Master Thesis

Improving the efficiency of the assembly department

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List of Abbreviations

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AS/RS	Automated Storage and Retrieval System	37
BOM	Bill of Material	10
COI	Cube-per-Order Index	20
CODP	Customer Order Decoupling Point	11
DC	Dual Command	41
DMAIC	Define Measure Analyze Improvement Control	27
ERP	Enterprise Resource Planning	4
ETO	Engineer-to-Order	11
GT	Group Technology	18
I/O-Point	Input/Output Point	24
KPI	Key Performance Indicator	5
LIFO	Last In First Out	26
MHE	Material Handling Equipment	20
MPS	Master Production Schedule	10
MRP (1)	Material Requirement Planning	10
OOS	Order Oriented Slotting	21
PLWC (Dutch)	Sheet metal center	9
SC	Single Command	41
SKU	Stock Keeping Unit	20
SLP	Systematic Layout Planning	18
SWI	Standardized Work Instruction	36
DDC	DD Cabinet	31
VLM	Vertical Lift Module	2
WIP	Work In Process	4

Management Summary

Motivation

Company X is a supplier of sheet metal and metal compositions. They are specialized in a broad range of areas: sheet metal working, welding, powder coating, assembly, cleanroom, and bonding. The proceedings of their assembly department have been increasing over the years. The assembly department has a fixed amount of floor space, which bulges with (assembly) items, thus reducing productivity and accessibility in the department and creating safety concerns.

Central Research Question

The central research question that is answered via this research project investigates improvements in the picking, storing, and assembly operations, and how to use the VLM pod (a VLM with multiple units) in the best way possible in alignment with the department processes, which improve the flow of material overall, hence increasing the efficiency of the assembly department.

Methods used

We discovered that the put-away process was the bottleneck of the picking operations in the assembly department. So, we created three solutions (based on Lean Six Sigma principles) to address the root cause. The first solution was a new policy for the stock transfer for the production and purchase articles. The second solution was an update of the warehouse management application which makes the change of the 'standard location' of the articles easier and more accessible for employees. The third solution was the development of a formal procedure to keep track and clean up 'old' articles in the picking systems.

We identified that the inefficient storage strategy was the bottleneck of the storage operations in the assembly department. We developed a class-based storage concept for the aisles AA and AB to address the root cause. This storage concept is a hybrid option between random and dedicated storage. We assigned production and purchase articles that are intended for the assembly department to these aisles. During the thesis, this class-based storage concept was partly implemented in the aisles AA and AB. Also, we developed a formal procedure to keep track and clean up 'old' articles in the storage systems, using Lean Six Sigma principles.

We discovered that the inefficient assembly process of large series repeat orders was the bottleneck of the assembly operations in the assembly department. We created a strategy to improve the efficiency for these types of orders, whereby we split large series into multiple batches in the production department before the assembly department. First, we reduced the amount (box) of pallets (with unique production articles) required during the assembly of the product. Second, we reduced the number of production articles on a box (pallets) to the amount required for a single batch.

We investigated how to place the articles in the VLM pod in such a way that we minimize the total completion time required to collect a set of customer orders. First, we investigated three alternative storage location assignments via experiments: the current storage location assignment, the COI method, and the OOS method. Hereinafter, we extended our research to a situation where we use multiple VLM units simultaneously. In these experiments, we used an adaptation of the OOS method to distribute the articles over the trays over the VLM units and vary the number of VLM units over the scenarios.

Results

The proposed solutions to improve the efficiency of the picking process resulted in the following: The new replenishment policy allows the employee to better monitor the location and stock of an article. The update of the warehouse management application to make the 'standard location' change easier and more accessible for all employees results in a reduction of articles that are not directly assigned to a picking system or a specialized area. With the formal procedure to keep track and clean up 'old' articles in their picking systems, Company X creates the possibility of storing new articles in the picking system or increasing the capacity of an existing article in the system.

The proposed solutions to improve the efficiency of the storage process resulted in the following: The new dedicated storage concept for the aisles AA and AB result in a decrease in the travel distance for the storage location of inbound purchase articles and inbound production articles and the I/O-point of 50% and 52% compared to the old strategy, respectively. With the formal procedure to keep track and clean up ‘old’ articles in their storage systems, Company X creates the possibility of storing articles destined for the assembly department in the storage locations near the I/O-point.

The proposed solution to split the large series into multiple batches in the production department before the assembly department resulted in less stock transfer (with a forklift) by the expedition department. In addition, we reduced the storage space utilization of the dedicated area for the DDC by 24% compared to the old strategy.

For the storage location assignment experiments, the OOS method provided us with the least completion time for the orders, and the highest throughput of the VLM unit in every scenario. Also with fewer tray retrievals ranging from 27% to 36% and 24% to 31% compared to the COI method and the current storage location assignment, respectively.

For the experiments with the number of VLM units, the completion time to pick a set of orders decreases by 28%, while we increase the number of VLM units from 1 to 2 and increases by 15% when we increase the number of VLM units from 2 to 3. We also observe that an increase in VLM units provides us with an increase in throughput in the VLM pod, the use of 2 and 3 VLM units resulted in 20% and 47% more tray retrievals, compared to a single VLM unit.

Recommendations

As mentioned, we could not quantify the discrepancy between the ‘old’ and ‘new’ strategies, in terms of the picking time for the employees. However, by the partial implementation, we saw the results of the proposed method. We suggest that Company X investigates the actual picking time for an order inside the department by collecting real-time data. With this data, they could determine other inefficiencies with the picking operations. Furthermore, they could test a different picking strategy, such as batch picking, to improve these operations further.

Based on the conclusion of the proposed storage concept, Company X should consider implementing this concept at all (production) departments, hereby lowering the travel distance between the articles and the departments, since the storage of articles is inter-related. In addition, Company X could extend their research to other storage concepts. For this, Company X must track data regarding the size (width and height) of a pallet. The benefit of this is that someone could develop a method for the automatic allocation to storage location based on certain preferences.

The proposed strategy for large series production order resulted in a decrease in used floor space, and less set-up time for the employees. Unfortunately, further research is needed to determine whether the NACA hours are significantly worse or better because of insufficient replications. To generalize this method for these types of orders, Company X should investigate the ‘new’ strategy more extensively. First, by replicating the pilot more often, then extending the strategy to other large series repeat orders, and finally by compiling a framework to create a generic solution for these orders.

Based on these conclusions for VLM, Company X should consider using two VLM units for picking operations, and to assign the articles to the tray with the OOS method. This provides considerable advantages over the settings currently used. Company X could extend the current research to the further greater use of the VLM. For example, by allowing fragmented storage in the warehouse. We believe that by creating duplicate VLM units, the completion time for a set of orders could be reduced, and the VLM becomes more robust in case of failure. In addition, Company X could investigate the alternative picking strategy to improve the throughput of the VLM pod.

Preface

This report is the result of my master's thesis project at Company X to complete my study in Industrial Engineering and Management at the University of Twente. I would like to thank several people who contributed to this thesis.

First, I would like to thank Company X for the opportunity to carry out my master's thesis project at the company. I look back on a very interesting and exciting period at Company X, where I had the chance to work in a very challenging environment. I would like to thank my company supervisor, for his effort during the guidance of my Master's Thesis. I would also like to thank other colleagues at Company X. They were always willing to help me with my project by making time to answer my questions and brainstorm together.

I want to thank Derya Demirtas and Peter Schuur for their help and support during this thesis. The feedback helped me greatly, and I could not succeed without their help. Finally, I would like to thank my friends and family for the continuous support and the interest they have shown in my research.

Samson Loboka

Utrecht, 14-06-2022

1. Introduction

To obtain my master's title in Industrial Engineering and Management at the University Twente, I have conducted a thesis at Company X based in the Achterhoek. In this thesis project, we investigate how to improve the efficiency of the assembly department. By improving the efficiency of the department, Company X hopes to meet the rising demand in the future.

Chapter 1 describes the research proposal of the thesis, subjects such as the context, the problem description, and the research motivation. Chapter 2 contains a context study of the current situation in the assembly department. The literature study in which applicable opportunities to improve the operations in the assembly department is presented in Chapter 3. An analysis of the current performance in the department is presented in Chapter 4. Chapter 5 contains the alternative strategies, that could be implemented in the assembly department. The results and discussion are presented in Chapter 6, and the concluding chapter contains the conclusion and recommendations.

1.1 Context

Company X is a supplier of sheet metal and metal compositions. They are specialized in a broad range of areas: sheet metal working, welding, powder coating, assembly, cleanroom, and bonding.

Company X produces 8.000 types of products diffused in 20.000 orders annually. The focus of Company X lies on the small and big products, ranging in small to medium series regarding quantity, examples in terms of products are frames, machine covers, and (electro) mechanical modules. Company X aims to provide the manufacturing industry with high-quality sheet metal and metal compositions.

In the assembly department, the workers assemble the product, which consists mainly of metal parts, and attach parts like screws, hinges, and handles. Some products require electrical connections, rubber attachments, or need to be glued together. Within the assembly department, a cleanroom is present, which is used to remove any contamination from the products. Customers from the medical and the semiconductor sector usually require these types of operations.

The ventures of the assembly department are increasing over the years, whereby the workplace is becoming too busy. To ensure that the assembly department can provide the same level of quality and service in the coming years, it needs to streamline its processes, minimize its space usage and promote productivity for the workers.

1.2 Research motivation

This thesis project focuses on the assembly department of Company X, of which its proceedings have been increasing over the years. The assembly department has a fixed amount of floor space, which bulges with (assembly) items, thus reducing productivity, and accessibility in the department and creating safety concerns. Figure 1 displays the current situation at the assembly department.

Most of the materials/items that are needed to assemble the products are gathered in conventional 'picker-to-parts' systems. The (individual) items are collected in bins inside a shelf rack, boxes are stored in a shelf rack. The larger items are stocked on box pallets, some of those are put inside pallet racks. The choice of conventional systems resulted in congestion of the floor space because the larger items (that do not fit in the pallet racks) are put on the floor next to the assembly table of the workers. The disturbing part is that most of these items are not directly needed, but for production orders in a later stage.

Figure 1: Current situation of the assembly department.

Company X recently has bought an automated ‘parts-to-picker’ system to clear the floor space and improve the throughput in the department. The ‘new’ hardware uses less floor space, and utilizes the vertical storage of the warehouse more, in contrast to conventional systems. Company X chose to buy a Vertical Lift Module (VLM), also known as ‘Lean Lift’. They want to know how to use the VLM in the best way possible in alignment with the department processes, which benefits the overall efficiency of the assembly department. Several processes, such as picking, assembling, and storing, need to be examined, which are directly and indirectly related to the exploitation of the new VLM.

Directly:

- The optimization of items in the VLM in terms of picking and storing.

Indirectly:

- The new material flow through the assembly department.

1.3 Problem description

In the previous section, we explained the assignment given by Company X. There are related problems that are the cause(s) or consequence(s) of the core problem. A problem cluster has been used to identify the core problems in a cause-effect scheme, which can be seen in Figure 2.

