Figure 43.

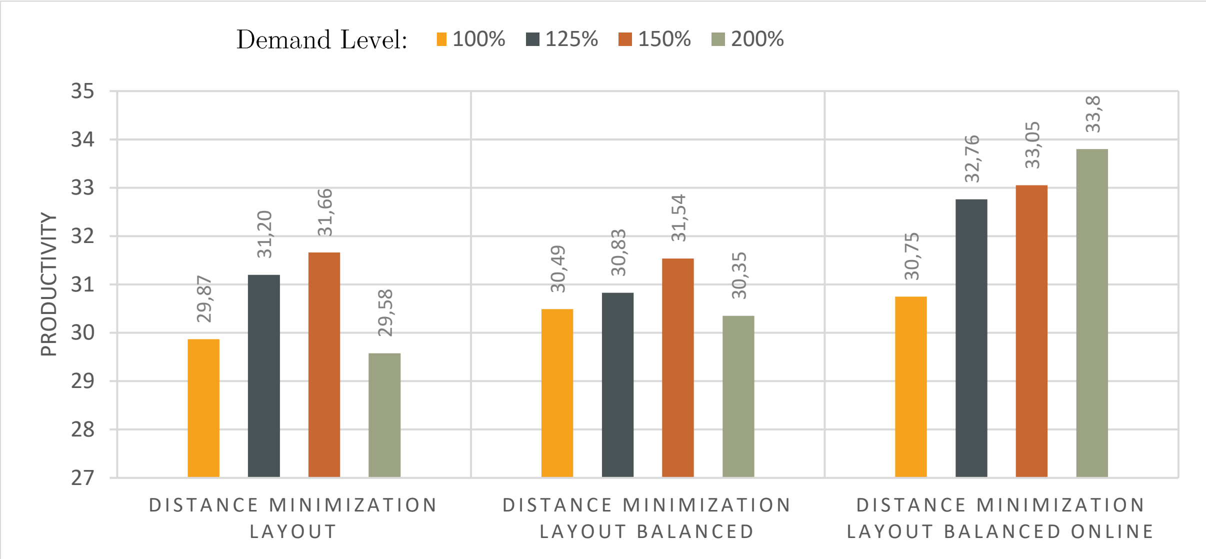

Figure 43 - Productivity performance of interventions applied to the distance minimization layout

In Figure 43, we observe the same productivity decrease for the standard version of the layout and the balanced version that we observed for the base layout. However, the decrease in productivity at high demand levels is notably less strong in the distance minimization layout. A possible cause for this behaviour is that the order flow is separated into three flows in the distance minimization layout. It is only after the order control stations that the order flow is merged again. At that point, the pickports and order control stations, have already been passed. As a result, queueing or imbalances in workload that occur at one of the three order flows do not influence the other two order flows.

In Section 5.2.1, we concluded that moving the inserts from the order control station to the pickports overcompensated for the imbalance in workload. In the balanced and the standard configuration, the system can hardly cope with the 200 % demand level. Using online line balancing that incorporates the proposed dynamic pick to light system, the workload is divided better among the available stations. As a result, the distance minimization layout that uses online line balancing performs well, even in the 200% demand load case.

The average performance over all demand scenarios are 30.58, 30.80 and 32.59 orders per man hour for the standard layout, the balanced version of the layout and the online balanced layout respectively. Although on average all interventions improve the performance of the layout, only a small improvement is observed after applying line balancing. In some demand cases, line balancing does not improve the performance of the system. It therefore seems that the remaining imbalance in workload that remains after moving the inserts to the pickports is still causing a significant reduction in productivity.

The third group of intervention combinations that we present the productivity performance of is the group that is based on a cellular manufacturing layout. In our comparison of the three layouts, we already noted that the cellular layout is the best performing layout. The performance of several intervention combinations for the cellular layout is presented in Figure 44.

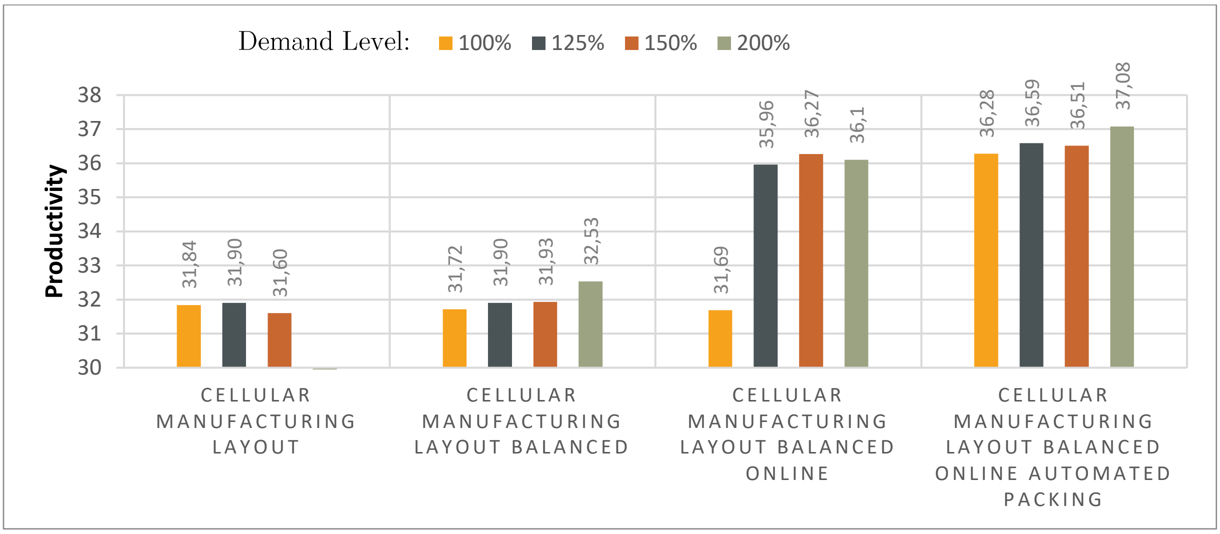

Figure 44 - Productivity performance of the interventions applied to the cellular manufacturing layout

For the cellular manufacturing layout, we do not observe the productivity decrease as a result of increasing demand that we saw in the base layout and the distance minimization layout. All configurations of the cellular manufacturing layout perform more stable compared to the other layouts. The cellular layout can achieve steady high-level performances. Recall that no suitable setting was found for the standard layout for the 200% demand case. The obtained productivity performance that we find with a number of unfinished orders that exceeds our threshold is not valid and thus not presented.

We observe that the performance of the cellular manufacturing layout using online line balancing is relatively low at the current demand rate compared to the other demand rates. The online line balancing functions only if queues occur in the system, this seems to not be the case for the “low” demand rate.

The average productivity performance for the demand levels ranging from 100% to 200% equal 31.78 orders per man hour for the standard layout, 32.02 orders per man hour for the balanced layout, 35.01 orders per man hour for the online balanced layout and 36.62 for the online balanced layout that uses automated packing. We thus conclude that all interventions improve the performance for this layout. However, at least basic line balancing is needed to be able to cope with a demand rate that is at 200% of the current demand.

An overview of all the tested systems and their productivity performance results can be found in Table 28. The average productivity performance for all demand levels per configuration is provided in the last column of the table.

	Productivity per demand level				
Configuration	100%	125%	150%	200%	Average
Base Layout	26,24	27,07	27,45	22,93	25,92
Base Layout Balanced	26,49	27,44	28,06	22,79	26,20
Base Layout Balanced Automated Packing	30,87	31,23	29,31	29,75	30,29
Distance minimization layout	29,87	31,20	31,66	29,58	30,58
Distance minimization layout balanced	30,49	30,83	31,54	30,35	30,80
Distance minimization layout balanced online	30,75	32,76	33,05	33,8	32,59
Cellular manufacturing layout	31,29	31,90	31,60	infeasible	31,78
Cellular manufacturing layout balanced	31,72	31,90	31,93	32,53	32,02
Cellular manufacturing layout balanced online	31,69	35,96	36,27	36,1	35,01
Cellular manufacturing layout balanced online Automated Packing	36,28	36,59	36,51	37,08	36,62

Table 28 - An overview of the productivity performance of all tested systems

We conclude that, in terms of productivity, the cellular manufacturing layout that uses online balancing and automated packing performs best. Almost all interventions cause a productivity increase except the line balancing intervention applied to the distance minimization layout. This configuration performs less good compared to the standard distance minimization layout for the demand levels of 125% and 150%. In general, we can state that the performance ranking of the three layouts is as follows:

1. Cellular manufacturing layout
2. Distance minimization layout
3. Base layout

With the cellular manufacturing layout performing best. The achieved average utilizations scores for both the pickports and the order control station that demonstrate the correct functioning of our line balancing intervention can be found in Appendix 6.

6.1.3. Savings per option

Labour costs form the biggest portion of variable costs for the AutoStore order processing line. The average costs of one employee are roughly €23,- per hour. The productivity increase presented per intervention in the previous section directly imposes savings due to a reduction in required employee hours to achieve an equal order throughput. The labour costs can be directly allocated to processed orders by dividing the required number of employee hours by the number of processed orders, resulting in the average labour costs per order. Note that the actual labour costs per order can vary strongly, since the processing time per order varies with respect to the characteristics of the order. To give an impression of the impact of improving the efficiency of the AutoStore order processing line, we plot the average labour costs per order for several efficiency levels in Figure 45. We calculate the labour costs per order by dividing the labour costs per employee by the number of orders processed per man hour, i.e. the productivity.

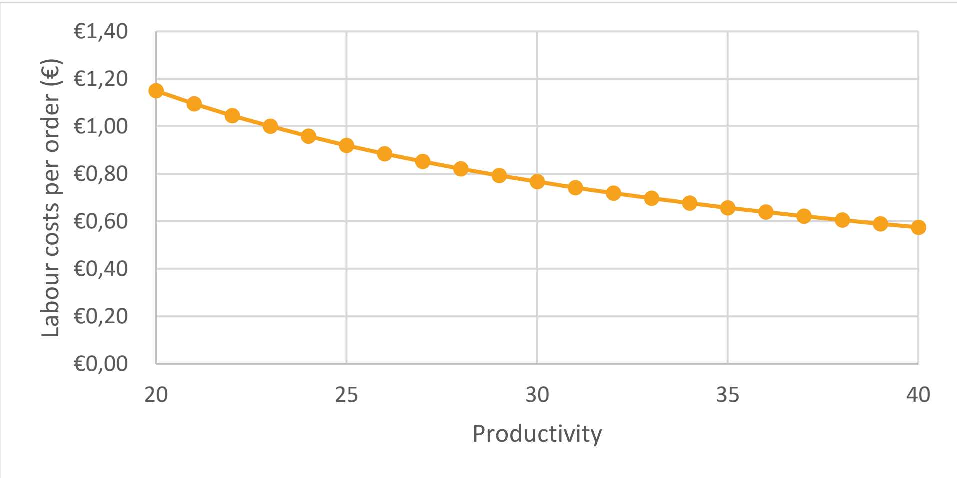

Figure 45 - The effect of productivity on labour costs per order

From Figure 45 we can directly calculate the labour costs per order for the tested systems based on the achieved productivity. These labour costs per order are presented in Table 29 for all configurations. Please note that, as said, these costs form the largest part of the variable costs per order. For example, variable costs also include filling material, boxes and tape. Constant costs such as the depreciation of the processing line and the AutoStore itself are also not considered in the presented costs per order.