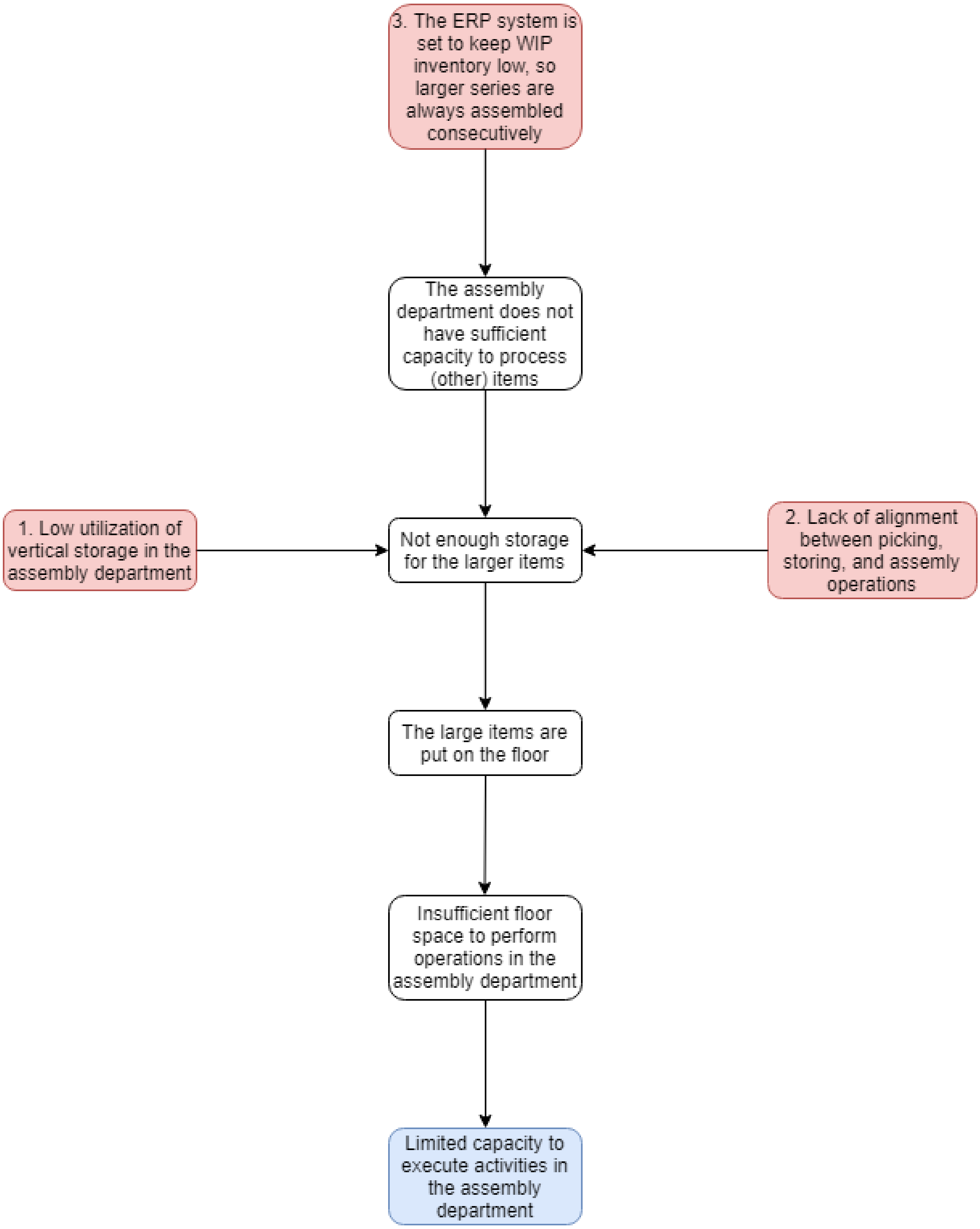


Figure 2: Problem cluster assembly department Company X.

The initial problem that Company X is experiencing is that there is limited capacity available to execute activities in the assembly department, which has been increasing over the years. The cause of this initial problem is that there is not enough floor space to perform these operations.

The cause of not having enough floor space is subordinate to one cause. The floor space of the assembly department is filled with large items (that are kept on box pallets). The employees place these items on the floor because there is not enough storage for the pallets.

Two core problems can directly be linked to the above-mentioned consequence. The first core problem is the low utilization of vertical storage. The height of the warehouse is poorly used to its potential, because of a lack of vertical storage possibilities. The second core problem is a lack of alignment between picking, storing, and assembly operations within the assembly department. These processes are currently not matched to each other, to operate effectively.

The third core problem is a direct cause of capacity problems that the assembly department is experiencing. The Enterprise Resource Planning (ERP) system is currently set to keep the Work In Process (WIP) inventory at a low level by assembling products of large series in succession. The assembly of these large series cause complications, because is not enough capacity to process other items. They cannot store these pieces temporarily, which creates a pile-up in the department.

The first core problem is the poor utilization of vertical storage space in the assembly department. In the section ‘Research Motivation’, we explained that Company X uses a lot of conventional storage systems that are easily accessible to the employees. The systems use a lot of ground space without utilizing the vertical storage capability inside the warehouse, resulting in insufficient storage for the larger items in the assembly department. As a result, most of these items are placed on the ground space within the department.

The second core problem is the lack of alignment between the picking, storing, and assembly operations at the assembly department. Presently, there is not a clear flow of materials visible through the assembly department. The different systems and methods chosen for these operations are opted for convenience and not geared toward each other. The material flow is a necessity to perform the activities efficiently in the assembly department.

The last core problem is the programming of the ERP system, which will keep the WIP inventory at a low level, so reducing the number of partially finished goods. Products comprising larger series usually have multiple due dates, so not all products have to be delivered simultaneously, and thus not all need to be assembled at the same time. Currently, products that consist of large series are assembled and shipped at the same time. The ERP system can be programmed according to two settings.

The first option is to produce all the products at once (before the due date of the first batch) which reduces the capacity to produce other products in that space of time. The other option is to let the employees can produce a part of the series. However, the remaining items of products need to be stored in the pallet racks, which are available in the expedition department. These items need to be picked again by a logistic employee, also the assembly table needs to be prepared again for the specific product. Currently, the second option is used in which products are assembled consecutively. In the case of a large series, there is not sufficient capacity to work on other products as usual. So these items are mostly temporarily stored on box pallets on the floor, because of the lack of vertical storage possibilities and the ease for the employees (less travel distance).

The problem that I (in consultation with Company X) will solve is the second core problem. We believe that it is possible to create a more efficient flow of material in the department, through improvement in the alignment of the picking, storing, and assembly operations.

1.4 Research objective

There has been a rapid rise of ventures in the assembly department of Company X. To meet this demand in the future, the efficiency of the department needs to be improved. So Company X can assemble the same or more products with less input, looking at floor space and time as 'input'. This thesis describes improvements in the picking, storing, and assembly operations, which improves the flow of material overall, hence increasing the efficiency of the assembly department.

1.5 Research (sub) questions

Several research questions have been formulated to help answer the main research question, these questions are devised to guide the research.

The main research question of the thesis is:

"How can we create a more efficient flow of material in the assembly department, by improving the picking, storing, and assembly operations?"

To understand the current situation in the assembly department, the first research question has been formulated. This question will be answered by analyzing the current methods of picking, assembling, and storing items and products in the assembly department. In addition, the current flow of material and the layout (style) will be examined. To retrieve this information, interviews will be conducted with employees and joining along with the activities that they perform, to get a detailed understanding of all relevant operations.

Chapter 2: Context Study

1: ***"How are the picking, assembling, and storing operations currently organized in the assembly department?"***
1a: *What is the current layout of the assembly department?*
1b: *How is the current flow of material organized in the assembly department?*
1c: *How are items/products of the assembly department currently picked?*
1d: *How are items/products of the assembly department currently stored?*
1e: *How are items/products of the assembly department currently assembled?*

The second question has been drawn up to analyze the processes, design solutions, and test solutions in the assembly department. With help of articles and books, we will collect information regarding layouts (for operations), picking systems, and picking strategies in warehouses. Next to the above-mentioned topics, other subjects are also investigated, such as storage systems and storage strategies in warehouses.

Chapter 3: Literature Study
2: ***"Which methods are available in the literature for storage and picking in warehouses?"***
2a: *Which types of layout styles are available in the literature?*
2b: *Which layout methodologies for warehouses are available in the literature?*
2c: *Which types of storage systems for warehouses are available in the literature?*
2d: *Which types of storage strategies for warehouses are available in the literature?*
2e: *Which types of picking systems for warehouses are available in the literature*
2f: *Which types of picking strategies for warehouses are available in the literature?*

The third question was formulated to analyze the processes in the assembly department, with help of information gathered via the context and literature study. With those chapters as input, all the causes from inefficient processes will be mapped out, and the root causes will be extracted This will provide a handle while tracking and analyzing the data from the ERP system because there are no suitable Key Performance Indicators (KPIs) available to discover the bottleneck firsthand.

Chapter 4: Data analysis
3: ***"What are the inefficient operations that disturb the flow of material in the assembly department?"***
3a: *What are the bottlenecks in the current situation of the assembly department?*
3b: *What are the inefficient processes within the picking operations of the assembly department?*
3c: *What are the inefficient processes within the storing operations of the assembly department?*
3d: *What are the inefficient processes within the assembly operations of the assembly department?*

We have put together the following research question to design possible strategies that could be implemented in the assembly department, with the help of the data analysis and the literature study. Next to suggested improvements regarding the picking, storing, and assembly operations, the VLM will be optimized in terms of picking and storing, with the help of mathematical models.

Chapter 5: Methods
4: **"What are possible strategies to create a more efficient flow of materials through the assembly department?"**
4a: *What are possible strategies to improve the efficiency of the picking operations of the assembly department?*
4b: *What are possible strategies to improve the efficiency of the storing operations of the assembly department?*
4c: *What are possible strategies to improve the efficiency of the assembly operations of the assembly department?*
4d: *How can the VLM of the assembly department be optimized in terms of picking and storing?*

The fifth research question was formulated to analyze the processes in the assembly department again while testing strategies and comparing the results with the present policy. For the storing and picking operations, mathematical models will monitor the effects. For the assembly operations, we will execute a pilot to keep track of the implications.

Chapter 6: Results
5: ***"What is the influence of the chosen strategy on the operations in the assembly department?"***
5a: *What is the effect of the new strategy on the efficiency of the picking operations of the assembly department?*
5b: *What is the effect of the new strategy on the efficiency of the storing operations of the assembly department?*
5c: *What is the effect of the new strategy on the efficiency of the assembly operations of the assembly department?*
5d: *What is the effect of the methods on the VLM in terms of picking and storing?*

To implement the suggested improvements in the assembly department effectively in the short, middle, and long term, we created a sixth research question.

Chapter 7: Conclusion, recommendation, and discussion
6: ***"How can*** Company X ***implement the suggested improvements for the processes in the assembly department?"***
6a: *How can the suggested improvements of the picking operations be implemented most effectively?*
6b: *How can the suggested improvements of the storing operations be implemented most effectively?*
6c: *How can the suggested improvements of the assembly operations be implemented most effectively?*
6c: *How can the suggested improvements for the VLM be implemented most effectively?*

1.6 Scope

- The focus of this thesis lies in the assembly department. However, some activities take place outside of this area. For example, the employees store most of the WIP inventory in the expedition department. Therefore, departments that are directly linked with the processes of storing, picking, and assembly will be included in the analysis regarding the improvement of efficiency of the assembly department. But, other processes (i.e. receiving in the expedition department) in these departments are excluded from this thesis.

- We have introduced three core problems in the 'problem description' section. The second problem is the focus of this thesis, the lack of alignment between the picking, storing, and assembly operations. We include the other two problems in this thesis, in form of sub-research questions.

- The first problem, the low utilization of vertical storage, will not be solved as a stand-alone problem. Company X has already made efforts to solve it, by buying a 'Lean Lift' using the vertical storage more. We will look at the optimization of the VLM regarding the picking and storing process.

- The third problem, the consecutive assembly of large series, will also not be solved as a stand-alone problem. We will analyze the influence of WIP inventory on the efficiency of the assembly department. We will look at the possibilities of assembling products in smaller series more effectively in the department.

- Changes to the ERP system besides anything related to the third core problem are excluded from this research, because of the limited available time.

1.7 Deliverables

The deliverables of this thesis consist of a report, which can be dissected in separate chapters, which can be seen in Figure 3.