	Labour costs per order			
Configuration	100%	125%	150%	200%
Base Layout	€ 0,88	€ 0,85	€ 0,84	€ 1,00
Base Layout Balanced	€ 0,87	€ 0,84	€ 0,82	€ 1,01
Base Layout Balanced Automated Packing	€ 0,75	€ 0,74	€ 0,78	€ 0,77
Distance minimization layout	€ 0,77	€ 0,74	€ 0,73	€ 0,78
Distance minimization layout balanced	€ 0,75	€ 0,75	€ 0,73	€ 0,76
Distance minimization layout balanced online	€ 0,75	€ 0,70	€ 0,70	€ 0,68
Cellular manufacturing layout	€ 0,72	€ 0,72	€ 0,73	inf
Cellular manufacturing layout balanced	€ 0,73	€ 0,72	€ 0,72	€ 0,71
Cellular manufacturing layout balanced online	€ 0,73	€ 0,64	€ 0,63	€ 0,64
Cellular manufacturing layout balanced online Automated Packing	€ 0,63	€ 0,63	€ 0,63	€ 0,62

Table 29 - Labour costs per order for each configuration

Now that we determined the labour costs per order for each configuration and each demand rate, we can calculate the savings for each configuration per demand rate. We base the savings on the current layout and the predicted performance of the current layout for higher demand levels that we presented in the previous section.

In Figure 46, we provide the potential savings of the configurations with respect to the current AutoStore order processing line. That is, we compare the performance of the new configurations with the current performance level of the processing line. The savings have been calculated using the current demand level assuming an average of 6916 orders per week.

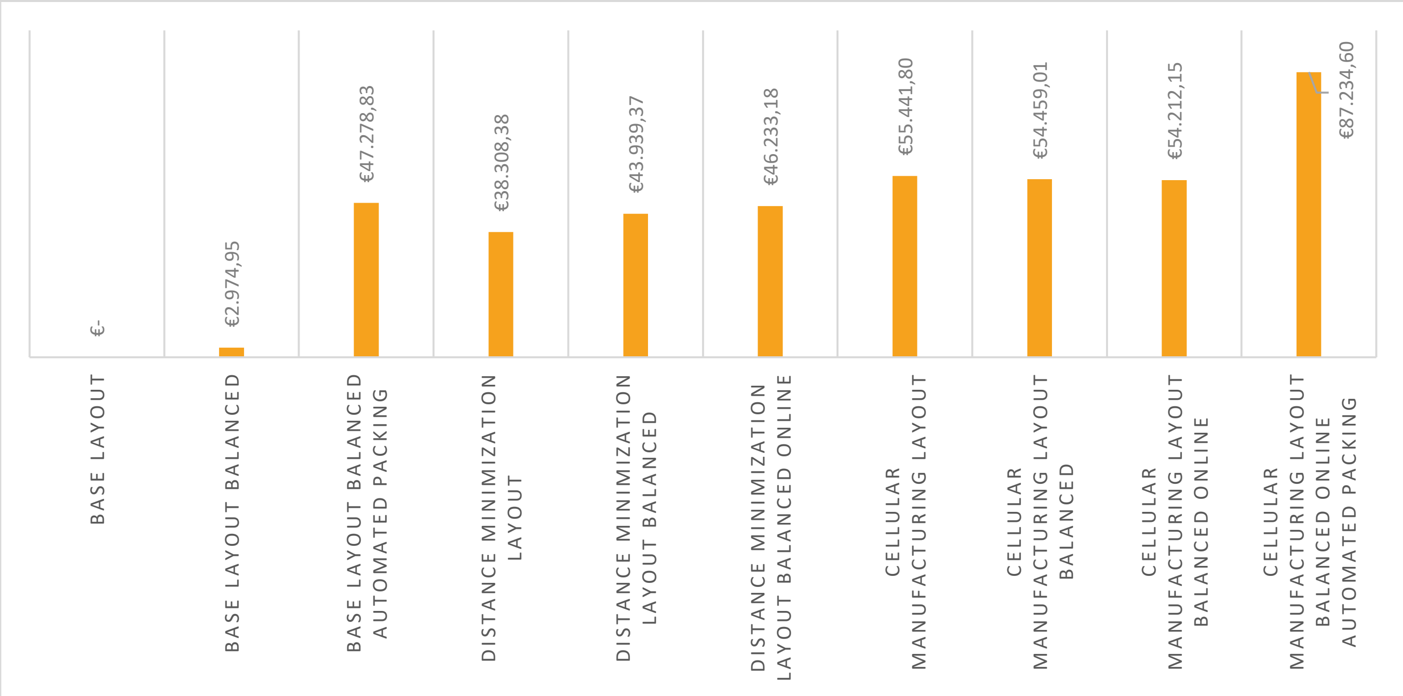

Figure 46 - Potential savings of the interventions at the current demand rate

Significant cost reductions can be achieved using the interventions presented in this report. However, in evaluating the named savings, one must keep in mind that significant investments must be made to implement the interventions. These implementation costs will be considered in Section 6.4.

To also provide insight in the savings in a future scenario where demand has doubled, we calculated the potential savings for the interventions in that case as well. We want to note again that these savings are based on the predicted performance of the base layout at a demand rate of 200%. The potential savings of all interventions at that demand level are provided in Figure 47.

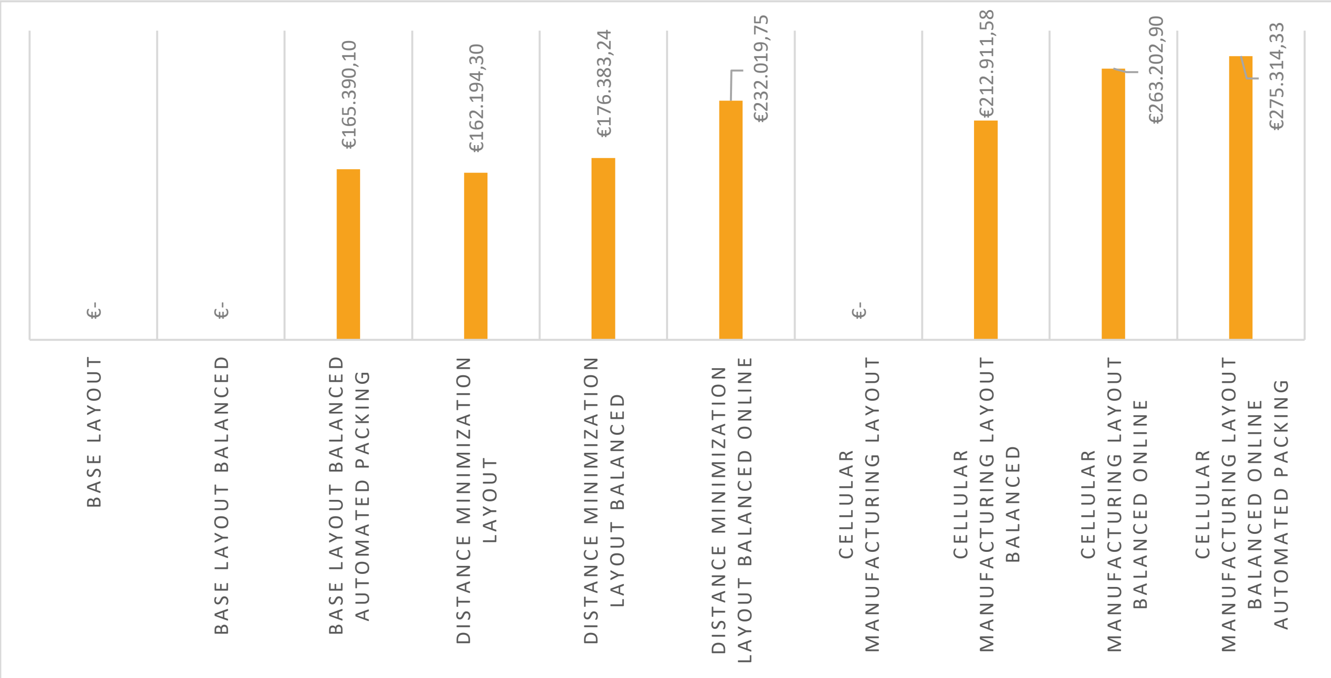

Figure 47 - Potential savings of the intervention with at a doubled demand rate

6.2 Sensitivity Analysis

We conduct a sensitivity analysis for all tested configurations to evaluate the sensitivity of the tested models with respect to important input variables of the simulation model. As announced in Section 3.4.3 we test our models on variation of three variables. These variables include the distribution of Bel/Bus orders, the demand rate and the processing time. In performing the sensitivity analysis, we use the settings for each configuration that we also used to achieve the highest productivity performance. It is possible that another, better setting can be found for the changed input variables. However, in this sensitivity analysis, we are mainly interested in the behaviour of the configurations with the found optimal settings applied.

6.2.1 Effects of changing the percentage of Bel/Bus Orders

To start with, we evaluate the effect of changing the distribution of Bel/Bus orders. It is expected that increasing the relative amount of Bus orders will improve the performance of the system as these orders generally result in lower processing times. Whereas the original setting for the distribution uses a ratio of 75/25 for Bel and Bus parcels respectively as introduced in Section 3.3.2, we now vary both percentages by 5 %. The results of the sensitivity analysis on this input variable are provided in Table 30.

Configuration	Original setting	70/30	80/20
Base Layout	26,24	26.34	26.21
Base Layout Balanced	26,49	26.59	26.41
Base Layout Balanced Automated Packing	30,87	30.97	30.77
Distance minimization layout	29,87	29.92	29.86
Distance minimization layout balanced	30,49	30.48	30.54
Distance minimization layout balanced online	30,75	31.00	30.56
Cellular manufacturing layout	31,29	31.68	31.01
Cellular manufacturing layout balanced	31,72	32.05	31.45
Cellular manufacturing layout balanced online	31,69	32.11	31.43
Cellular manufacturing layout balanced online Automated Packing	36,28	36.34	36.06

Table 30 - Sensitivity analysis of the Bus/Bel distribution

As expected, increasing the relative number of Bus orders improves the performance of the model. Although the productivity changes slightly with a different Bus/Bel distribution setting, the relative ranking of the configurations remains the same. All models thus roughly respond in an alike manner to the input change.

6.2.2 Effects of Changing Demand

Next to the Bel/Bus distribution, we also vary demand for all our models. Although we already presented extensive results of varying demand from 100% up to 200%, we now investigate the effect of small changes to the demand rate. We vary the demand rate by only 5% by both increasing and decreasing demand with respect to the current demand level. The results of these demand rate changes are provided in Table 31.

Configuration	100%	105%	95%
Base Layout	26,24	27.03	25.37
Base Layout Balanced	26,49	27.17	25.36
Base Layout Balanced Automated Packing	30,87	31.87	30.05
Distance minimization layout	29,87	30.79	29.02
Distance minimization layout balanced	30,49	31.38	29.62
Distance minimization layout balanced online	30,75	31.58	29.83
Cellular manufacturing layout	31,29	31.70	30.88
Cellular manufacturing layout balanced	31,72	32.89	30.92
Cellular manufacturing layout balanced online	31,69	32.78	30.80
Cellular manufacturing layout balanced online Automated Packing	36,28	37.75	34.72

Table 31 - Sensitivity analysis of the demand rate

Changing demand results in predictable productivity changes, the relative ranking remains unchanged. However, in for the balanced base layout configuration and the cellular manufacturing layout that uses online line balancing and automated packing, increasing the demand rate with 5% resulted in infeasible results due to the number of unfinished orders exceeding our threshold (3650) with 9442 and 20552 unfinished orders respectively. For these configurations, the actual productivity performance level will be lower than the provided values in Table 31 since additional employees are required to process all orders.

6.2.3 Effects of Changing Processing Time

As a final step in our sensitivity analysis, we evaluate the effect of changing the processing times of all processing stations. Processing times have been carefully measured by hand. However, in case minor measure errors occurred, we now evaluate what would be the effect of possible errors. We again evaluate processing times that are both 5% higher and lower compared to the standard processing times. The results for this sensitivity analysis are provided in Table 32.

Configuration	Standard processing times	+5%	-5%
Base Layout	26,24	25.68	26.27
Base Layout Balanced	26,49	25.77	26.78
Base Layout Balanced Automated Packing	30,87	30.43	31.66
Distance minimization layout	29,87	29.17	30.65
Distance minimization layout balanced	30,49	29.77	31.27
Distance minimization layout balanced online	30,75	29.94	31.51
Cellular manufacturing layout	31,29	30.34	31.74
Cellular manufacturing layout balanced	31,72	31.21	32.26
Cellular manufacturing layout balanced online	31,69	31.12	32.18
Cellular manufacturing layout balanced online Automated Packing	36,28	36.15	36.37

Table 32 - Sensitivity analysis of the processing time

The results of the sensitivity analysis on the used processing times are as expected. The relative ranking of the configurations is not changed. The unfinished order threshold is not complied with by two configurations.

This time, the number of unfinished orders add up to 12465 for the balanced base layout and 10392 for the balanced cellular manufacturing layout. The observation that these configurations cannot comply with the threshold after increasing the processing time or demand implies that the chosen settings for both configurations are already at their capacity limit.

The evaluation of the sensitivity of the tested configurations with respect to the Bel/Bus distribution, the demand rate and the processing time shows that the relative ranking of the configurations in terms of performance remains unchanged in all cases. Furthermore, the models are relatively insensitive to changes in the Bel/Bus distribution while changing demand and processing times results in larger deviations from the values that were measured with the initial input variables set. There is, however, no inducement for changing conclusions drawn from the initial experiment results.

6.3 IT Requirements

In the previous sections, quantitative performance measures were provided. In this section and in the next section, the configurations will be evaluated based on qualitative criteria. To start with, we evaluate the expected IT requirements for implementing the interventions. We describe the changes that must be made IT landscape to enable implementation of the interventions. For a description of the current IT landscape, we refer to Section 3.2.

6.3.1 Line Balancing and Minor Optimizations

The implementation of the line balancing intervention in which we also cut out unnecessary processing steps requires some changes to the IT systems that run the processing line. Currently, a barcode scan is required at the reject station for order to be proceeded towards the order control station. In case of removing the order reject station, the barcode check must be disabled in Astro (the WMS system). Furthermore, we rebalance the line by moving the insert adding activity to the pickports, which requires the pick-to-light systems to be moved to the pickports. Moving this system requires the rerouting of cables and a change in the order of completing the processing steps. Currently, inserts are added once the orders are scanned at the order control station. This procedure should be integrated in the picking procedure at the pickports where the barcode is already being scanned by the operator.

Although a fair amount of changes must be made, these mainly include removing logic from the process flow and for some aspects inserting them in other parts of the process flow. The procedures themselves (e.g. the insert procedure) can be copied as a whole and does not need any adjustments. The expected workload for implementing the IT changes required for this intervention is therefore limited.

The main changes that must take place in the IT landscape are:

- Adjusting the physical location of the pick to light systems
- Removing unnecessary steps form the process flow implemented in Astro

6.3.2 Distance Minimization

Implementing the distance minimization intervention requires the entire layout of the processing line to be changed. It is likely that new conveyors must be bought as PostNL's supplier for conveyor belts now uses different conveyor systems compared to the conveyors used in the current processing line. The physical relocation of the processing stations requires rerouting of cables and the process flow must be redesigned and embedded into the IT-landscape. The effort required for implementing this intervention is comparable to the implementation of the current processing line. However, the fundaments of the systems that will be used to drive the processing line are already present. The processes inside the processing stations remain the same and can thus be copied from the existing processing line.

The changes required for implementing the distance minimization layout are:

- Implement new conveyor driver software
- Adjusting the physical location of all stations except the pickports
- Redesign process flow Astro, invert consolidation and order control

6.3.3 Cellular Manufacturing layout

The IT-impact of the applying the cellular manufacturing layout is comparable to the impact of the distance minimization intervention. Compared to that intervention, extra adjustments are needed in LogiCS, the software of the AutoStore. In the cellular layout, we require the AutoStore to separate order flow based on order characteristics. Although this is already possible using the current systems, the process of assigning orders to a processing line must be automated and improved. Currently, it often occurs that orders that do not belong to the selected category for a pickport are still assigned to that pickport. This is caused by the way in which the order selection is performed. Currently, Astro assigns pickports to the orders and then transfers these orders to Logics. According to the supplier of the AutoStore, it is better to let LogiCS assign the orders to a pickport based on the order characteristics.

Next to the adjustments in LogiCS, new conveyors must be installed and the processing stations have to be moved to a different physical location just like in the distance minimization intervention.

The changes required for implementing the cellular manufacturing layout are:

- Implement new conveyor driver software
- Adjusting the physical location of all stations except the pickports
- Redesign process flow Astro, invert consolidation and order control
- Order characteristic specific release of orders by LogiCS

6.3.4 Online line balancing

The online line balancing intervention is challenging to implement since this is an uncommon solution that cannot be bought. Instead, the solution must be tailor made for the processing line. Queue length measuring devices must be installed in the conveyor system and the feedback from these devices must be incorporated in the to be created dynamic pick-to-light system.

One of the most challenging aspects of the implementation of online line balancing is the duplication of the pick-to-light system and the dynamic switching between them. Although the theoretical logic that is to be implemented is relatively simple, implementing the system successfully requires extensive testing to assure quick response to queue formation.

Implementing the online line balancing system requires the following changes in the IT landscape:

- Integration of active queue measurement devices
- Feedback of queue length information into dynamic pick to light system
- Double pick-to-light system that assigns workload between the two instances

6.3.5 Automated packing

The automated packing machine is a machine that can be bought directly from a supplier. The machine is delivered with the accompanying software included. This reduces the impact of this intervention significantly. The implementation of the automated packing machine only requires correct interfacing between the existing IT landscape and the packing machine software.

The automated packing machine can automatically apply shipping labels to packed parcels. Currently, this shipping label is applied by hand to the parcels in the order control station. This processing step has to be excluded from the order control station and the shipping label information has to be communicated to the automated packing machine. Moreover, using this feature of the automated packing machine requires the machine to identify orders before they enter the machine. This is possible using the barcodes that are already in use. However, the exchange of information between the automated packing machine and Astro is intensified and as a result the implementation of the communication protocol requires more effort.

Integrating the automated packing machine in the order processing lines raises the following requirements:

- Orders must be identified using a scanner before they enter the packing machine
- A communication protocol between Astro and the automated packing machine must be created

- The shipping label processing step must be removed from the order control station, the shipping label information must be provided to the automated packaging machine

The estimated impact of implementing the various interventions must be investigated once PostNL decides it wants to implement one or more interventions. For now, we provide a comparison of the expected impact using a relative scaling to classify the adjustments required in the IT landscape ranging from minor (--) to significant (++) on a four points scale. The score awarded to each intervention is closely related to the number of actions points provided for each intervention in this section. We did however, also take into account the severity of each action point.

Intervention	**Effort required (--, -, +, ++)**
Line balancing & minor optimizations	--
Distance Minimization	+
Transition to cellular production layout	++
Online proactive line balancing	+
Automated packing	-

Table 33 - An indication of the effort required for the IT implementation of the interventions

6.4 Customer Suitability

In Section 3.4, we introduced the decision model that PostNL uses to assess whether new customers are suitable for the AutoStore. Several requirements should be met for a customer to be stored in the AutoStore. These requirements have been set with the current processing line and AutoStore characteristics in mind. Changing the processing line setup also changes the requirements for the products that are processed on it.

The current requirements table used by PostNL that we also provided in Section 3.4 is provided in Table 34 again. Although many of the requirements introduced are related to factors that remain equal in the new layouts, some limitations imposed can be lifted in case of using a cellular manufacturing layout. These requirements are highlighted in orange in Table 34.

	Old requirements	
Variable	**AutoStore suitable**	**Not suitable**
Pallet replenishments	<monthly	>= monthly
Weight: >30kg per container	<5%	>=5%
Size	>95% larger than 5/60x40x30cm	>5% larger than 60x40x20cm
Delivery notes	Black & white or not	Color or double-sided
Specific packing requirements	None	Fragile/present/extra
Distributor	PostNL track&trace	mail/UPS/other
Value (Theft-likeliness)	< €250	>= €250
#containers pick storage required	<4.000	>4.000
# SKU/day	<10	>=10
# SKU ADR (dangerous materials)	0	>=5%
# orders/hour outside AS	<25	>30
% single line	<80%	>90%
Large batches of 1 SKU	None	Yes
Customer specific packaging	None	Yes

Table 34 – The current AutoStore suitability requirements used at PostNL

The cellular manufacturing layout allows for specialized order processing lines for specific order groups. In the intervention we propose, we use one line for Bus orders, one line for consolidation order and one line for the normal Bel orders. The specialized Bus order processing line can be used for orders that require less processing steps compared to the standard processing path. Currently, customers that process large batches of a single SKU are not placed in the AutoStore as processing these orders by hand from a pallet is considered to be faster. This is a correct assumption since processing all the single line orders as separate orders using the current AutoStore order processing line would be inefficient. The orders would have to travel over the conveyors, every order must be scanned several times, and every order requires a barcode.

An important advantage of the cellular manufacturing layout is that the specialized Bus parcel line is flexible for use for other specialized processing processes. The line can be used to create tailored processes for product groups that are irrelevant for other order groups. Using the specialized processing line for Bus parcels, single line batches can also be efficiently processed. As introduced in Section 5.2.3, scanning barcodes can be skipped on the specialized processing line and the batch can be picked into a crate that can then be processed at the order control table quickly without disturbing the order flow at the other processing lines.

Another example of an order group that can be processed efficiently at the bus parcel line are orders that require customer specific packaging or gift wraps. At the end of the specialized processing line, Bus orders are normally transferred to trolleys. Machines for customer specific packaging can be integrated in at the end of the specialized processing line without interrupting any of the other order flows.

In conclusion, we see that the specialized Bus order processing line allows for specialized processing of other special orders as well. The specialized processing line offers the opportunity to offer customer specific services without interruption of the main order flow.

6.5 Conclusion on Solution Evaluation

In this chapter, we evaluated the performance of all proposed interventions and all possible combination of interventions. Both quantitative and qualitative aspects of the interventions have been evaluated. We answered the last two unanswered research questions in this chapter. We will now summarize our main findings for both research questions. The first research question that we answered is:

How will the new processing line layout designs perform with respect to the current situation under various system and capacity settings?

We tested all layout designs including all combinations with the other interventions that we proposed. In Section 6.1, we compared the productivity performance of the best settings for each configuration that complies with the maximum number of unfinished orders of 3650 orders. We conclude that the cellular manufacturing layout performs best, followed by the distance minimization layout. The current layout performs worst of the three tested layouts. An overview of the experimentation results in terms of productivity is provided in Figure 48.