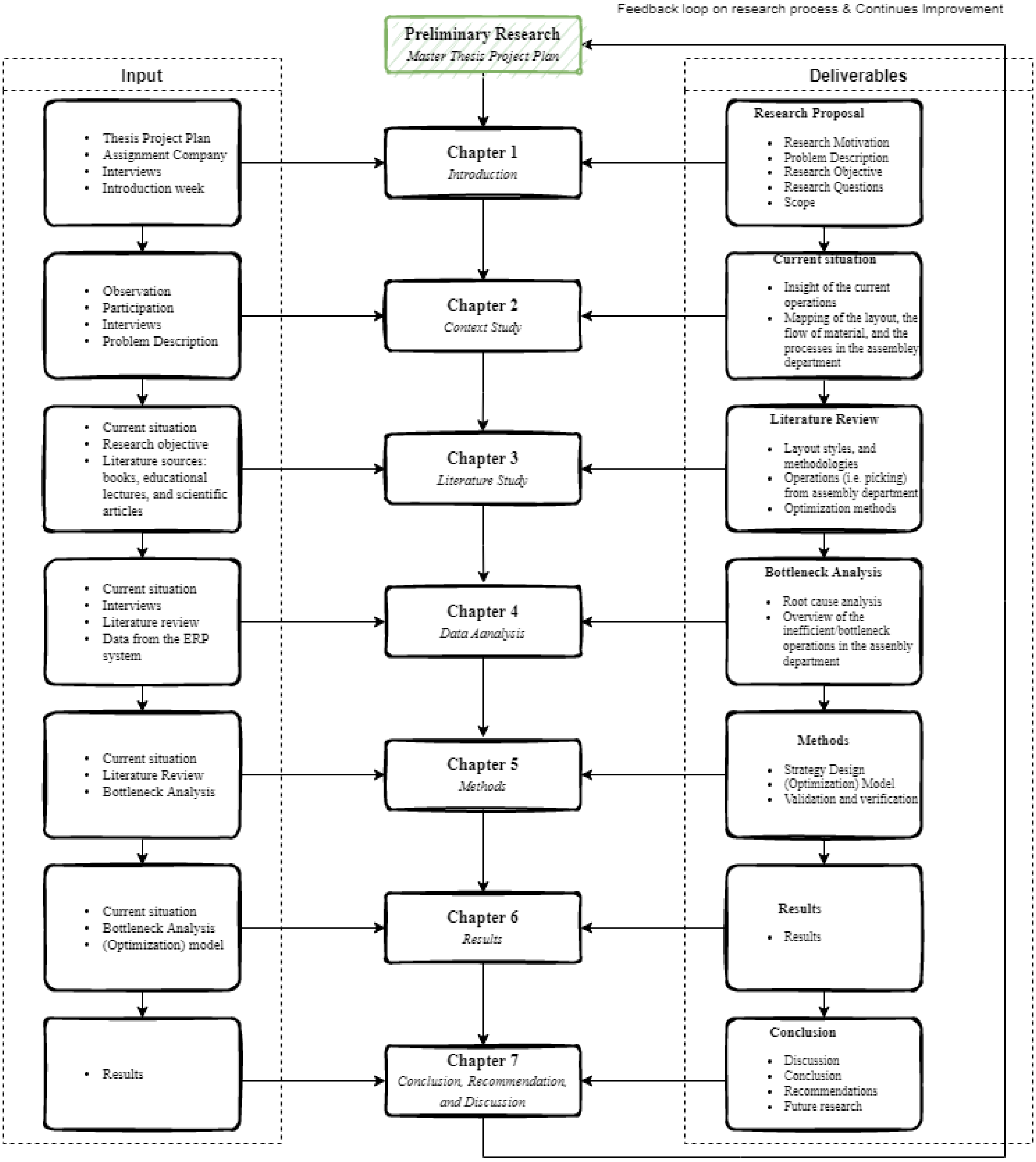


Figure 3: Deliverables adapted from (Thwaites 2020)

2. Context study

In this chapter, we describe the context of this study. Section 2.1 describes the current layout of the assembly department, Section 2.2 explains the current flow of material, and Section 2.3 elaborates on the picking operations. Section 2.4 describes the storing operations, and Section 2.5 concludes with the assembly operations in the department.

The goal is to provide a detailed understanding of all the relevant operations in the department. The information was collected with help of interviews with employees and management, also by observing and joining along with the activities that the employees perform. We answer the following research question in this chapter:

"How are the picking, assembling, and storing operations currently organized in the assembly department?"

2.1 The layout of the assembly department

In this section, we discuss the type of layout of the assembly department, describing the hardware which is present in the area. The assembly department of Company X is divided over two separate buildings positioned across from each other in the yard. One section is in the same building as the sheet metal center (Dutch abbreviation: PLWC), which was constructed at a later stage. This area is arranged for solely project-type manufacturing and is not used regularly. Because of the inconsistency of activities and the change of layout style per project, this area is excluded from this thesis.

Company X stationed the other section of the assembly department in the 'old' structure, with other (production) departments such as welding, the paint shop, and the expedition. Company X handles 8.000 types of products annually, whereby the series comprises small to middle size quantities. We can categorize these products into three manufacturing process types, project, job shop, and batch. The other two types, mass, and continuous manufacturing processes do not apply to the range of products assembled in the department.

Three potential layout types are loosely related to these three manufacturing processes, fixed-position, functional, and cell layout, but only one type is related to all three processes, the functional layout (Slack, Jones, and Johnston 2016). The management of Company X designed the assembly department with a functional layout. This design guarantees a high mix and product flexibility, easy supervision of transforming resources (i.e. products), and robustness in case of disruption. But on a contrary, the layout can have a very high WIP, low facilities utilization, and a complex flow of material (Slack et al. 2016).

In Appendix A, the current layout of the assembly department is presented, we categorized the resources and processes of the department. One important note regarding the layout, the box pallets that are used to store items/products temporarily are left out because of the inconsistent use (in terms of quantity and location) by employees. In the next sub-section, every category is briefly explained, and in Appendix B, we attached photos of each resource.

General warehouse tools: Tools that are required to maintain the warehouse in an orderly appearance.

Office desk: Desks that are furnished to handle paperwork with items, such as a computer, printer, and workbooks.

Consumables: Products (mainly packing supplies) that are used daily, for example, cardboard boxes and bubble wrap.

Picking/Storage system static: Systems designed to store items and products to be picked (for assembly) in a later stage. Static means the workers cannot move these systems without auxiliary equipment.

Picking/Storage system dynamic: Systems designed to store items and products to be picked (for assembly) in a later stage. Dynamic means the workers can easily move these systems because of the presence of a caster wheel in most cases.

Assembly workstations static: Workstations to assemble items in a fixed position within the assembly department. The type of workstation is based on the products.

Assembly workstations dynamic: Workstations to assemble items at a flexible position within the assembly department. The workers can easily move these stations, because of the presence of a caster wheel in most cases. The type of workstation is based on the products.

Assembly tools static: Auxiliary equipment to assist with assembly operations, which can be required based on the type of product. Some tools can not be moved because of their size. These tools are static.

Assembly tools dynamic: Auxiliary equipment to assist with assembly operations, which can be required based on the type of product. The workers can move these dynamic tools with the help of a cart, for example.

Transport/assembly tool: Instruments to move items/products from one resource to another, for example, a trolley. Next to its application from transportation, these tools can provide ergonomic assembly aid, because of their height.

QA/QC: Set of processes to measure and assure the quality of the product, and ensure that the product meets the consumer expectation.

2.2 Flow of material

In this section, we discuss briefly discuss the ERP system in place, and Company X's production typology. Additionally, we explain the flow of material and the in-house logistics of Company X.

With a functional layout, they position similar processes close to each other, for convenience or to improve the utilization of transforming resources (Slack et al. 2016). This is also true for Company X, the products will flow through the (production) departments from process to process, based on their needs. This means that different products will take different routes, which creates a complex flow.

2.2.1 Materials Requirement Planning

The logistic processes within Company X are controlled by their ERP system. In the ERP system, an article number tracks all the articles that Company X produces or buys from other suppliers. So, for every production article and purchase article, a production order or purchase order is made, respectively. To organize and follow production processes in the factory, a Materials Requirement Planning (MRP) is used. The MRP requires three sources of input, to generate a detailed job shop schedule (for each department).

The first source is the Master Production Schedule (MPS) which specifies the amount and timing of the end product in the system to meet the demand of solely unaggregated items. Input for MPS consists of firm customer orders, forecast of future demand by item, and seasonal plans (Nahmias and Olsen 2015). The second source is the Bill of Material (BOM), which is the structure of a product. It contains information about every component, data such as their quantity, sequence, and lead-time. The third source is the inventory data, a record for each article, with information such as the inventory at hand, their location, and outstanding orders (Anon n.d.).

2.2.2 Production typology

Company X mainly produces orders on a hybrid engineer-to-order (ETO) basis, the fundamental idea of an ETO remains in place. Thus, that is their customer order decoupling point (CODP) is set on a raw materials level. The CODP defines the stage in the manufacturing process where a product is linked to a customer order (Peeters and van Ooijen 2020). Meaning that raw material is bought based on the forecast and that Company X will not produce any components, subassemblies, or end products before a customer order, which is illustrated in Figure 4.

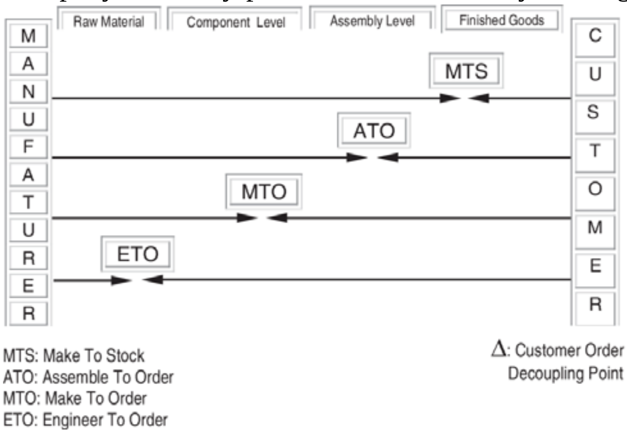


*Figure 4: Customer order decoupling point (Bhattacharya, Sarkar *, and Mukherjee 2005)*

Company X uses a hybrid component in combination with the classic ETO, a so-called floating CODP. In this hybrid set-up, the CODP is allowed to float or move implicitly between production steps (Peeters and van Ooijen 2020). This enhances the flexibility during production because departments can start the production of a certain product, while certain specifications such as the color and due date are unclear.

2.2.3 Article Flow

At Company X, the production orders are not 'hard-coupled', meaning that one production order, for a subassembly is not directly coupled to a production order for an end product. Besides the above-mentioned fact, after every production order, stock for that part is created in the ERP system (for accounting). So after finishing a production order for a subassembly, the subassembly is booked into stock. For example: *Production order Subassembly 1 → Subassembly 1 Finished → Stock → Production order Product 1 (Subassembly 1+2+3) → Product 1 Finished →* Stock.

This gives a benefit, if production order *subassembly 1* is finished, this *subassembly* can be freely assigned to another *product*. Also, it is possible to produce a larger series of *subassemblies*, for multiple orders of *products* to reduce the set-up costs.

There are four separate flows of material at Company X. Note: articles are always received and used from the stock:

1. **Receiving purchase items**: Purchase receipt from a purchase order to the stock.
2. **Usage of purchase items**: Material release from purchase stock to a production order.
3. **Finalizing a production order**: Production order receipt of a production item to the stock.
4. **Delivering the production order**: Sell order issue from the stock to the sales order line.

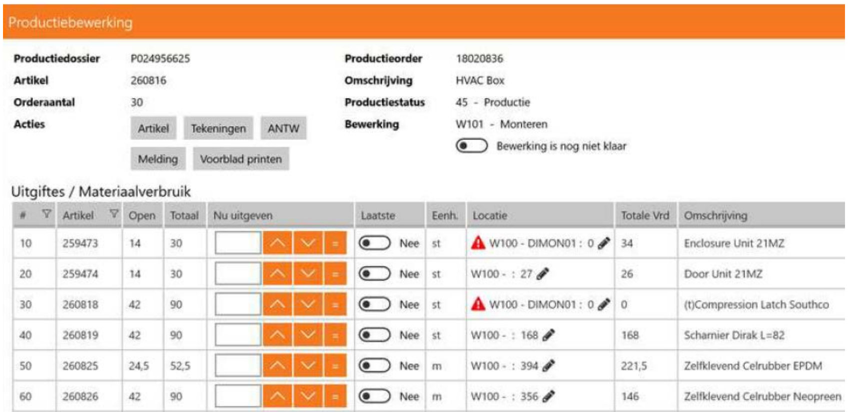
Not all the above-mentioned flows of material take place within the assembly department. The expedition department solely handles the fourth flow of material because the finished goods (end products) are in that area.

Receiving purchase items: The expedition department receives purchase items from outside suppliers. If a purchased item arrives, the staff books the article into the ERP system. The system will generate a purchase receipt with information, such as the date and its origin, which is displayed in Figure 5. In addition, a label is created with a bar code, article number, and the number of pieces, but more importantly, the designated department and specific location. The location can be in the expedition area, or a specific (production) department. The staff will put it inside a pallet rack in the expedition area, if applicable. Otherwise, they placed the article in the drop-in section of the designated (production) department.


Inkoopartikelontvangst (Voorraad)
Datum : 11/11/2021
Afkomst : [redacted]
220527
WS tube distance switch
Maat/norm/opmerking: / /
Klant : [redacted]
Locatie : W100 -[redacted]
Bestemming : Voorraad (verbruik over 3d)
Aantal : 36
Paraaf :

Figure 5: Purchase receipt

Usage of purchase items: In the case, purchased items are utilized for a production order, a material release form is used to update the inventory data. The ERP system changes the stock position with the used number of pieces. Also, the subsequent calculation of the production order is updated with the real consumed material. The material release form is presented in Figure 6.


Productiebewerking

Productiedossier P024956625
Artikel 260816
Orderaantal 30
Acties: Artikel | Tekeningen | ANTW | Melding | Voorblad printen
Productieorder 18020836
Omschrijving HVAC Box
Productiestatus 45 - Productie
Bewerking W101 - Monteren
Bewerking is nog niet klaar

Uitgiftes / Materiaalverbruik

#	Artikel	Open	Totaal	Nu uitgeven	Laatste	Eenh.	Locatie	Totale Vrd	Omschrijving
10	259473	14	30		Nee	st	W100 - DIMON01 : 0	34	Enclosure Unit 21MZ
20	259474	14	30		Nee	st	W100 - : 27	26	Door Unit 21MZ
30	260818	42	90		Nee	st	W100 - DIMON01 : 0	0	(t)Compression Latch Southco
40	260819	42	90		Nee	st	W100 - : 168	168	Scharnier Dirak L=82
50	260825	24,5	52,5		Nee	m	W100 - : 394	221,5	Zelfklevend Celrubber EPDM
60	260826	42	90		Nee	m	W100 - : 356	146	Zelfklevend Celrubber Neopreen

Figure 6: Material release form.

Completing a production order: After completing a production order at a production department, this article will temporarily be stored at the drop-out zone to be moved. An employee of the accompanying department will make a production order receipt, which is presented in Figure 8. A logistic employee will pick the crate with a forklift, to move this article to the next production step, or the warehouse if the article has not been called off yet (to be further processed).


Productieontvangst (VOORRAAD)
Datum : 12/7/2020
App gebruiker: APPDEFAULT
221763
Exhaust duct isol. shield
Tek.nr. : 40224861082-4
Klant : [redacted]
Herkomst : Prod.ord 20012506
Bestemming : Voorraad (verbruik over 4d)
Std. locatie : W110 -
Aantal :
16
Paraaf :
Ontvangstlocatie
W110 DOEXP01
Verbruikslocatie
W110 DOEXP01

Figure 7: Production order receipt.

2.2.4 Routing

Company X has six production departments that execute five main processes: assembling, bending, cutting, painting, and welding. Each production has its identification number, for example, the assembly department has the number W100. The product will flow through the factory while visiting multiple departments, which was explained in the previous sections. However, within a production department, there are separate edits, which are also labeled via an identification number. The engineers of Company X make a routing plan that is based on the need of the product, an example is presented in Appendix C. So, next to the flows of materials presented in the previous sub-section, additional transport movements (over small distances) are present in the assembly department. These motions will not be analyzed in this thesis.

2.3 Picking operations

In this section, we discuss the picking of articles from storage locations to prepare for the assembly operations. The activity of (order) picking consists of more ventures, such as the release of orders on the floor. However, in this section, the focus is on the first part.

Before a product assembly, various articles need to be gathered, which are stored inside the assembly department or warehouse. Currently, it is the assembly employee's responsibility for picking the correct articles for their production order. The smaller parts, such as bolts and nuts, are predominantly present in the assembly department and the large parts in the warehouse. We give more information about the storage strategies at Company X in the next section.

2.3.1 Articles list

With every production order, Company X generates an articles list for that product, an example is presented in Figure 8. Various information is presented on the list, such as stock level, storage location, and the required amount. The employee can use this list to gather the articles within the assembly department. For the larger articles (that are present in the warehouse) they can file a request, so that a logistic employee will bring the articles to the department with a forklift. While picking the articles, the employee will fill in the material release form to update the inventory data accurately.

Rege	Artike	Pos	Omschrijving	Aantal	Voorraad	Voorra	Locatie	PartNorn	Maat	Voor
10	257132	1	Veer snapper	12,000	49,00	W100	[redacted]		245.54.7	☐
20	123795	2	HEX HEAD SCR	12,000	151,00	W100	[redacted]	DIN933	M6x10	☐

Figure 8: Articles list

2.3.2 Picker-to-parts and Parts-to-picker system

The assembly department uses a variety of picking systems, which are spread across the whole area. These systems are mapped and categorized in Section 2.1 and explained in more detail in Chapter 3. We can subdivide these systems into two types, picker-to-parts, and parts-to-picker systems. As previously reported, Company X bought a VLM, their only parts-to-picker system. The VLM is currently not set up, thus not operated by the workers, so will not be discussed in this section.

Currently, the large majority of the picker-to-parts systems within the assembly department are set up for low-level picking. This means that the staff can grab the articles from the shelf racks or bins without aid. The employees pick these kinds of articles by hand or with help of a trolley. High-level picking systems are not very present in the department. The only high-level picking system is the pallet racks, which are mostly filled with box pallets for one certain client. The assembly employees set these pallet racks up to a certain extent so that a pallet jack can pick up a crate. This allows the workers to get the crate themselves, so without a logistic employee in combination with a forklift.

2.3.3 Picking strategies

The assembly workers always work on one production order at a time. This means that the only picking strategy possible is strict (order) picking, meaning that they grab all the articles from a single order.

2.4 Storage operations

In this section, we discuss the transport of incomings articles to the storage locations, which are later picked again for a production order. As previously stated, the articles stored inside the assembly department are a combination of purchase and production parts.

2.4.1 Storage systems

The picking systems that are currently in place also functions as storage systems. Company X installed a forward pick area inside the assembly departments for the smaller types of articles. It minimizes the travel distance between the storage facilities and the workstations for these articles. They store the bulk reserve articles on pallet racks, inside the assembly department and the warehouse.

The replenishment of articles that are present in the forward pick is done from these pallet racks. With purchase articles that arrive via the expedition area, the workers place these articles in the drop-in area. The assembly workers will replenish the articles in the designated location daily.

2.4.2 Storage strategies

Company X uses two strategies for the storage systems that are currently present in the assembly and expedition departments. In the bulk reserve which is stored on pallet racks, a random storage strategy is used. This means that the employee who handles the goods decides the allocation of the storage location.

For the low-level storage systems in the assembly department, both random and dedicated concepts are used. In Appendix D, the storage plan of Company X is presented. In this plan, the storage systems are pointed out that use a dedicated storage concept. Each shelf or rack contains articles for one or multiple clients, which are presented in Table 1. Within these shelves and racks, Company X sorted the articles by number or by combination frequency. The other low-level systems consist of consumables that are randomly ordered.

Location	**Client**
Storage A	Client A
Storage B	Client B
Storage C	Client C
Storage D	Client D
Storage E	Client E
Storage F	Client F
Storage G	Client G, Client H, Client I, and Client J

Table 1: Storage location per client.

2.5 Assembly operations

In this section, we explain how the assembly operations at Company X are currently conducted. The goal is to provide some insight into the resources and processes that are involved with the assembly, not the manufacturing of parts into a product itself.

2.5.1 Dashboard

Every production department has a dashboard at its disposal that presents the production orders of the department. We present the dashboard of the assembly department in Appendix E. Company X places these production orders in three categories, *launchable*, not *launchable*, and *in progress*.

The first category consists of orders for products that the employee can make immediately because all the articles are present. The second category comprises orders with missing articles, and the latter category includes orders that are already in production. The production orders are also labeled, based on their status, for example, as a rush, a backlog, or a reparation order. The employee picks the production order at the top of the *launchable* list via the registration system, then the assembly preparation can start.

2.5.2 Workbook

Company X supplies every production order with a workbook, which is comprised of: a *routing plan*, a *production map*, a *work card*, an *article list*, a *working drawing*, a *manual*, and a *checklist*. With this workbook, an employee can successfully start with an order.

- The *routing plan* is a list with the edits that the product has to complete at the (production) departments.

- In the *production map*, general information about the production is presented, such as the article, edits order, destination, and disapproval in the past.
- On the *work card*, information is provided about the calculated production and set-up time per production step, also an extra instruction text is given if appliable. The employees can clock in via a barcode, so their production time is tracked.
- An *article list* is part workbook, it holds all the articles that are required for the order. The employee can use this list to pick every article, in their storage location.
- A *working drawing* is added, which is a 3D technical drawing of the product. In addition, Company X added an appendix with the article list and its relation to the drawing.
- An (instruction) *manual* is provided for products with a higher degree of difficulty.
- The *checklist* is used to verify that all required articles are processed in the product, according to the correct way.

2.5.3 Workstations and tools

The employees manufacture the articles primarily on top of a worktable because of the ergonomic benefits. Worktables that are present in the assembly differ a lot regarding size and height. Company X suited most workstations for a specific type of product. For example, they assemble products for Client A on southern workstations; they have placed also the storage locations for these products next to the workstation, to reduce the travel distance. The same reasoning applies to the tools used for the manufacturing of products. The workstations and tools are categorized and mapped in Appendix D.

2.6 Conclusion

In this section, we summarize Chapter 2 and draw conclusions based on the analysis of the current situation. I answer the following research question in this section:

"How is the picking, assembling, and storing operations currently organized in the assembly department?"

Company X constructed the layout style of the assembly department with a functional layout to assure a high mix and product flexibility. Similar resources, such as picking/storing systems and workstations for a specific client, are grouped together, which is visible in Appendix D. Unfortunately, the functional layout produces a high WIP in the department and a complex flow of material.

Company X controls its logistic processes with their ERP system, which uses an MRP method to track all the articles produced or bought (from other suppliers). They produce their orders on a hybrid ETO basis, so they will not produce any components, subassemblies, or end products before a customer order. However, Company X can move the CODP (for certain products) from a raw materials level forward to produce components of subassemblies in advance, in case of a ´confirmed´ forecast.

Company X deals with four separate flows of material, the reception of purchase items, the usage of purchase items, the completion of a production order, and the delivery of a production order. The former three flows take place within the assembly department, the third flow takes place within and outside the department, because a product may visit various departments in the factory. An engineer creates a routing plan to guide the product, based on their needs.

The employees of the assembly department perform the picking operations with the help of an articles list. Company X generates a list for each product with information such as stock level, storage location, and the required amount for each article. The employee can pick the smaller articles within the assembly department from primarily low-level picker-to-parts systems, such as shelf racks. They pick the large items from high-level picker-to-parts systems, which are present in the assembly and expedition departments. To pick articles from these pallet racks, they use auxiliary equipment, such as pallet jacks and fork lifts. The assembly workers always work on one production order at a time, so they grab all the articles from that order.

Company X uses the picking systems in place which also functions as a storage facility. The low-level storage systems that are present function as a forward pick area to minimize the travel distance between the storage location and workstation. Most of these systems contain articles for one or multiple clients and stand close to the associated workstations. The rest of these systems contain consumables, such as bolts and nuts. They stored the reserve bulk in high-level systems on pallet racks inside and outside the department. For these articles, Company X uses a random storage strategy.

Company X uses a dashboard at every department to present their production orders, which are placed into three categories *launchable*, not *launchable*, and *in progress*. Every production order comes together with a workbook containing items, such as drawings and manuals. This workbook is a necessity to manufacture the product successfully.

3. Literature study

In this chapter, we describe applicable opportunities to improve the operations (picking and storing) in the assembly department via a literature study. We also investigated other subjects, such as layout methodologies and styles. With the help of this literature study, we can analyze the operations in the departments, design solutions, and test these solutions. In this chapter, we answer the following research question:

"Which methods are available in the literature for storage and picking in warehouses?"

In section 3.1, we give an introduction to the (common) processes in warehouses. Section 3.2 describes the layout styles which are common for operations. Section 3.3 describes the methodologies for internal layouts and facility layouts of warehouses that are available in the literature. In Section 3.4, we describe the storage systems that can be used in warehouses. In the subsequent section, we evaluate the accompanying strategies of the storage systems. In section 3.7, we describe the picking systems that can be used in warehouses, in the concluding section, I evaluate the accompanying strategies of the picking systems.

3.1 Introduction to warehouse processes

In this section, we describe the typical processes that take place within a warehouse. We can view warehouses from three different angles, the processes, the resources, and the organization. In this section, we primarily focus on the processes. Processes are the steps that the articles take upon their arrival at the warehouse, resources are all the equipment and personnel needed to operate the warehouse, and the organization includes the planning and control procedures used to run the system (Rouwenhorst et al. 2000).

We can divide the flow of goods/material in warehouses into six processes, receiving, transfer and put away, order picking/selection, accumulation/sortation, cross-docking, and shipping, the corresponding areas. We present the corresponding flows of the processes in Figure 9 (de Koster, Le-Duc, and Roodbergen 2007). Depending on the type of company (i.e. manufacturing), additional processes can be present in the flow of goods inside the warehouse.

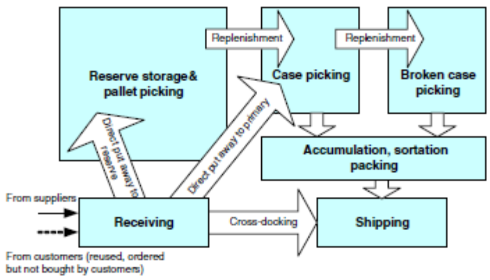


Figure 9: Typical warehouse functions and flows (Riedel 2011).