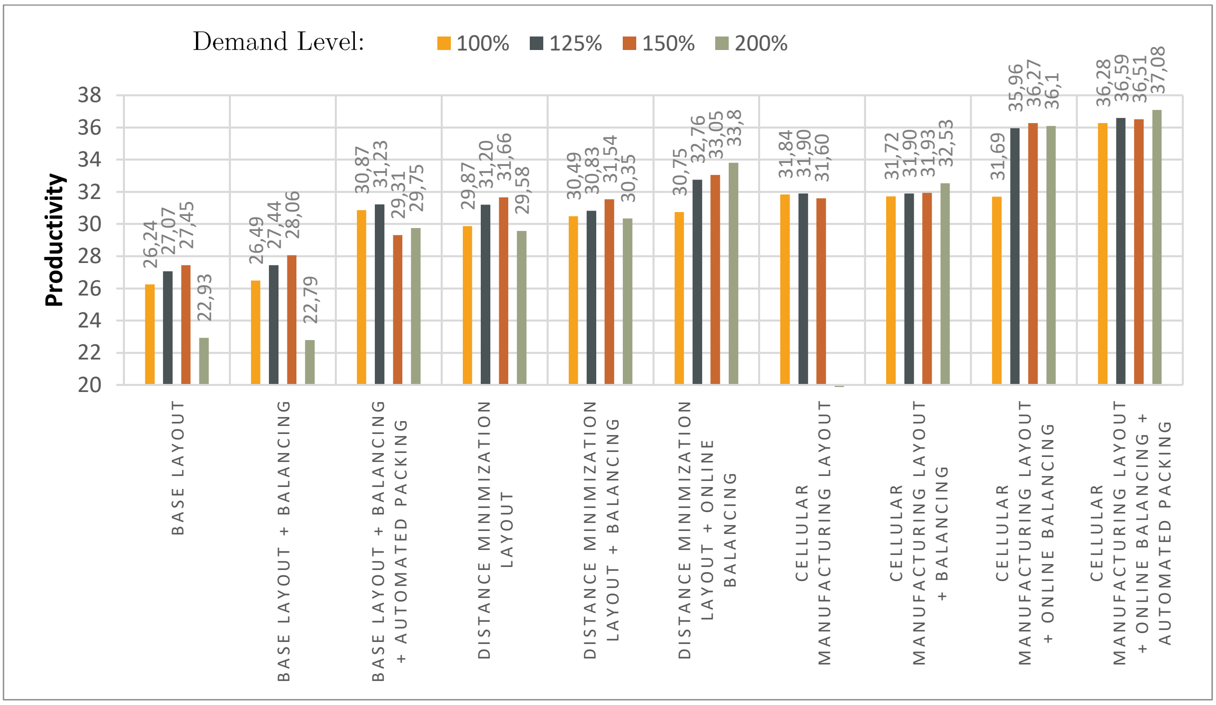

Figure 48 - An overview of the performance of all interventions

We conclude that all interventions improve the performance of the processing line layout they are applied to, except for line balancing in the distance minimization layout. Line balancing in the distance minimization layout results in a lower productivity for the demand levels of 125% and 150% of the current order inflow. We also note that for the cellular manufacturing layout, line balancing is a prerequisite to comply with the maximum number of unfinished orders. Without this intervention, the layout is not able to cope with a demand level of 200% compared to the current order flow.

In Section 6.2, we conducted a sensitivity analysis to conclude that the relative ranking of the available configurations remains unchanged after changing the percentage of Bel and Bus orders, the demand, or the processing time. We varied all three factors by 5% both positively and negatively.

In Section 6.3 and Section 6.4, we answered the last remaining research question:

What will be the effects on the requirements for the IT systems of the AutoStore order processing line and what are the other consequences of the new processing line layout designs?

In Section 6.3, we concluded that the changes required in the IT-landscape to implement the proposed interventions result in the highest workload for the cellular manufacturing layout and only a limited amount of changes must be implemented to realize the line balancing intervention.

We also found that changing the layout to a cellular manufacturing layout opens up possibilities for specialized gift packaging and single line batch picking in Section 6.4 thereby broadening the range of suitable customers for the AutoStore competence centre.

7. Conclusion and Recommendations

In this chapter, we summarize the main findings of our research and answer the main research question posed in Chapter 1. We formulate the conclusion of our research and formulate a recommendation that follows from our findings. We also formulate our contribution to both practice and science. Lastly, we discuss the limitations of our research, the effects of these limitations and we propose future research that can be done as a follow-up on our research.

7.1 Research Conclusion

The current AutoStore order processing line at PostNL fulfilment in Houten is not operating at the desired efficiency that was determined in the business case of the AutoStore. Currently, the average productivity score of the processing line is 25.9 order per man hour. The aim of our research was to redesign and optimize the processing line such that the achieved productivity will be structurally above 30 orders per man hour, with an average score near 35 orders per man hour. In other words, the research question that we formulated is:

"How should the AutoStore order processing line be adjusted and redesigned such that the fulfilment centre can achieve its target productivity and output rate sustainably?"

We conducted an extensive data analysis in which we found the order characteristics of the orders that are processed by the AutoStore order processing line and performance measures of the current layout. We also investigated processing times at the five stations of the processing line: the pickports, the consolidation area, the order reject station, the order control station and the filling and sealing station.

Using our data analysis of the current situation as input, we created a simulation model of the processing line and completed precise validation and verification procedures to assure the fit between our model and reality. The simulation model was subsequently used to test several interventions.

We proposed a total of five interventions. We now provide a brief summary of the interventions:

1. (Offline) Line balancing and minor optimizations. We shifted workload between the stations to balance workload and removed unnecessary process steps.
2. Distance minimization. Following most of the scientific literature found, we created a new layout by compressing the processing line to minimize the travel distance of orders and as a result, created a new layout.
3. Product grouping. We created another layout that uses specialized production lines for specific order groups. This way, orders only pass those processing stations and processing steps that they require.
4. Online pro-active line balancing. The first intervention only shifts entire processing steps between stations, which still results in an imbalance in workload division. In this intervention, we proposed the use of a dynamic pick to light system that can assign workload to the processing station online (during a shift), thereby relieving a busy workstation and making use of available capacity at another workstation.
5. Automated packing. In our final intervention, we evaluated the effects of integrating an automated packing machine in the processing line, effectively leading to a reduction of the number of workplaces to be occupied in the processing line.

We implemented all interventions in our simulation model and evaluated their effects. We selected the best performing settings that complied with our threshold of a maximum of 3650 unfinished orders during a simulation run of two years. The achieved productivity scores for all combinations of interventions are provided in Figure 49. The colours represent different demand scenarios.

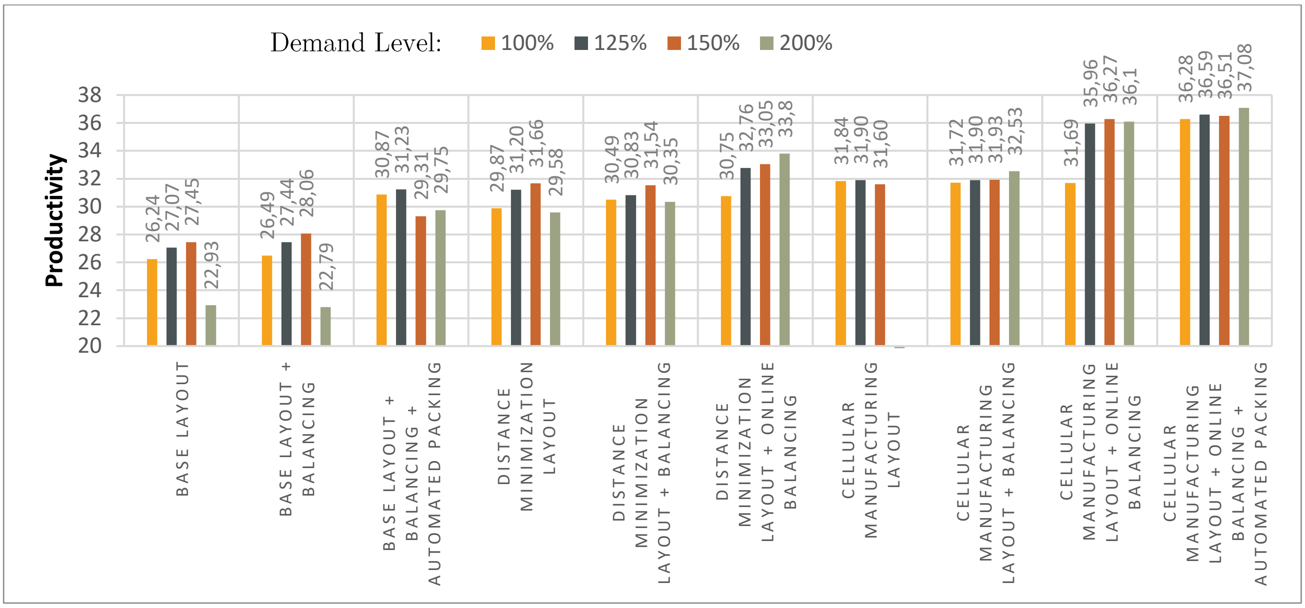

Figure 49 - An overview of the productivity performance for all intervention combinations

From the simulation results displayed in Figure 49, we conclude that the cellular manufacturing layout performs best compared to the second best performing distance minimization layout and the worst performing current processing line layout. Line balancing generally improves the achieved productivity, especially under higher demand levels. The effects of online line balancing are also most significant under higher demand levels, the overall performance improvement resulting from online line balancing is considerably better compared to standard (offline) line balancing. Lastly, we note that automated packing improves performance in all tested intervention combinations at all demand levels as a result of the direct reduction of required workplaces.

The presented productivity scores can be directly translated into potential savings. The savings are based on the labour cost reduction that can be achieved with improved productivity. The potential savings for each configuration assuming the current demand pattern are provided in Table 35.

Configuration	Savings per year
Base Layout	€ -
Base Layout + Balancing	€ 2.974,95
Base Layout + Balancing + Automated Packing	€ 47.278,83
Distance Minimization Layout	€ 38.308,38
Distance Minimization Layout + Balancing	€ 43.939,37
Distance Minimization Layout + Online Balancing	€ 46.233,18
Cellular Manufacturing Layout	€ 55.441,80
Cellular Manufacturing Layout + Balancing	€ 54.459,01
Cellular Manufacturing Layout + Online Balancing	€ 54.212,15
Cellular Manufacturing Layout + Online Balancing + Automated Packing	€ 87.234,60

Table 35 - Labour cost savings per configuration assuming current demand

From Table 35, we conclude that significant savings can be achieved by implementing the proposed interventions. Introducing automated packing results in relatively large savings, however, the expected investments costs for this intervention are significant. The presented potential savings can be used to decide on the implementation of interventions once the required investment costs have been obtained from suppliers.

Next to the financial advantages of the interventions, we also highlighted some qualitative advantages of our intervention. For the cellular manufacturing layout intervention, we found that the specialized Bus order processing line can also be used for other specialized processes such as gift wrapping or single line batch picking, providing the opportunity to also process other order groups more efficiently.

The impact of the interventions on the IT landscape varies. Whereas the line balancing interventions require only limited adjustments in the landscape, moving towards one of the two new layouts generally results in a much larger impact. The cellular manufacturing layout requires even more adjustments since product flows have to be split structurally. We therefore conclude that the impact on the IT landscape will be heaviest for the transition towards a cellular manufacturing layout.

7.2 Recommendation

Following our evaluation of the proposed interventions, we recommend implementing the cellular manufacturing layout. This layout achieves stable improved performance compared to the current layout and outperforms the other layout alternatives, especially in future increased demand scenarios.

The cellular manufacturing layout requires at least offline line balancing to cope with doubled demand compared to the current demand pattern. We therefore recommend incorporating the move of insert picking from the order control station to the pickports during the transition towards a cellular manufacturing layout. In doing so, the management of PostNL fulfilment in Houten should decide on the future demand the processing line should be prepared for. In case the processing line is to be prepared for increased demand of up to 200% of the current demand, line balancing is a prerequisite for being able to cope with that demand level.

Our research focussed on evaluating the performance effects of interventions. The costs of implementation of the new layouts have been briefly addressed in Section 6.4. If PostNL decides to implement the suggested interventions, a more detailed implementation plan should be created, and the precise costs of the changes should be obtained via Requests for Quotations (RfQ). Once these precise costs have been obtained, the definite decision on implementation of one or more interventions can be made. We therefore recommend requesting suppliers to offer a quotation for the various interventions proposed in this research and decide on implementation based on these offers and the potential savings presented in this thesis.

7.3 Limitations and Future Research

Now that we summarized our research, provided the research conclusion and a recommendation, we elaborate on the limitations of our research and propose future research that can strengthen our research or further improve the productivity of the AutoStore order processing line.

To start with, we limited our research to the AutoStore order processing line and did not investigate the AutoStore itself since there is currently no inducement for assuming that the AutoStore is the bottleneck in the current process. Implementing the interventions that we suggest could however shift the bottleneck of the process to the AutoStore. In that case, the AutoStore, more specifically the interaction between the AutoStore and the processing line, should be subject of further research for improving the performance of the AutoStore competence centre.

Secondly, we mentioned several advantages of interventions that require further investigation. These include the single line batch picking in the cellular layout and the inflow of orders from other departments in the automated packing intervention.