3.2 Layout styles

In this section, we explain the layout styles that are frequently used for operations in warehouses. The layout of an operation (i.e. assembly) focuses on the position of transforming resources (people, technology, knowledge, information, and partners) relative to each other, the allocation of tasks to these resources, and the general appearance of these resources (Slack et al. 2016) (Bennett 2018).

There are four basic layout styles for operations, fixed-position, functional(process), cell, and line (product) layout. The cell layout is a hybrid style in which elements from the fixed-position and the line layout are combined (Bennett 2018). In Figure 10, we show a restaurant with these four layout styles.

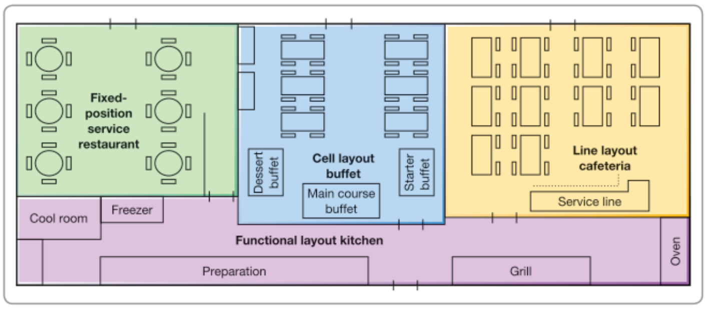


Figure 10: Four basic layout styles in a restaurant setting (Slack et al. 2016).

In this paragraph, we only define the functional layout because of its relevance to this thesis. In a *functional layout*, we place similar transforming resources or processes close to next to each other, for convenience or/and to increase utilization. The transformed resources flow through the operation and take a specific route from activity to activity, based on their requirements. Examples of *functional layouts*: hospitals, and supermarkets. We can couple this layout style to three potential manufacturing process types, project, batch, and job shop (Bennett 2018) (Slack et al. 2016) (Prince and Kay 2003).

The volume-variety characteristics of an operation help narrow the choice for a certain layout style to two options. However, each layout style has certain advantages and disadvantages, which can be critical for an operation (Slack et al. 2016). In the case of the functional layout on a positive note, it provides a high mix and product flexibility, relative robustness with disruption, and relatively easy supervision of transforming resources. Conversely, it facilities low utilization, a high WIP or customer queuing, frequent setups, extensive material movement, long throughput times, and a complex flow, which can be difficult to control (Slack et al. 2016) (Bennett 2018).

To overcome the above-mentioned disadvantages, we can use Group Technology (GT) and a cell layout style. During the design phase of a functional layout, the primary goal is to offer the best 'efficiency' in the area. We can accomplish this by minimizing the total material movement, and additionally minimizing the movement of workers and information between the process areas (Bennett 2018). Several tools, such as computer software packages, exist to design the 'ideal' functional layout. I discuss these tools in the next section.

3.3 Layout methodologies

In this section, we explain the layout methodologies for designing the internal layout for a warehouse and the facility layout. We can dissect the layout design into two subproblems. The first problem relates to the *facility layout problem*, which is related to where to locate various departments in a facility, for example, the receiving area. The second problem relates to the layout within the order-picking system, also called the *internal layout design* (de Koster et al. 2007).

3.3.1 Facility layout problem

In the case of the *facility layout problem*, the goal is to minimize the handling costs, which is often represented by a linear function of the travel distance (de Koster et al. 2007) (Slack et al. 2016). Over the years, researchers have developed many methods to help the facility planner to design facility layouts. We can dissect these methods into two categories, construction layout methods, and improvement layout methods (Riedel 2011).

The flow in a functional layout is complex, mainly because of the very large number of different options. Over the years, researchers developed three procedures that provide a systematic plan of approach to design facility layouts. Reed (1961) developed a systematic plan of approach, describing steps to conduct for the planning and preparation for the facility layout. Apple (1977) gave a sequence of steps to produce a plant layout. The best-known procedure is Muther's (1973) Systematic Layout Planning (SLP), which designs the facility layout in such a manner that processes with a high-frequency relationship are placed close to each other. With this procedure, we can identify, visualize and rate the various activities, relationships, and alternatives in a facility layout project. We assess the selection based on input data, the flow of materials, activity of relationships, and relationship diagrams (Tarigan and Ambarita 2017). Unfortunately, the three above-mentioned procedures are not tailored for a functional layout, the SLP procedure designs the most ‘reasonable’ solution.

The problem is that the combinatorial complexity of functional layouts makes it hard to achieve an optimal solution in practice. So they use heuristic procedures to find reasonably ‘good’ solutions (Slack et al. 2016). Examples of these computer-based heuristics procedures are the BLOCPLAN, LOGIC, and CRAFT. Unfortunately, these algorithms cannot capture and use human experience and judgment, which takes a critical role in the design of a layout. So, these computer-based layout algorithms are intended as ‘design aids’, enhancing the productivity of the layout designer (Riedel 2011).

3.3.2 Internal layout design

The second problem, the *internal layout design*, relates to the design of picking/storing operations. An effective warehouse layout can reduce operations costs and increase productivity. By determining the right location for unique items in a storage system, we can use space, equipment, and people resources efficiently (He et al. 2020). The parameters that affect the layout the most are the total length of the aisle, the number of picks per tour, and the shape of the aisles (Caron, Marchet, and Perego 2000). In this section, we primarily focus on the latter topic.

In traditional unit-load warehouses (pallet) racks are set out to create parallel picking aisles, which provides good storage density. The choice for parallel aisles has two major advantages, it minimizes the construction costs, and it reduces the travel distance for the picker (Meller and Gue 2009). Since order picking accounts for approximately 60% of all operational costs in a typical warehouse, and 50% of these costs are related to travel distance, the urge arises to minimize the travel distance. Over the years, they have invented new designs to minimize the expected travel distance to a single pick (Frazelle and Apple 1994) (Frazelle 2001).

3.4 Storage systems

In this section, we describe the storage systems intended for reserve bulk areas in warehouses. We discuss systems for the forward picking areas in section 3.6. After receiving articles in the warehouse from outside supplies, these articles need to be put away into storage locations before someone can pick them again for a customer order. During the warehouse design phase, we must decide in which storage system, the storing and picking activities to take place, while considering the resources. Subsequently, a storage strategy needs to be chosen to assign the products to a specific location (de Koster et al. 2007). We describe the latter in the next section.

Next to the choice of the type of storage system for the warehouse, another decision (from an organizational point of view) has to be made (de Koster et al. 2007). The question is whether to install a separate reserve area, also known as a forward pick area, which directly affects the storage process and the order picking process. The direct advantage of a forward pick area is that the picking area becomes smaller, which results in shorter walking distances. The downside is that employees have to replenish this area from the reserve bulk area.

The storage systems used in the reserve bulk area are primarily intended for storage pallets. The choice for a certain type of (pallet) racking system is based on speed, cost, and capacity characteristics. Over the years, warehouse specialists have developed a lot of new concepts to provide more storage. The basic idea is, the greater the storage requirement for an operation, the greater the density of pallet storage needed (Richards 2014). In Table 2, the most common storage systems are presented and compared with their rivals, based on the above-mentioned characteristics.

	Use of floor space	Use of cubic space	Speed of throughput	Access to individual pallets	Special Material Handling Equipment (MHE) required	Rotation of stock	Pallet stored at ground level in 4,636 sq. meters (50k sq. Ft.)	Cost per location *
Adjustable pallet racking	**	**	***	****	No	FIFO	1,250	100
Very narrow aisle	***	***	***	*****	Yes	FIFO	1,600	100
Drive-in racking	*****	***	**	*	No	FILO	2,120	200
Double-deep racking	***	***	**	**	Yes	FILO	1,650	100
Push-back racking	***	***	**	**	No	FILO	1,950	500
Gravity-fed racking	****	***	****	*	No	FILO	2,400	700
Mobile racking	****	***	*	****	No	FILO	2,325	400
Satellite racking	*****	****	***	*	Yes	FILO	2,500	500
* The cost column assumes that standard adjustable pallet racking is given a base cost of 100.								

Table 2: Overview Warehouse racking systems (Richards 2014).

3.5 Storage strategies

In this section, we discuss the storage strategies which are used for storage systems in warehouses. Storage strategies determine how to assign an individual stock-keeping unit (SKU) to a storage location (Battini et al. 2015).

The choice for a storage strategy is an organizational problem at a tactical level and is part of a cluster of problems, which should be treated simultaneously. Other problems are the dimension of the picking zones and the determination of replenishment problems (Rouwenhorst et al. 2000). We cannot design the solution for these problems without considering the resources of the warehouse, such as the layout and the workforce capacity.

The employees of the receiving department (in a warehouse) are usually responsible for the storage of incoming goods. These goods primarily arrive in boxes and on (box) pallets destined for the reserve bulk area. If needed, they will replenish these articles in the forward pick area. In the following sub-sections, we explain three storage strategies commonly used in the reserve bulk area.

3.5.1 Random storage

The easiest storage strategy that can be implemented in a warehouse is random storage. With this strategy, every SKU that enters the receiving area is randomly placed at an eligible storage location, with equal probability (Petersen 1997). The allocation of the storage location has to be done by a computer, otherwise, employees will pick a location close to the depot, which is also known as a closest open location storage policy (de Koster et al. 2007). This method gives the advantage of high space utilization (or a low space requirement). The drawback of the random stage strategy is the increased travel distance for the pickers (Sharp, Il-Choe, and Yoon 1991).

3.5.2 Dedicated storage

In a dedicated storage concept, every product has a fixed location. One major drawback of this method is that a location remains unused when a product is out of stock. Besides that, the location must have sufficient volume to store the maximum inventory level, resulting in lower space utilization. On a high note, the harmony between order-picking routing and storage is fine-tuned, which reduces de throughput time and improves the throughput.

To optimize the dedicated storage strategy for single commands (pick), the SKUs need to be stored most conveniently for the picker. We consider three policies for the allocation of SKUs. The first option is allocation by the highest number of trips per storage location. An alternative option is by setting the lowest cube-per-order index (COI), or allocation by the highest pick density (Heskett 1963).

To optimize the dedicated storage strategy for multi commands (picks). Two methods will generate sub-optimal solutions. The first policy is family grouping, where SKUs are clustered, which frequently appear in the same order (Frazelle and Sharp 1989) (Brynzer and Johansson 1996). The second policy is Order Oriented Slotting (OOS), in which we allocate the SKUs of a set of the order in such a way, that the total travel distance is minimized, given a specific routing strategy (Mantel, Schuur, and Heragu 2007).

3.5.3 Class-based storage

Next to the strategies that solely use random or dedicated storage, there is a hybrid option, in which we can combine these policies. With class-based storage, they group the SKUs into classes based on their popularity via the Pareto method (de Koster et al. 2007). They assign each class to a dedicated storage area, where they assigned randomly the SKUs to a specific location. Other policies that can be used as 'assign policy' are COI and OOS, which were explained in the previous sub-section.

As mentioned before, they commonly use these three storage strategies for reserve bulk areas. However, some concepts could be applied in the forward pick areas. The key difference between these areas is the travel distance of the picker, which is a less important factor in the latter area. Class-based storage concepts can even be used for parts-to-picker systems, which are introduced in the next section.

3.6 Picking systems

In this section, we describe the process of (order) picking and the picking systems primarily intended for the forward picking areas in warehouses. (Order) picking is the clustering and scheduling of customer orders and the assignment of the stock on location to the order lines. Other ventures are the release of orders to the floor, picking the SKUs from storage locations, and the disposal of these SKUs (de Koster et al. 2007).

We store SKUs in different quantities, hence in different unit loads, such as box pallets or carton boxes. Because of this, SKUs are stored and picked at different locations inside the warehouse and different order-picking systems are used. We can dissect these systems into two types, picker-to-parts systems, and parts-to-parts systems. With the first-mentioned system, the order picker travels to the aisles to pick the SKUs (de Koster 2004). The parts-to-parts systems use automation to move the SKUs from the storage location to the pickers.

3.6.1 Picker-to-parts systems

We can subdivide the picker-to-parts systems into two types, low-level and high-level order-picking systems. At low-level picking, the pickers can grab the SKUs from shelf racks or bins. At high-level picking, other high storage racks are used. The low-level type is very common and used in 80% of all the order-picking systems in Western Europe(de Koster et al. 2007). Various case studies have shown that travel ingests a lot of time of the order-pickers, which can be seen in Figure 12 (de Koster, Roodbergen, and Van Voorden 1999) (Dekker et al. 2004). Also, the travel time is considered a waste, because it does not add any value, so the urge to improve this is great (Bartholdi and Hankman 2019).

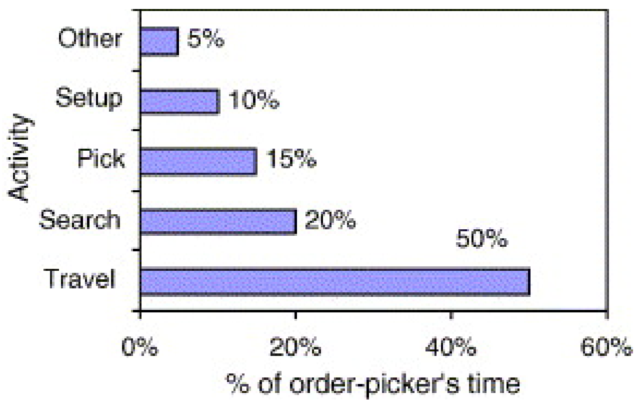


Figure 11: Typical distribution of an order picker's time (Riedel 2011)

3.6.2 Parts-to-picker systems

Parts-to pickers systems are more expensive than picker-to parts systems in terms of design, construction, and maintenance. However, the picker spent less time traveling through the warehouse increasing the picking utilization. A lot of benefits can be obtained with the use of a parts-to-picker system, such as the reduction of the system's footprint, ergonomic workstations, product security (Richards 2014). There are a lot of automated systems such as mini loaders, carousels, and VLMs. However, we only discuss the VLM will because of its relevance to this thesis. A VLM is an enclosed storage system, which comprises two columns with trays, which can hold loose items, bins, or cartons. We present an example of a VLM in Figure 13. At an ergonomic-friendly height at the front, each tray is extractable via a device, which locates the correct tray and retrieves it (Richards 2014).

Figure 12: Example of a VLM (Richards 2014).

3.7 Picking strategies

In this section, we discuss the picking strategies which are used for picking systems in warehouses. We can execute the picking of SKUs from the warehouse storage locations via different strategies. We evaluate four policies on how to group orders during picking tours

The first strategy is *strict order picking*, which is also known as *order picking*. The picker travels down a route, grabbing all the SKUs from a single order. With *batch picking*, the employee combines multiple orders in a single picking tour. With *batch zone picking*, revolves around picking in your zone, so every picker stays in its zone and picks the SKUs, then the order goes to the next zone until the order is finished. The last strategy is *wave picking* in which the picker picks non-stop until the wave is over. They base the duration of the wave on time, not on the number of orders. The next wave starts when the first wave is finished, creating a non-stop process (Petersen 1997)(Richards 2014).

3.8 Conclusion

In this section, we summarize Chapter 3 and draw conclusions based on the literature study. We answer the following research question in this section:

“Which methods are available in the literature for storage and picking in warehouses?”

We can divide the flow of goods/material in warehouses into (basic) six processes, receiving, transfer and put away, order picking/selection, accumulation/sortation, cross-docking, and shipping. In the case of a (manufacturing) company, additional processes/operations are usually included in the flow of material.

The layout style of a warehouse is important to execute operations effectively. The layout style focuses on the position of transforming resources relative to each other, the allocation of tasks to these resources, and the appearance of the resources. We can distinguish four basic layout styles for operations, fixed-position, functional (process), cell, and line (product) layout. We can couple each style to multiple manufacturing process types, for example, a cell layout to a job shop.

A functional layout style provides a high mix and product flexibility, relative robustness in the case of disruption, and relatively easy supervision of transforming resources. During the design phase of a functional layout, the primary goal is to offer the best ‘efficiency’ in the area. We can accomplish this by minimizing the total material movement and additionally minimizing the movement of workers and information between the process area(Bennett 2018).

We can divide layout methodologies into two subjects, the facility layout design, and the internal layout design. In the case of the first-mentioned subject, the goal is to minimize the handling costs. The flow in a functional layout is complex, mainly because of the very large number of different options. Because of the combinatorial complexity, it is hard to achieve an optimal solution in practice. So we can use (computer) heuristic procedures to find reasonably ‘good’ solutions. The latter subject relates to the design of picking/storage operations in the warehouse. The picking processes account for approximately 60% of all operational costs in a typical warehouse. Several parameters, such as the total length of the aisle, the number of picks per tour, and the shape of the aisles, influence these costs.

During the warehouse design phase, we must decide in which type of storage system, the storing and picking activities to take place for the reserve bulk area, while considering our available resources. In this area, we primarily use storage pallets, because of the storage density requirement. We can assign SKUs via different strategies in these storage systems, well-known strategies are random, dedicated, and class-based storage. We can use most of the storage concepts in other areas, for example, the forward pick area. The key difference between these areas is the travel distance of the picker, which is a less important factor in these areas.

In the case of the picking and storing activities in the forward picking area, we can dissect the systems into two categories. The first category is the picker-to-parts systems, hereby the pickers travel to the storage location of the SKU. We can subdivide the picker-to-parts systems into two types, low-level and high-level order-picking systems. At low-level picking, the pickers can grab the SKUs from shelf racks or bins. At high-level picking, they used other high storage racks which require auxiliary equipment, such as forklifts or pallet jacks. In the latter category, parts-to-picker system, the SKU travels/moves to the picker via automation. Four strategies exist to pick the SKUs in this area, strict order, batch picking, batch zone, and wave picking.

4. Data analysis

In this chapter, we analyze the processes in the assembly department using the context and literature study as input. We map out the inefficient processes (picking, storing, and assembly) in the assembly department via the context study and analyzing the data. In this chapter, we answer the following research question:

"What are the inefficient operations that disturb the flow of material in the assembly department?"

In section 4.1, we give an introduction to the inefficient processes in the assembly department. We describe the inefficient picking, storage, and assembly operations in section 4.2, 4.3, and 4.4, respectively.

4.1 Introduction

We exhibit the inefficient processes in the assembly department, with a two-step plan. First, we define the bottlenecks in the processes, after that I measure the performance of those processes with KPIs. The KPIs express the performance in a quantifiable measure over a period. Company X tracks suitable KPIs via their ERP system unfortunately, some KPIs do not relate to the problem at hand. So, we create new KPIs for those bottlenecks.

Bottleneck 1: *The put-away process is not efficient.* Company X stores consumables (i.e. screws and bolts) inside picking systems, such as mobile carts and warehouse cabinets, which are present in the assembly department. Replenishment of these systems is an important part of the picking process, to ensure that the correct pieces are present for the assembly operations, to meet the customer demand. Currently, the employees store a significant number of articles on (box) pallets on the floor of the assembly department, because of the lack of storage possibilities in the picking systems. The storage of articles on (box) pallets reduces the area to perform activities in the assembly department, which limited the overall assembly capacity of the department.

Bottleneck 2: *The storage strategy of the reserve bulk area is not efficient.* Company X stores the larger articles and the bulk reserve articles inside pallet racks which are located within the assembly and expedition area, which is the main warehouse. Here, they use a random storage concept for several production departments. This means that the logistic employees who handle the goods, decide where to allocate the article in the storage location. The employees try to store articles intended for the assembly department close to the I/O-point. Unfortunately, because of a lack of possibilities at the favored aisles, the articles are being stored in storage locations further away. This results in longer travel distances and so in travel times.

Bottleneck 3: *The assembly process of large series repeat orders is not efficient.* Company X creates products for various customers if a customer orders the same product again. They call this a repeat order, which is often a smaller series. However, some of these orders comprise larger series (with multiple due dates), so not all products have to be delivered simultaneously. For the large series, Company X performs edits in the production departments in the largest series possible to minimize the costs and production time. However, in the assembly department, which is the final production department, they shorten the series because of work capacity limitations. By doing so, the order has to be set up for each batch. To reduce the overall set-up time of the order, they pick once the required items and store them on box pallets in the assembly department. By doing so, they occupy the limited floor space, which results in insufficient space to perform other operations.

4.2 Inefficient picking operations

4.2.1 Bottleneck 1: The put-away process is not efficient

In section 4.1, we briefly announced the bottleneck in picking operations of the assembly department at Company X. In this sub-section, we describe the bottleneck extensively and support my claim with the help of KPIs.

Company X disposes of a variety of picking systems inside the assembly department, such as mobile carts, warehouse cabinets, and shelf racks (with bins). In Appendix B, we present the picking systems of the assembly department with photographs. The mobile carts and warehouse cabinets are primarily suitable for smaller articles, inside the (shelf) racks Company X mainly keeps boxes and large articles. Replenishment of these systems is an important part of the picking process, to ensure that the correct pieces are present for the assembly operations, to meet the customer demand.

Company X replenishes two types of articles, purchase articles that arrive from outside suppliers, and production articles originating from other (production) departments. Company X sets a ‘standard storage location’ for these articles, to ensure that they supplement the article at the correct location. They label each storage location with a ‘W… number’ that species the (production) department. Company X complements the location with information about the specific area or appointed picking/storage system. For example, ‘W100 – MK7–R’ embodies the right-hand side of ‘Mobile Cart 7’ which stands in the assembly department. The picking systems within the assembly department also function as a storage system.

The storage location of purchase articles is often a warehouse cabinet or a mobile cart, close to the workstation where the employee consumes the article. They primarily store production articles (for the assembly department) in the expedition department because of their size and needful. Production articles are often composite parts that occupy more space. In addition, the assembly employees frequently do not immediately require the articles (for an order), so it is not convenient to store them within the department because of the limited available floor space.

It required cooperation from multiple departments to replenish the articles successfully. The employees of the expedition department place articles at the I/O-point, after delivery from an outside supplier or on request (with production articles). The I/O-point, which is also known as the drop-in area, is depicted in Figure 13. From the drop-in, one assembly employee will distribute and replenish all the articles to the picking system/area or deliver it to the assembly location (if necessary). We present a visual representation of the process via a Swimlane flowchart in Appendix F. By drawing this chart, the opportunity for improvement becomes more obvious.

Figure 13: Drop-in Assembly Department

Unfortunately, this put-away process does not show the preferred result in terms of efficiency. In the current situation, they store a significant number of articles on (box) pallets inside the assembly department, which is shown in Figure 14. The storage of articles on (box) pallets reduces the area to perform activities in the assembly department, which limited the overall assembly capacity of the department.

Figure 14: Storage articles in (box) pallets inside the assembly department

A few causes underlie this problem, firstly the assembly employees do not adequately replenish articles into the picking systems after the delivery at the drop-in. Currently, Company X does not have a replenishment system in place, which yields the specified actions: Employees replenish after the depletion of the complete stock in the picking system, leaving the articles on the box (pallet) or on top of the picking system. Sometimes they pick from boxes/ (box) pallets in a Last In First Out (LIFO) manner, leaving the 'old' stock. By replenishing in this manner, they occupy floor space unnecessarily. In Figure 15, we depict the current situation at the mobile carts, which are used for picking consumables.

Figure 15: Current situation mobile cart (picking system)

The second cause of the limited assembly capacity is that Company X has not directly assigned a significant amount of articles to a picking system or area, causing them to remain in boxes/ (box) pallets around the department. This often happens to relative 'new' articles, because the employees poorly execute the follow-up procedure in place.

Via the procedure, the project engineers assign a 'general' storage location to a new article because they have inadequate knowledge about their specifications regarding size and the use inside the department. The project engineers often choose one of these options as a 'general' storage location. The first option is to select 'W-100', the assembly department. With the second option, they assign an article to a dedicated area, where they assemble products of a certain manufacturer. Company X has not furnished dedicated areas for all manufacturers in the assembly department.

With the first option, the article will roam through the department on a (box) pallet until the assembly operation starts and the article is required. Along with the second option, the employees will place the article in the direct vicinity of the assembly location on a box (pallets) or in an unlabeled shelf rack. With both options, they reduce the floor space of the department and increase the picking time of an employee. Because an employee has to search for an article in an unlabeled shelf rack, (box) pallet, or a box within the area.

Normally, after receiving the article in the department, the team leader should alter the storage location to a picking system that suits the article. Unfortunately, the last part of the procedure is often overlooked. This leads to a congestion of floor space, which results in a reduction of assembly capacity. To measure the performance over time, we introduce two KPIs to measure the bottleneck of the picking operations. The first KPI of the examined bottleneck is the number of 'general' assigned articles. Currently, Company X assigned 8% of the articles inside the assembly department to a dedicated area, and 31% of the articles are assigned to the department, with no specification.

The third cause of the limited assembly capacity is that Company X keeps 'inactive' articles in their picking systems. Company X uses mobile carts to store consumables for specific manufacturers and accompanying products, and warehouse cabinets for general consumables. They produce and buy certain consumables on stock to decrease the lead time of repeat orders. It may be possible the employees do not use certain articles anymore, after 3 years it is considered inactive.