Lastly, during our research, we noted two general points of improvement. To start with, we suggest registering downtime and failure causes for all competence centres to be able to decrease the downtime structurally and to gain insight in the costs of downtime. Moreover, we suggest storing performance data of all competence centres in a centralized database and automate dashboarding and reporting using this database, thereby reducing the manual computations and effort to obtain performance data drastically.

7.4 Contribution to Science

We reviewed our research and its limitations in the previous sections, we will now evaluate the contribution of the research to both practice and science.

At the start of this report in Chapter 2, we announced that we would like to challenge the traditional distance minimization approach for creating a layout for a manufacturing or assembly facility. We did so, by comparing the results of using the traditional approach and the cellular manufacturing layout. The latter procedure focusses more on the efficient use of available resources than on the distance travelled by the products created. Moreover, using our simulation model, that we also used to come up with a suitable layout, we were able to assess new layouts based on the productivity performance, the number of unfinished orders and the utilization of the processing stations. This way, the effects of moving to a new layout could be assessed in far more detail compared to only using the travelling distance as a performance indicator. Although several studies already suggest that the use of simulation in layout design most probably provides better results, we proved this suggestion in this research.

Next to the use of advanced simulation to assess layout performances, we also introduced a new form of line-balancing. Whereas most traditional methods use offline line balancing to balance workload statically during the design phase of a process, we use an online dynamic line balancing method that further reduces the imbalance in workload between workstations. Examples of semi-online line balancing can be found in the sense that jobs are dynamically assigned to machines at the start of the day, shift or week. However, shifting workload to other processing stations while an order has already entered the system and is being processed is an uncommon approach that we have not encountered in our literature review. We hope to be able to contribute to other research as a source of inspiration to this end.

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Appendix 1: Literature Research

Literature Study on Parcel Handling and Packaging Context

We used Scopus to find literature in a structured way. The used search strings and search details are provided in Table 36, the process of filtering the obtained results is provided in Figure 50.

Search term	Scope	Date of search	Date scope	Number of entries
(Facility AND design) AND (material AND handling AND system) AND (parcel)	Title, ABS and keyword	9-1-2019	All Years	12
(Facilities AND planning AND design) AND (internal AND transportation)	Title, ABS and keyword	9-1-2019	All Years	93
(Material AND handling AND system) AND (planning) AND (design) AND (facility)	Title, ABS and keyword	9-1-2019	All Years	932
(Production AND facility AND design) AND (material AND handling AND system)	Title, ABS and keyword	9-1-2019	All Years	463

Table 36 - Search details

Entering the search strings in Scopus resulted in a total amount of 1536 entries. Based on this selection, we refined our search scope to articles that fall into the categories of “Business, management and accounting” or “Engineering”. The resulting 1055 entries were subsequently filtered based on the number of citations. Only articles that have been cited more than ten times remained in our selection, resulting in 322 articles. For these articles, we made a manual selection of 17 articles that we considered to be useful based on their title and abstract. The seventeen articles in our final selection have been partially used in our literature review.

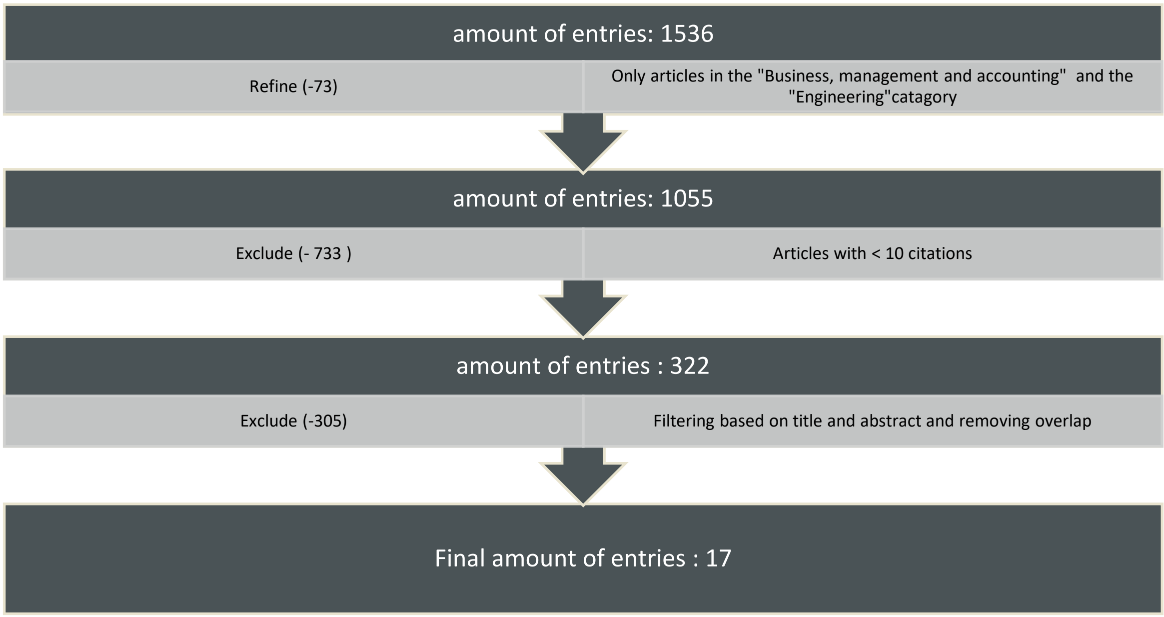


Figure 50 - Search procedure

Literature Study on Solution Generation

We used Scopus to find literature in a structured way. The used search strings and search details are provided in Table 37, the process of filtering the obtained results is provided in Figure 51.

Search term	Scope	Date of search	Date scope	Number of entries
(Systematic layout planning) AND (manufacturing)	Title, ABS and keyword	9-1-2019	All Years	158

Table 37 - Search details

Entering the search strings in Scopus resulted in a total amount of 158 entries. Based on this selection, we refined our search scope to articles that contain the word “Manufacturing”. The resulting 57 entries were subsequently filtered based on their subject area being “Business” or “Engineering”. The selection is now reduced to 45 entries. For these articles, we made a manual selection of four articles that we considered to be useful based on their title and abstract. The four articles in our final selection have been partially used in our literature review.

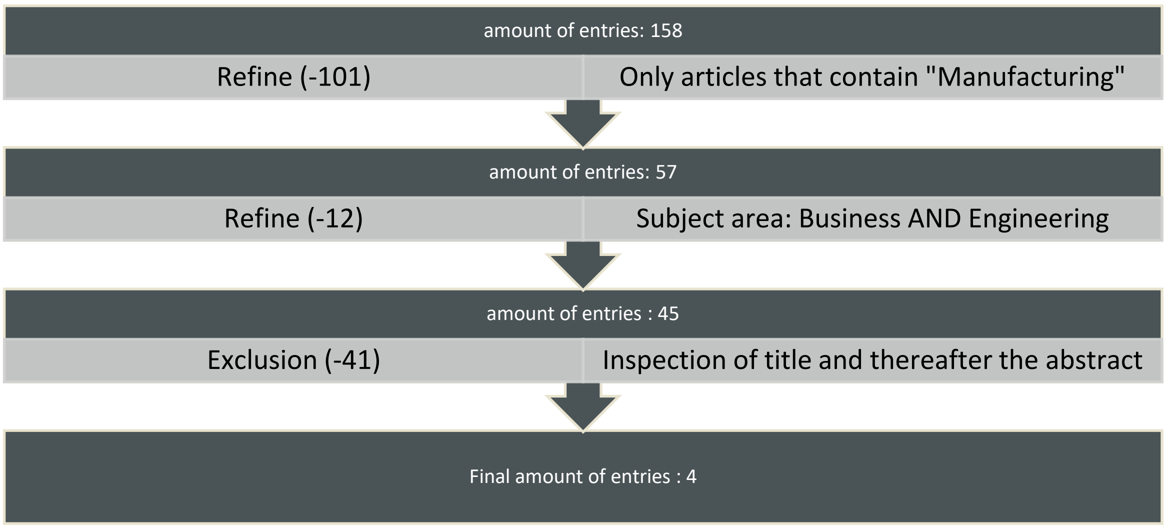


Figure 51 - Search procedure

Literature Study on Product Grouping for Production Cells

We used Scopus to find literature in a structured way. The used search strings and search details are provided in Table 38, the process of filtering the obtained results is provided in Figure 52.

Search term	Scope	Date of search	Date scope	Number of entries
(Cellular AND manufacturing) AND (grouping AND design) AND (assignment)	Title, ABS and keyword	9-1-2019	All Years	807

Table 38 - Search details

Entering the search strings in Scopus resulted in a total amount of 807 entries. Based on this selection, we refined our search scope to articles that are related to "Engineering". The resulting 594 entries were subsequently filtered based on the number or citations. The selection is now reduced to 152 entries. For these articles, we made a manual selection of twelve articles that we considered to be useful based on their title and abstract. The twelve articles in our final selection have been partially used in our literature review.

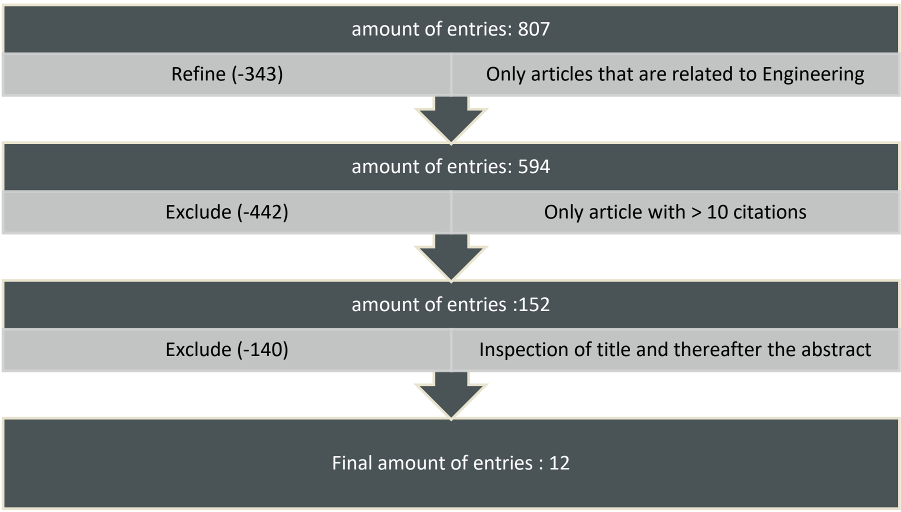


Figure 52 - Search procedure

Appendix 2: Technical description of the simulation model

The concept of using frames was introduced in Section 4.2.2. The two main frames of the simulation model, the controlpanel and the orderprocessingline, have been introduced in this Appendix. In this Appendix, we will elaborate further on the other frames used in the model. Although we will not go into detail on the technical implementation of each frame, we will illustrate the main components and the basic flow of orders through the frame.

For every frame except the AutoStore frame, we use personnel entrances and workplaces to link workers to their respective workstations.

In Figure 53, the PickPort frame is displayed. This frame consists of a processing station that resembles all the jobs performed at the pickport. The order is the transferred to the processing line on the OrderProcessingLine frame in case of a Bel order. In case of a Bus order, the order is transferred to a crate where it is put in a batch of four orders. The Bus order is then transferred to the processing line on the OrderProcessingLine frame in a crate, together with the other three orders. Crates are stored at the CrateStore. The batch formation logic is programmed in the PickPortRouting method.

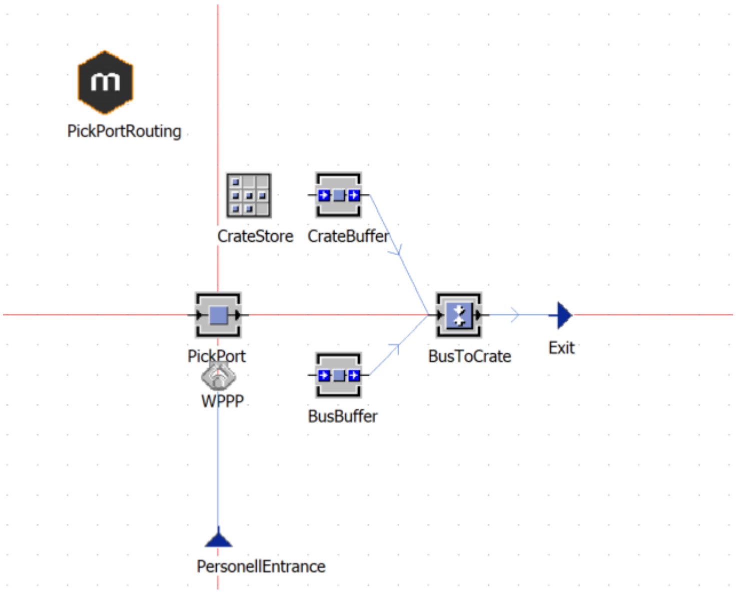


Figure 53 - The PickPort frame

The AutoStore frame is displayed in Figure 54. In this frame, we mimic the functioning of the AutoStore itself. Although the AutoStore itself is not in scope of our research, we do use this frame to generate orders using a poison arrival process. To allow for different order arrival rates over the day, we use a thinning procedure. The orders are generated at the largest arrival rate occurring at a day, the thinning procedure then “filters” out a portion of the arrived orders such that only the specific amount of orders that should arrive in a given hour remain. All orders that have entered the system and are accepted by the thinning procedure arrive at the DayBuffer, a storage for unprocessed orders. The ParallelProc represents the AutoStore picking orders after which a small buffer is used to store data and transfer the orders to PickPorts.

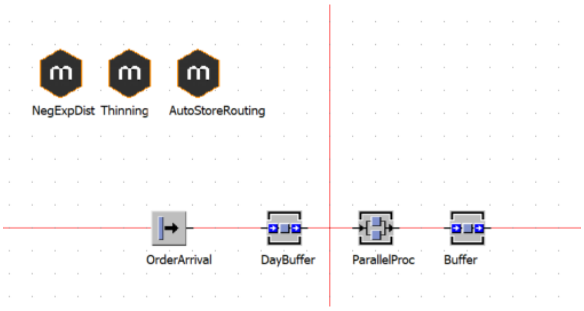


Figure 54 - The AutoStore frame

The Consolidation frame is displayed in Figure 55, this frame splits order streams into consolidation orders and non-consolidation orders. If an order is identified as a consolidation order, it is moved to the buffer and receives its consolidation treatment at the consolidation workstation. Non-consolidation orders are transferred to the next conveyor that is linked to the consolidation frame immediately.

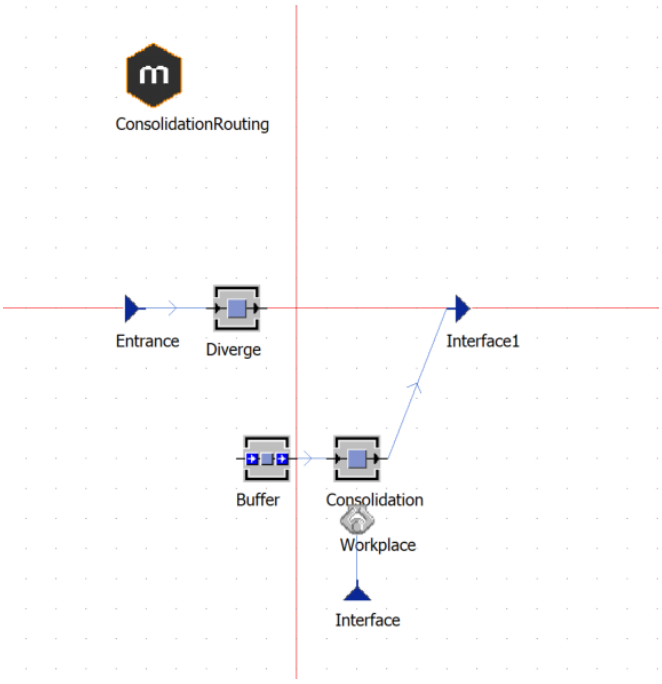


Figure 55 - The consolidation frame

Figure 56 contains the OrderControl frame. This frame is a relatively simple frame that consists of seven order control tables. These order control tables are filled with arriving orders. The method OCRouting is used to transfer orders to available order control tables. This method also moves orders towards the conveyor that follows upon the order control station in case of Bel orders and towards the Bus order trolley in case of Bus orders.

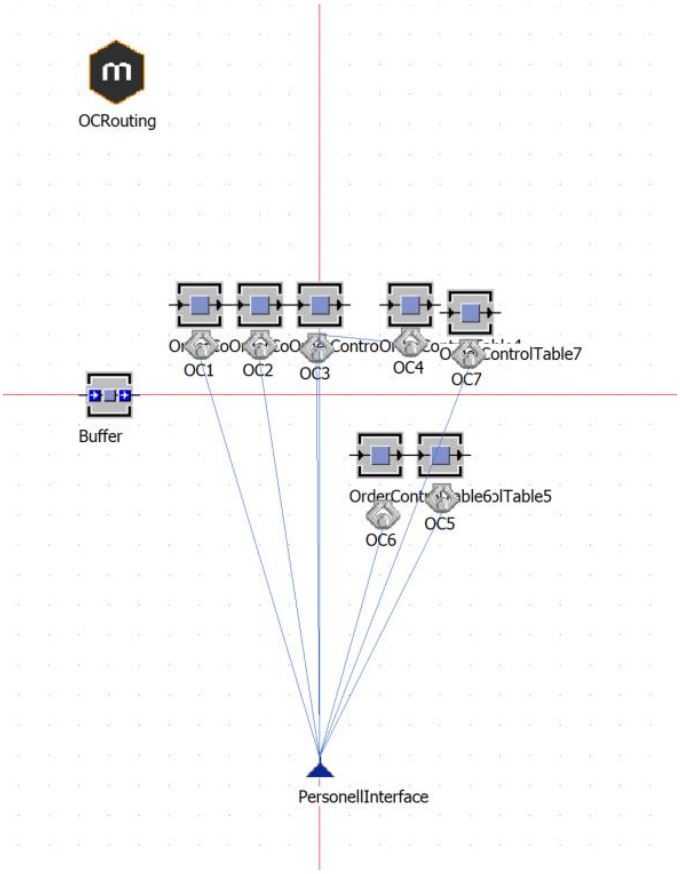


Figure 56 - The OrderControl frame

Appendix 3: Model Logic

To provide insight in the logic of our simulation model, we give a brief overview of the methods used in the simulation model. To repeat, methods represent pieces of logic that we implement in our model. Each method has its own purpose in the simulation model. Using the logic flows, our model can also be implemented in other programming languages if necessary. An overview of the methods that we use in our simulation model is provided in Figure 57. We grouped the methods into four categories based on their purpose.

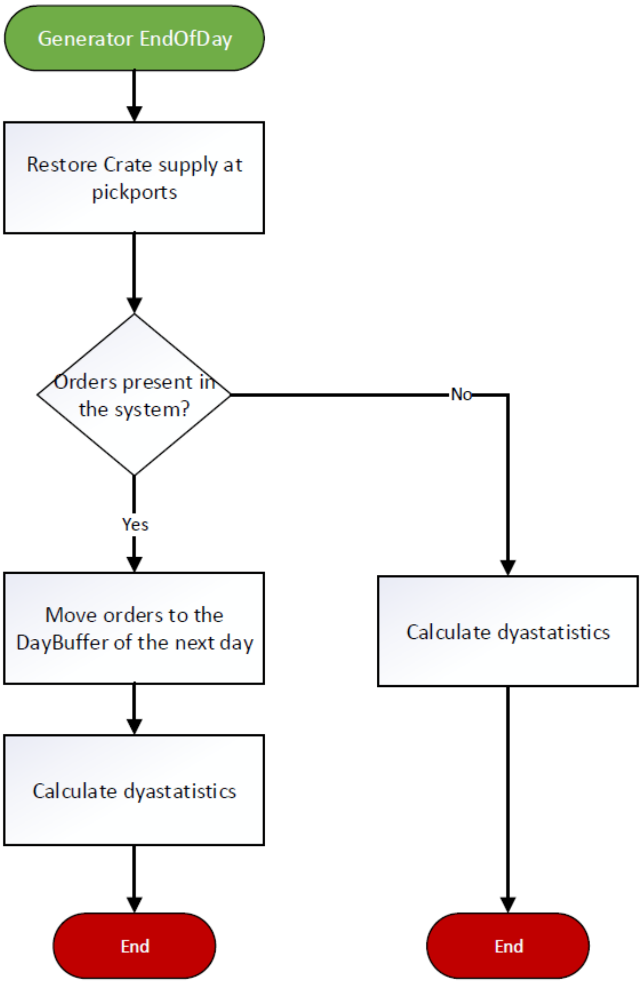
Figure 57 - Overview of (a selection of) the used methods

We will now provide the flowcharts for a selection of the methods. These methods are the most important methods that define the basic functionality of our simulation model.

Method: CloseFacility

Called by: Generator End of Day

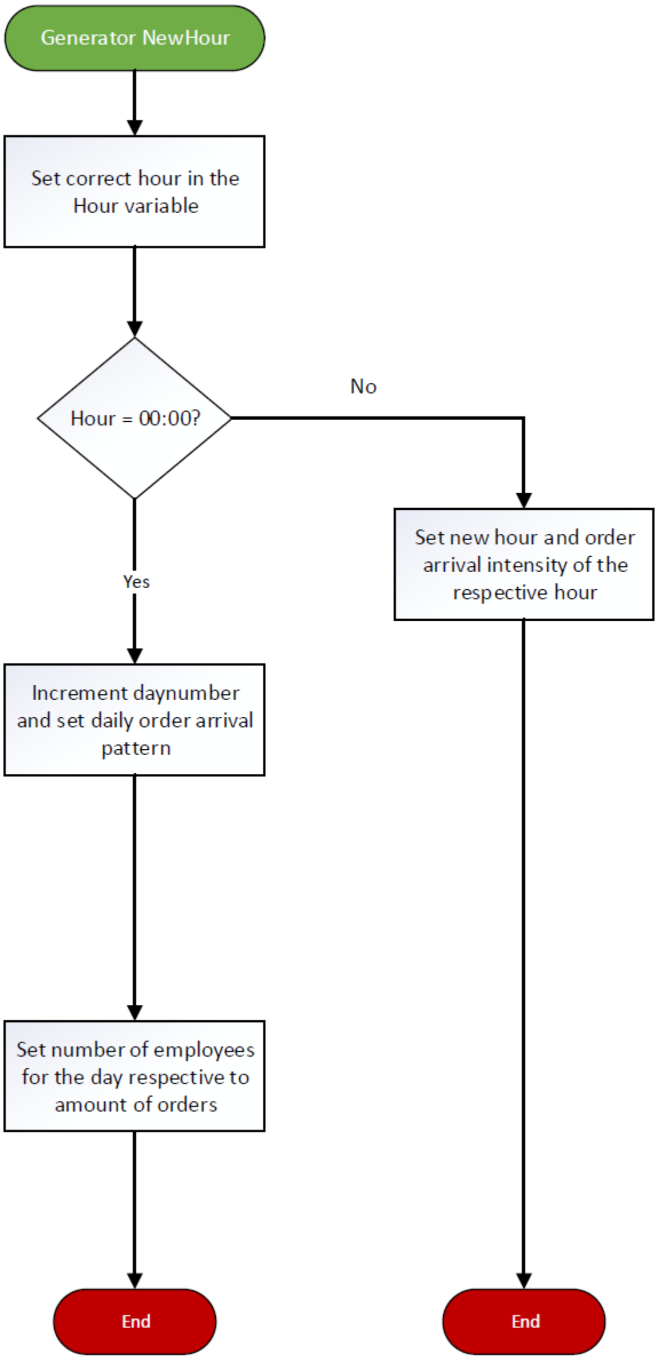
Purpose: At the end of a shift, the crates used during the day should be restored to the pickports for the next day.