Company X keeps these articles in the warehouse cabinets and mobile carts in the same storage location. By using this policy, they withhold potential storage locations for 'old' articles to increase their capacity. Also, it hinders the possibility for new articles to be stored in the picking system. By creating new storage locations, the roaming of boxes with stock will decrease inside the assembly department, which they now store on (box) pallets, and on top of mobile carts. The second KPI of the examined bottleneck is the number of 'inactive' articles inside the picking systems, which I present in Table 3.

In Appendix G, We present an overview of the potential causes in a fishbone diagram that yield the above-mentioned problem statement. We divided these causes into six groups: Manufacturing, Method, Material, Man, Measurement, and Mother Nature. In the next chapter, we suggest improvements and control measures according to the Define Measure Analyze Improvement Control (DMAIC) improvement cycle, which is a proven method within Lean Six Sigma (Theisens 2016).

Mobile Cart (MK) / Warehouse Cabinet (WC)	Location	Main Manufacturer	Number of Inactive Articles	Fraction of Inactive Articles	Total Number of Articles
MK1-L (MK)	W100	Client A	0	0%	25
MK1-R (MK)	W100	Client A	0	0%	67
MK2-L (MK) *	W100	Client A	6	86%	7
MK2-R (MK) *	W100	Client A	5	71%	7
MK3-L (MK) **	W100	Client H	0	0%	3
MK3-R (MK) **	W100	Client H	0	0%	3
MK4-L (MK)	W100	Client G	1	5%	21
MK4-R (MK)	W100	Client G	2	11%	19
MK5-L (MK)	W100	Client A	1	2%	54
MK5-R (MK)	W100	Client A	2	5%	40
MK6-L (MK)	W100	Client A	2	4%	48
MK6-R (MK)	W100	Client A	6	10%	58
MK7-L (MK)	W100	Client I	24	38%	63
MK7-R (MK)	W100	Client I	10	22%	45
MK8-L (MK)	W100	Client E, Client F	8	32%	25
MK8-R (MK)	W100	Client E, Client F	4	100%	4
MK9-L (MK)	W100	Client A	4	6%	63
MK9-R (MK)	W100	Client A	5	9%	56
MK10-L (MK)	W100	Client A	2	5%	39
MK10-R (MK)	W100	Client A	4	10%	41
MK11-L (MK)	W100	Client J	16	40%	40
MK11-R (MK)	W100	Client J	8	40%	20
MK12-L (MK)	W100	Client A	16	30%	54
MK12-R (MK)	W100	Client A	4	11%	36
Average			**130**	**16%**	**838**
WC-1 (WC)	W100	Various	23	17%	133
WC-2 (WC)	W100	Various	18	8%	229
Average			**41**	**11%**	**362**
* Currently rebuilding ** Currently out-of-service					

Table 3: Number of inactive articles in the picking system

4.3 Inefficient storage operations

4.3.1 Bottleneck 2: The storage strategy of the reserve bulk area is not efficient

In section 4.1, We introduced the bottleneck present in the storage operations of the assembly department at Company X. In this sub-section, we describe the bottleneck extensively and support my claim with the help of KPIs.

Company X has two separate storage areas in place for the assembly department, one within the department and one in the expedition area. The section inside the assembly department functions as a forward pick area for mostly smaller articles. The underlying thought is to minimize the travel distance between the storage facilities and the workstations (which are located inside the assembly department).

In the expedition area, which is also referred to as the reserve bulk area, Company X stores articles and products for the (production) departments and clients. In the case of the assembly department, they store three types of articles in this area, purchase articles, inbound, and outbound production articles. The first-mentioned type comprises articles purchased from other suppliers, and the inbound production articles are parts that are sourced from other production areas within Company X, which still need to be processed in the assembly department. The outbound production articles are products that have gone through all the edits and are ready for the customer.

In the reserve bulk area, Company X predominantly uses pallet racks to store the articles on (box) pallets. Company X makes use of a random storage strategy within the expedition area, so the employees randomly place (box) pallets at an eligible storage location. However, the management of Company X urges the employees to place the article close to the targeted destination. For example, they primarily placed articles designated for the assembly department in the aisle AA and AB, close to its I/O-point to reduce the travel distance. We present a layout of the reserve bulk area in Figure 16 to clarify the situation. We show an enlarged layout is presented in Appendix H.

Figure 16: Bulk Reserve Area (Expedition Area)

Unfortunately, the proposed storage strategy yields long travel distances for the pickers, which has multiple reasons. In the first place, the dedicated aisles for the assembly department experience a high storage utilization rate. Company X uses close to 70% of storage possibilities in these aisles on average. It is not viable to provide a fixed number because of the constant fluctuation of goods.

Currently, there is still some free storage location in pallet racks. However, the employees would like to store and pick the articles at a height that is reachable with a jack pallet. As a result, they do not need help from the logistic employees (with a forklift). They have largely taken these storage locations at the preferred height with other articles with no relation to the assembly department. The other available storage locations are primarily located close to the I/O-point. These storage locations are usually not accessible because of (box) pallets in front of the pallet racks.

In Figure 17, we present a layout of the expedition area, with all the articles that originate or are destined for the assembly department. We use different colors to depict the articles types in the storage location, also distinguishing between articles with and without a relation to the assembly department. We depicted articles destined for other departments with a purple colour, articles intended and originated for the assembly with a green/red or yellow colour, respectively.

The employees can pick articles from positions marked in blue. What sticks out is the distribution of articles with a green or red colour over the aisles, which would cluster preferably around the aisles AA and AB. Unfortunately, this is not the case, and it results in longer travel distances than necessary. We present the enlarged layout of the expedition area in Appendix I.

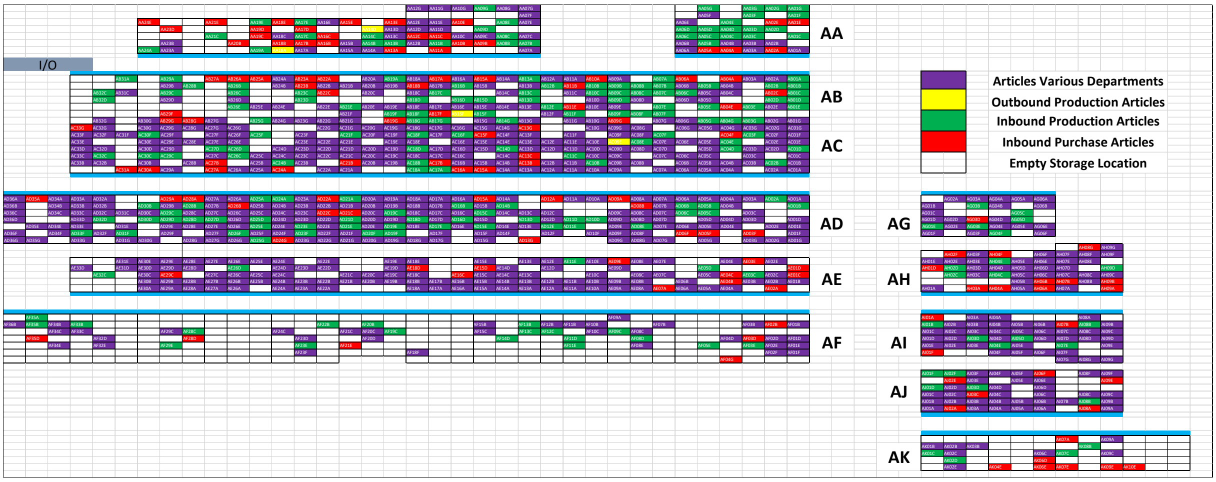


Figure 17: Layout Expedition Area categorized on article type

The second reason is that Company X keeps ‘old’ articles in dedicated storage aisles, and not moved to a storage location further away from the I/O-point after a large period of inactivity. Company X produces and buys certain articles on stock to decrease the lead time of repeat orders. It may be possible that clients do not order certain products (for a while), or are no longer used/sold anymore. Company X keeps these articles in the same storage location for that period. After approximately three years of inactivity, project engineers and team leaders review the usefulness of these articles.

Unfortunately, Company X does not have an automatic system to check the latest mutation date of these articles, so a lot of items slip through the mesh. In Figure 18, we present a layout of the expedition area with all the articles that originated or are destined for the assembly department and their corresponding mutation date. From the figure, it is noticeable that articles with a mutation date of over 1 year (and are less likely used in the short term) are very present in the aisles AA and AB. This results in longer travel distances for articles that are more likely to be used in the short term in the assembly department. We present the enlarged layout of the expedition area in Appendix J.

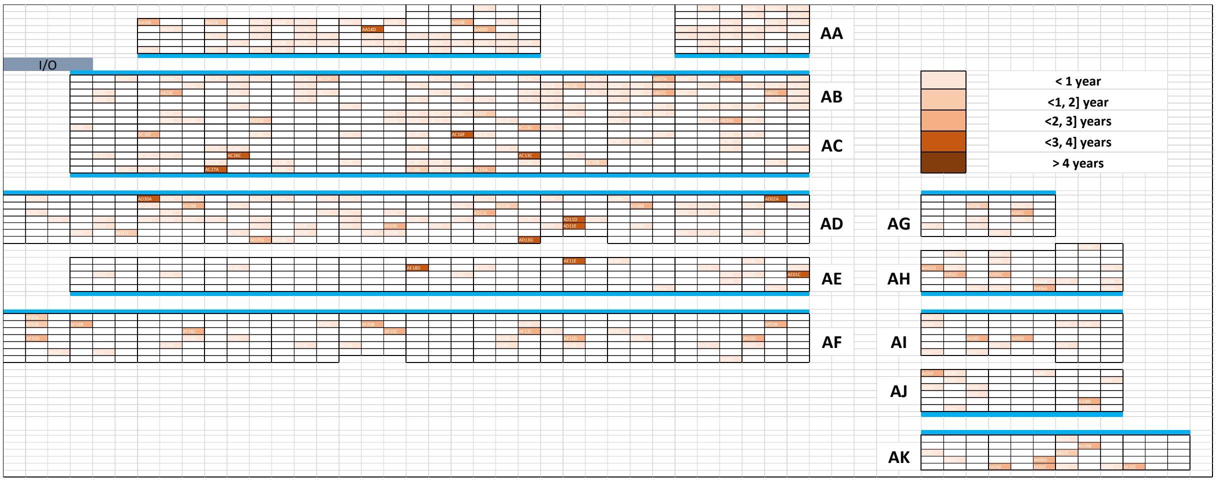


Figure 18: Layout Expedition Area categorized on mutation date

To measure the performance over time, we introduce one KPI to measure the bottleneck of the storage operations. The KPI of the examined bottleneck is travel distance, showing the distance between all the inbound articles in the expedition area and the I/O-point of the assembly department, which is picked (per one) by the logistic employees.

It is not feasible to monitor the articles for every (production) department at Company X, because of the time window of this thesis. So, we solely focus on the storage of inbound and outbound articles for the assembly department. The travel distance between all the inbound articles in the expedition area and the I/O-point of the assembly department is 8148.35 m and 12409.50 m for the inbound purchase articles and inbound production articles, respectively. In Figure 19, we present a histogram with the travel distance per type of articles per type.

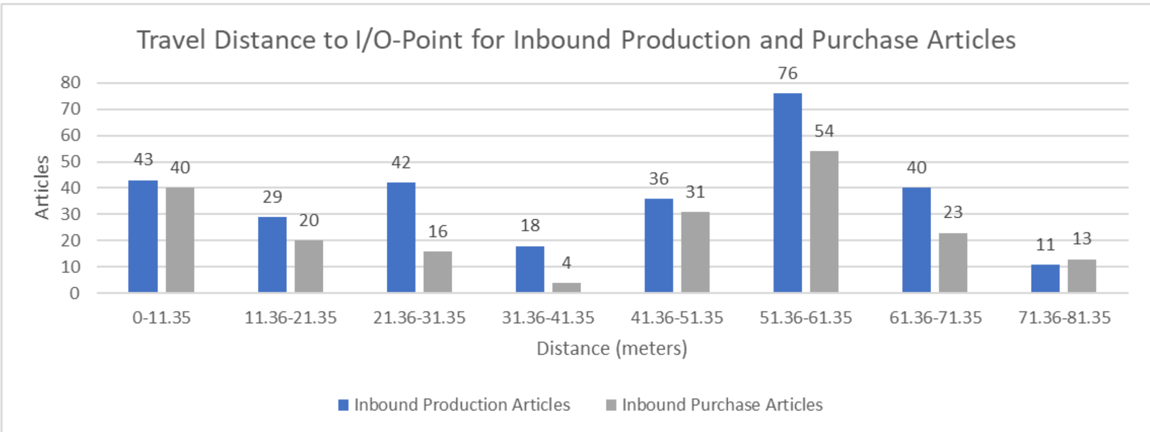


Figure 19: Travel Distance to I/O-Point for Inbound Production and Purchase Articles

4.4 Inefficient assembly operations

4.4.1 Bottleneck 3: The assembly process of large series repeat orders is not efficient

In section 4.1, we introduced the bottleneck present in the assembly operations of Company X. In this sub-section, we describe the bottleneck extensively and support my claim with the help of KPIs.