Method: NewHour

Called by: Generator NewHour

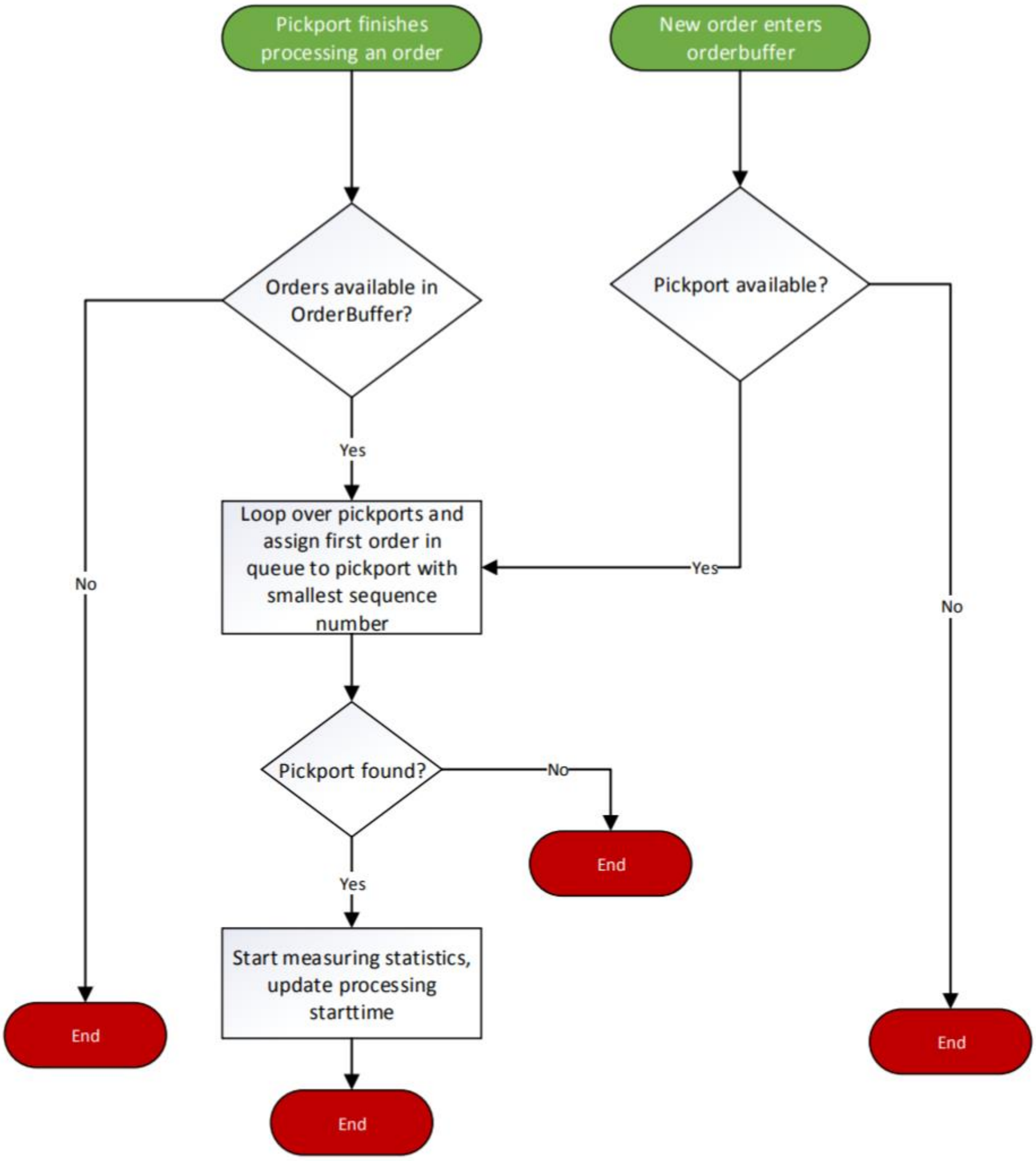
Purpose: Every hour, the method NewHour is called to perform actions that should happen at a specific hour of the day. At midnight, the new employee settings and order inflow for the next day have to be set.



Method: AssignToPP

Called by: Orders leave the pickport after processing or a new order enter the orderbuffer (of the AutoStore)

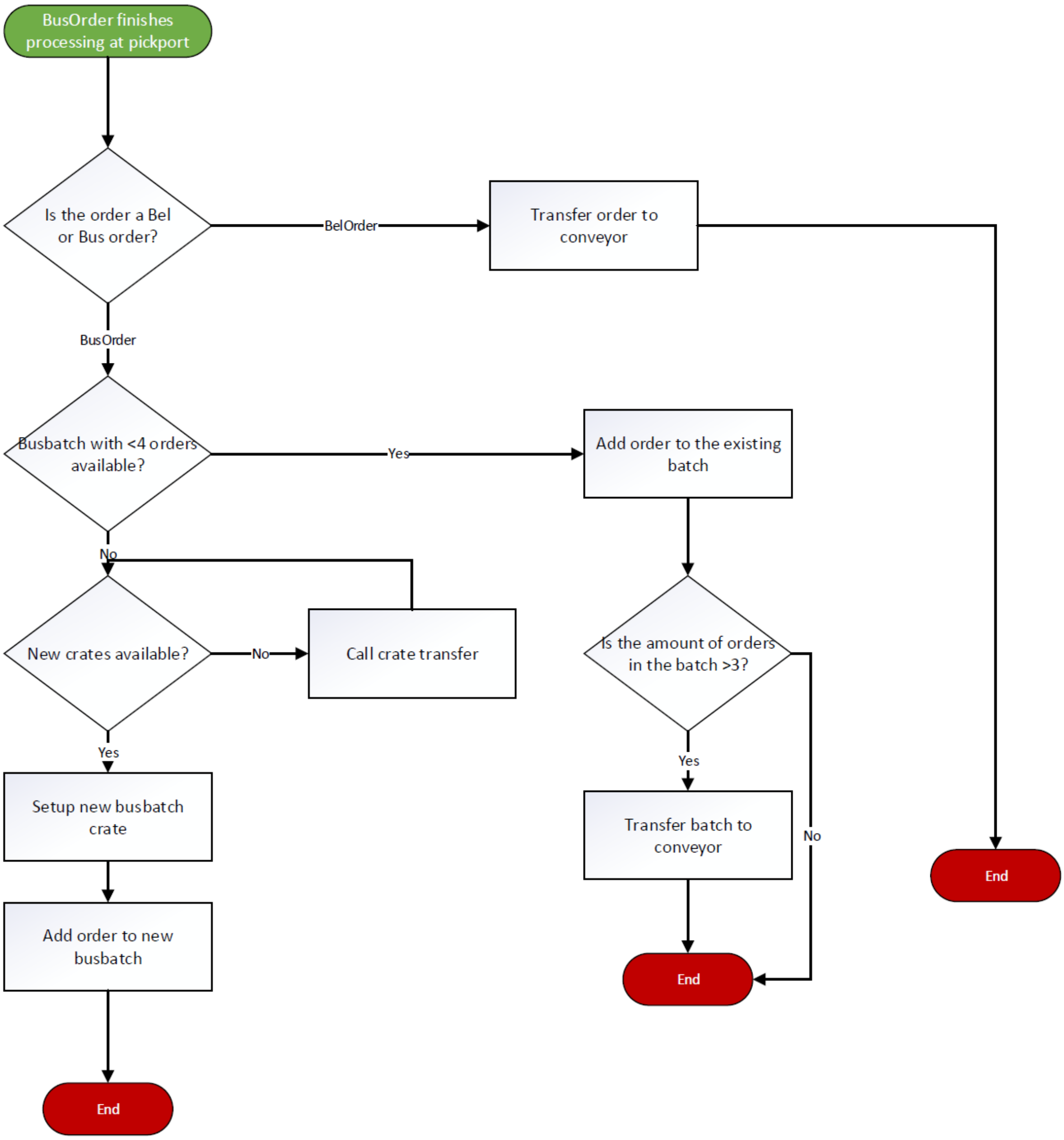
Purpose: Move an order from the AutoStore to the first available pickport.



Method: PickPortRouting

Called by: Exitcontrol of the processing station of a pickport.

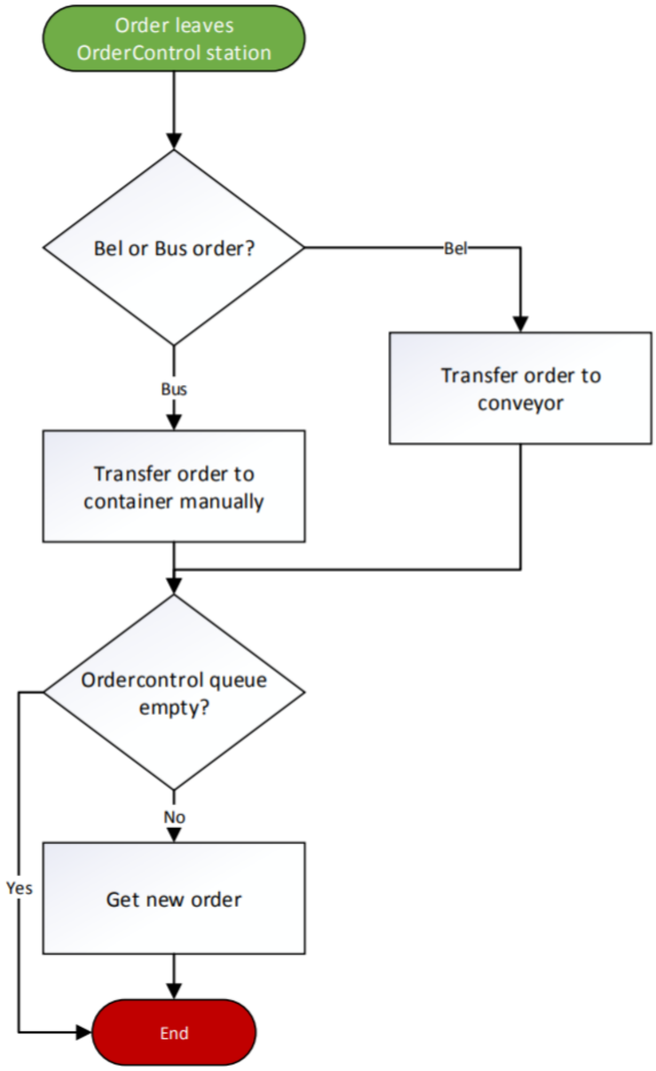
Purpose: This method creates batches of Bus orders that are transported in crates together. Bel orders are moved to the conveyor directly. If there are no crates available, the method for a cratetransfer is called.



Method: SplitBELBUS

Called by: An order leaving the order control station

Purpose: This method assures that Bus orders are transferred to a trolley once it has passed the order control station. Moreover, a new order is moved to the now empty order control station.



Appendix 4: Distribution Fitting

In Section 4.2.3, we elaborated on the probability distribution fitting procedure performed for all processing stations in the AutoStore order processing line. In this Appendix, more background information is provided on the procedure followed. The outcomes of every step in the procedure are also provided.

To start with, let us repeat the steps of the probability distribution fitting procedure. We first performed a visual exploration of possible fits with a range of probability distributions. Next, we identified the gamma distribution as the probability that seemed to have the best fit with the measurement data. To assess whether this probability distribution is indeed representative for the measured data, a chi-square test is performed. This test identifies the difference between the observed number of observations in an interval and the expected number of observations in that interval. By calculating the cumulative error, the chi-square test can determine whether the proposed probability is to be accepted.

The number of expected and observed observations are displayed in Figure 58.

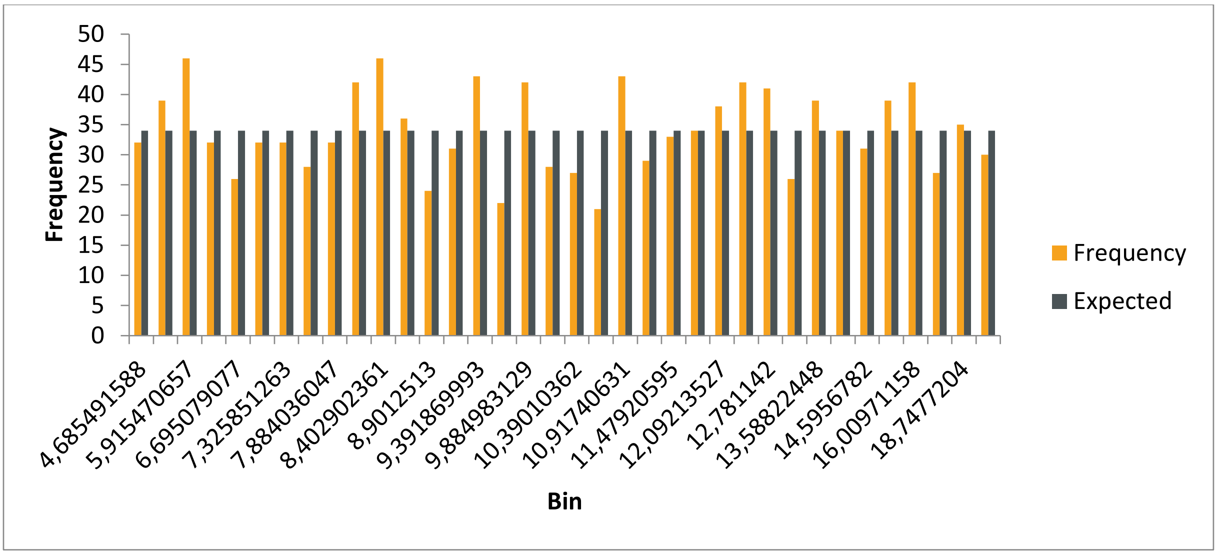


Figure 58 -The number of observed (frequency) and expected observations

Based on the cumulative error measured, we cannot reject the null hypothesis (H0) that the gamma distribution with the found parameters fits the measurement data. The distribution is thus accepted.

As an additional visual and statistical test to assure a good fit, we provide the QQ-plot and PP-plot for the fit between the proposed gamma distribution and the observed data. Ideally, both plots display a diagonal straight line, representing equal values in the percentiles for both the theoretical probability distribution and the observed values.

Both the QQ-plot displayed in Figure 59 and the PP-plot, displayed in Figure 60, can be found on the next page.

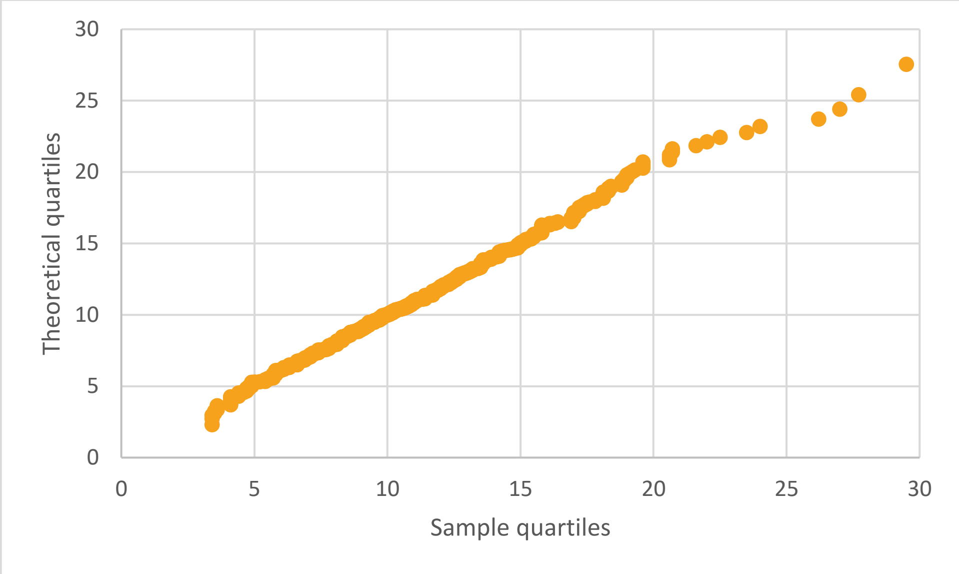


Figure 59 - QQ-plot

The QQ-plot compares the quantiles of the data distribution that we measured during our observations with the quantiles of a standardized theoretical distribution from a specified family of distributions. In this case, the proposed gamma distribution. We see that the quartiles match for the majority of the data points, resulting in a straight line. In the tail of the QQ-plot, we observe little deviation. Based on the QQ-plot, we conclude that there is a good fit between the proposed gamma distribution and the data that we measured.

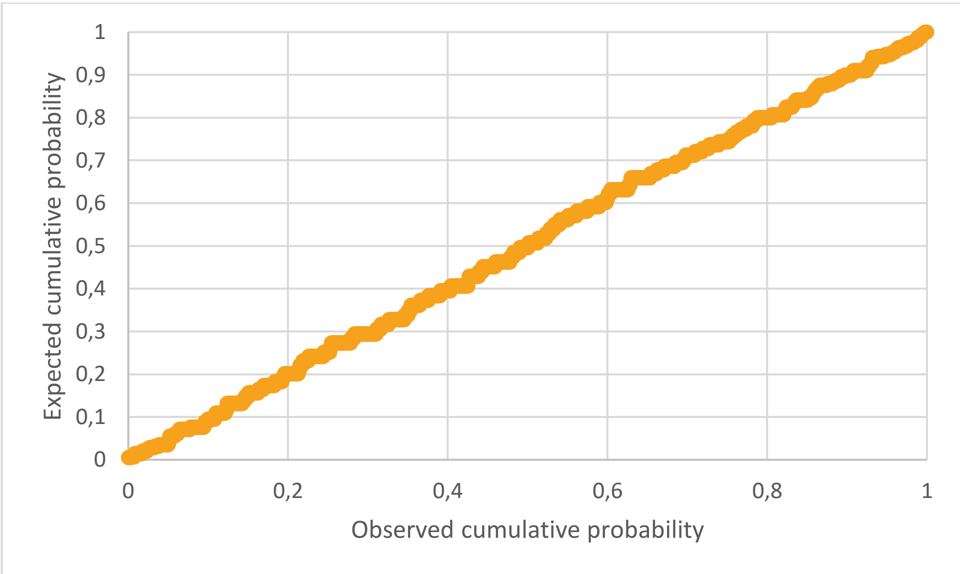


Figure 60 - PP-plot

The PP-plot displays an almost perfect straight line, again indicating a good fit between the measured data and the proposed gamma distribution. In contrast to the QQ-plot, the PP-plot compares the empirical cumulative distribution function of a data set with a specified theoretical cumulative distribution function. We again conclude, based on Figure 60, that there is a good fit between the measured data and the proposed gamma distribution.

Appendix 5: Impressions of the AutoStore order processing line

In this appendix, we provide impressions of the AutoStore order processing line stations that help

Pickports

One of the six pickports is depicted in the picture below.

The central grey opening in the pickport table is where crates containing items are presented to the picker. The picker uses a box from the boxrack (lower left side of the picture) to pick the order in and then places the order on the conveyor on the lower right side of the image.

Consolidation area

The consolidation area is displayed in the image below. The bypass in the conveyor system starts at the parallel section of the conveyor. The shelves next to the conveyors are used to store consolidation items on that can subsequently be added to the orders that are taken out of the main order flow on the conveyor.

Order Reject Station

The order reject station that is currently not in use is depicted below. The black conveyor section contains the weighing section of the order reject station that can be used to automatically reject orders based on the deviation between the expected weight of the order and the actual weight of the order on the conveyor. A camera is located straight above the weighing section. If an order is rejected, it is moved to a parallel conveyor that can be seen at the right side of the picture.

Order Control

The picture below provides an impression of one of the order control tables that together make up the order control station. An order control table consists of a computer and scanner that are used to identify orders and check the items in the order. On the left side of the screen, a pick-to-light system is integrated in the order control table. All possible inserts for customers processed at the AutoStore order processing line are located in one of the compartments of the pick-to-light system. There are also two printer present at each order control table for both Giro printing and delivery note printing respectively.

Filling & Sealing

In the impression of the filling & sealing station, we distinguish between the carton filling material machine (blue, on the left), the plastic filling material machine (middle) and the sealing machine (yellow, on the right). These three machines are used to first fill and then seal orders.

Appendix 6 Utilization of the workstations in our experiments

In this appendix, we provide the utilizations of both the pickports and the order control station for all the conducted experiments. We first provide the average utilization for the pickport workstations in Table 39 and the average utilization of the order control station in Table 40. The utilization scores were used to verify whether the line balancing intervention and the online line balancing intervention performed as expected.

	Average pickport utilization			
Configuration	100%	125%	150%	200%
Base Layout	0,455	0,564	0,502	0,45
Base Layout Balanced	0,519	0,514	0,624	0,684
Base Layout Balanced Automated Packing	0,515	0,509	0,635	0,691
Distance minimization layout	0,436	0,335	0,339	0,454
Distance minimization layout balanced	0,519	0,640	0,518	0,709
Distance minimization layout balanced online	0,571	0,572	0,692	0,611
Cellular manufacturing layout	0,237	0,290	0,379	inf
Cellular manufacturing layout balanced	0,313	0,426	0,451	0,602
Cellular manufacturing layout balanced online	0,339	0,342	0,410	0,543
Cellular manufacturing layout balanced online Automated Packing	0,418	0,422	0,416	0,557

Table 39 - Average utilization of the pickports

	Average order control station utilization			
Configuration	100%	125%	150%	200%
Base Layout	0,568	0,701	0,664	0,744
Base Layout Balanced	0,515	0,494	0,462	0,432
Base Layout Balanced Automated Packing	0,511	0,472	0,470	0,509
Distance minimization layout	0,537	0,552	0,556	0,746
Distance minimization layout balanced	0,380	0,469	0,38	0,517
Distance minimization layout balanced online	0,437	0,437	0,529	0,468
Cellular manufacturing layout	0,400	0,490	0,576	inf
Cellular manufacturing layout balanced	0,287	0,352	0,4137	0,460
Cellular manufacturing layout balanced online	0,396	0,323	0,473	0,470
Cellular manufacturing layout balanced online Automated Packing	0,400	0,500	0,433	0,471

Table 40 - Average utilization of the order control station

From Table 39 and Table 40, we conclude that in the configurations that use line balancing, the deviation between the average utilization of the pickports and the utilization of the order control station is smaller compared to the configurations that do not use line balancing. Moreover, we observe that the utilization of the pickorts is higher compared to the utilization of the order control station in the balanced configurations which follows the expectations raised in Section 5.2.1.

To ease the evaluation of the difference in utilization, we provide an overview of the deviation between the average utilization of the pickports and the order control station in Table 41.

	Deviation in Utilization (OC-PP)			
Configuration	100%	125%	150%	200%
Base Layout	0,11	0,14	0,16	0,29
Base Layout Balanced	0,00	-0,02	-0,16	-0,25
Base Layout Balanced Automated Packing	0,00	-0,04	-0,17	-0,18
Distance minimization layout	0,10	0,22	0,22	0,29
Distance minimization layout balanced	-0,14	-0,17	-0,14	-0,19
Distance minimization layout balanced online	-0,13	-0,14	-0,16	-0,14
Cellular manufacturing layout	0,16	0,20	0,20	inf
Cellular manufacturing layout balanced	-0,03	-0,07	-0,04	-0,14
Cellular manufacturing layout balanced online	0,06	-0,02	0,06	-0,07
Cellular manufacturing layout balanced online Automated Packing	-0,02	0,08	0,02	-0,09

Table 41 - Deviation in Utilization (OC-PP)