Company X assembles a few large series repeat orders regularly. For these products, they have arranged dedicated areas in which the required resources (such as specific consumables) for that customer/product are present. The employees can also assemble the different products in these areas, however, adjustments may need to be made to the resources present.

The ERP system schedules orders in such a manner, so that it keeps the WIP inventory at a low level, by creating large series. However, with large series (that have multiple due dates), a dilemma occurs because not all products have to be delivered simultaneously. The first option is to produce all the products at once (before the due date of the first batch) which reduces the capacity to produce other products in that space of time. Besides the above-mentioned disadvantage, these finished goods need to be stored somewhere in the warehouse until delivery.

The second option is to divide the series into batches, which are currently done in the assembly department. Shortening the series results in an increase in the completion time of the entire order, because of the multiple set-ups instead of once. For each batch, the required items need to be picked by a (logistic) employee, and the assembly table and tools need to be prepared. After the completion of a batch, all the items, except consumables, need to be stored in the pallet racks, which are primarily available in the expedition department.

Company X does not want to execute the above-mentioned actions for each batch, so they currently store most of the items temporarily on box pallets. They normally place these box pallets inside pallet racks but are now placed on an undercarriage or on the floor. One cause underlies this reasoning: the lack of vertical storage possibilities for these pallets within the department and the associated ease for the employees (less travel distance).

The assembly department has disposal over two pallet racks, one within the assembly department, and one in the expedition area. The storage system in the assembly department does not have sufficient capacity to store all the items for the products. The employees of the assembly department can use the pallet racks in the expedition area however, this yields a large travel distance or help from the logistics employees. The chosen assembly strategy results in insufficient floor space to execute other operations in the assembly department because of ingested areas, which limits the overall (production) capacity of Company X.

Unfortunately, it is not possible to investigate all dedicated areas in the assembly department within the timeframe of this thesis. Instead, the performance of a single area is evaluated in which the DD Cabinet (DDC) is assembled. The DDC is a product, of which Company X produces approximately 4 pieces per month. The product has a dedicated area of 75 square meters where its resources, such as assembly tools, workstations, and a mobile cart are located. We provide a layout of the dedicated area in Figure 20.

Figure 20: Dedicated Area DDC

To measure the performance over time, we introduce two KPIs to measure the bottleneck of the assembly operations. The first KPI of the examined bottleneck is storage space utilization. Storage space utilization represents the amount of floor space that is taken by storage systems within the dedicated area.

For each order, the employees pick items with the help of an article list for that specific order, which will be placed in the dedicated area. The employee use box pallets to ‘temporarily’ store these (larger) items originated from other production departments. They then place these pallets on undercarriages to work on an ergonomic height. Smaller items, mostly consumables, are stored and replenished in the mobile cart. They can move these carts to other areas within the assembly department. They keep other purchase items within the original boxes in the dedicated area. Image of these picking/storage systems can be found in Appendix B. We give the required items for the product order and associated dimensions in Table 4. These dimensions result in a storage space utilization for the DDC dedicated area of 14.9/75 = 19.86 %

Article Number	**Description**	**Location within the assembly department**	**Quantity (pieces)**	**Floor space (m^2)**
-	Consumables	Mobile Cart	1	0.50
259009	MC Basic Main Cabinet, door	Pallet Undercarriage	1	1.20
248523	Weld Assembly Underbase (C)	Pallet Undercarriage	1	1.20
251931	Right Door Weld Assy (C)	Pallet Undercarriage	1	1.20
251932	Left Door Weld Assy (C)	Pallet Undercarriage	1	1.20
256590	Welddassy Curved Sidepanel (C)	Pallet Undercarriage	1	1.20
251959	Merford 13m front door	Boxes	1	
251960	Merford curved panel short	Boxes	1	2.40
251961	Merford coverd panel long	Boxes	1	
256591	Weldassy Curved Sidep.Mir (C)	Pallet Undercarriage	1	1.20
256592	MC Side Struct. Beam Mirro (C)	Pallet Undercarriage	1	1.20
256589	MC Side Struct. Beam Weld (C)	Pallet Undercarriage	1	1.20
256588	Constructive Rib Assembly (C)	Pallet Undercarriage	1	1.20
256568	MC Top Base Weld Assembly (C)	Pallet Undercarriage	1	1.20
Total				**14.90**

Table 4: Picking/Storage systems in the dedicated area of the DDC

The second KPI of the examined bottleneck is NACA hours, which are the hours spent per edit in the (production) departments. We examine the hours for five edits, three in the paint shop, and two in the assembly department. We examined the historical data of the DDC for the years 2021 and 2022 for all production series of 4 pieces. We present an overview of the NACA hours in Figure 21.

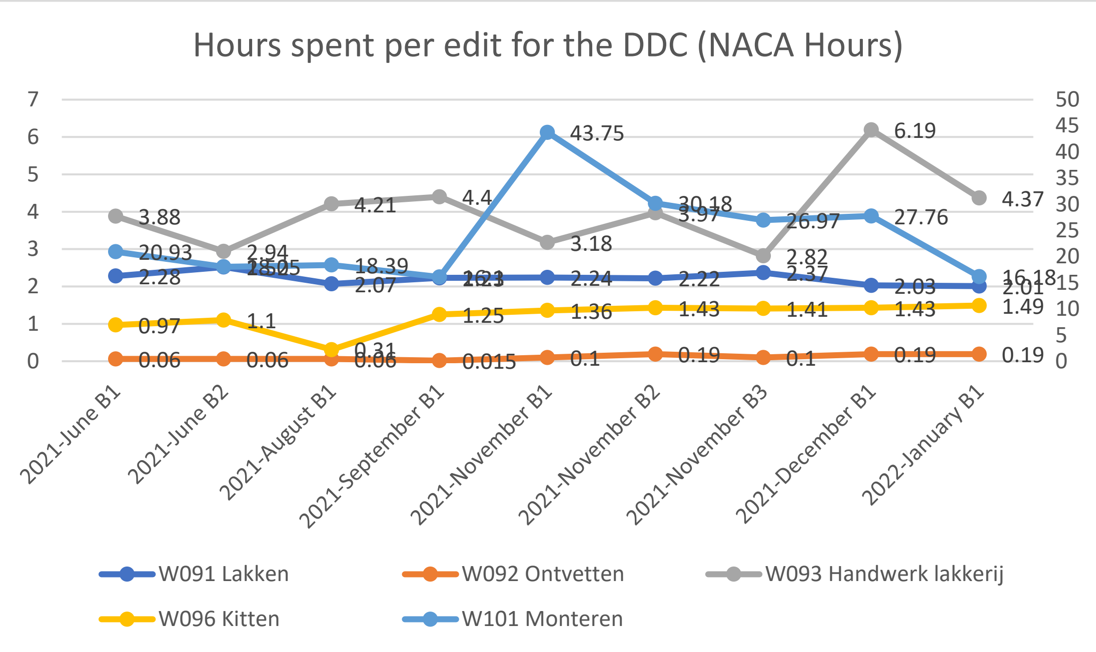


Figure 21: Hours spent per edit for the DDC (NACA Hours)

The hours of the paint shop are tracked because it is the last production department before DDC reaches the assembly department. The average values for the separate edits are given in Table 5.

Production Department	Edit	NACA Hours
Paint Shop	W091 Lakken	2.22
Paint Shop	W092 Ontvetten	0.11
Paint Shop	W093 Handwerk lakkerij	4.00
Assembly Department	W096 Kitten	1.19
Assembly Department	W101 Monteren	24.25

Table 5: Average Hours spent per edit for the DDC (NACA Hours)

4.5 Conclusion

In this section, we summarize Chapter 4 and draw conclusions based on the data analysis. We answer the following research question in this section:

"What are the inefficient operations that disturb the flow of material in the assembly department?"

We discovered three bottlenecks in the current situation of the assembly department, one per operation (picking, storing, and assembly). During the analysis of the picking operations, we discovered that the put-away process is not efficient. While assessing the storing operations, we observed that the storage strategy of the reserve bulk area is not efficient. Also, we revealed that the assembly process of large series repeat orders is not efficient in assembly operations. We present the bottlenecks of the assembly department and the associated KPIs below.

Bottleneck 1: ***The put-away process is not efficient.***

KPI 1 (Percentage)		
Percentage of articles 'general' assigned to a dedicated area in the assembly department	*257*	*8 %*
Percentage of articles 'general' assigned to no specific area in the assembly department	*1008*	*31 %*
Percentage of articles assigned to a specific picking/storage system in the assembly department	*2004*	*61%*
Total	*3269*	*100%*

In the current situation, the employees place 8% of all the articles present in the assembly department in the direct vicinity of the assembly location on a box (pallets) or in an unlabeled shelf rack. 31% of the articles roam through the department on a (box) pallet until the assembly operation starts and the article is required. With both options, they reduce the floor space of the department and increase the picking time of an employee, because an employee has to search for an article in an unlabeled shelf rack, (box) pallet, or a box within the area.

KPI 2 (Percentage)		
Mobile Carts		
Fraction of inactive articles	*130 articles*	*16 %*
Fraction of active articles	*708 articles*	*84 %*
Total	*838 articles*	*100%*
Warehouse Cabinets		
Fraction of inactive articles	*41 articles*	*11 %*
Fraction of active articles	*321 articles*	*89 %*
Total	*362 articles*	*100 %*

Company X keeps 'inactive' articles in their picking systems, such as mobile carts and warehouse cabinets. By using this policy, they withhold potential storage locations for 'old' articles to increase their capacity. Also, it hinders the possibility for new articles to be stored in the picking system. Currently, 16% of the articles are kept in mobile carts, and 11% of the articles kept in warehouse cabinets are inactive.

Bottleneck 2: ***The storage strategy of the reserve bulk area is not efficient.***

KPI 3 (Meter)	
Total travel distance between articles and I/O-point - inbound purchase articles	8148.35
Total travel distance between articles and I/O-point - inbound production articles	12409.50

Company X makes use of a random storage strategy within the expedition area, so the employees randomly place (box) pallets at an eligible storage location. However, the management of Company X urges the employees to place the article in the dedicated aisle close to the I/O-Point. Unfortunately, the dedicated aisles for the assembly department buckled under a high storage utilization rate. Because the employees use the dedicated storage locations also for articles without a relation to the assembly department. Also, Company X keeps 'inactive' articles in dedicated storage aisles, and not moved them to a storage location further away from the I/O-point after a large period of inactivity. This results in longer travel distances for articles that are destined for the assembly department.

Bottleneck 3: ***The assembly process of large series repeat orders is not efficient.***

KPI 4 (Percentage)	
Storage space utilization – Dedicated area DDC	19.86%

During the assembly of large series repeat orders, the employees store the (larger) items originating from other production departments temporarily on box pallets. They normally place these box pallets inside pallet racks but are now placed on an undercarriage or on the floor to save costly production time. This results in a storage space utilization for the DDC dedicated area of 19.86%.

KPI 5 (Hour)	***Production Department***	***Hour***
Average NACA hours – W091	Paint Shop	2.22
Average NACA hours – W092	Paint Shop	0.11
Average NACA hours – W093	Paint Shop	4.00
Average NACA hours – W096	Assembly Department	1.19
Average NACA hours – W101	Assembly Department	24.25

The average associated hours per edit in the production departments of the DDC.

5. Methods

In this chapter, we describe strategies to improve the efficiency of the picking, storing, and assembly operations in the assembly department. We discuss strategies to optimize the VLM to pick and store articles efficiently. In this chapter, we answer the following research question:

"What are possible strategies to create a more efficient flow of materials through the assembly department?"

We give strategies to improve the inefficient picking, storage, and assembly processes in the assembly department in sections 5.1, 5.2, and 5.3, respectively. Section 5.4 describes methods to optimize the VLM to pick and store articles efficiently.

5.1 Picking operations

In section 4.2, we explained the bottleneck in picking operations of the assembly department, which is the inefficient put-away process in the assembly department. In the following sub-section, we describe a strategy to make this process more efficient, with the help of Lean Six Sigma principles (Theisens 2016).

5.1.1 Bottleneck 1: The put-away process is not efficient

The inefficiency within the put-away process is failing to store articles accordingly in the picking systems. In the current situation, the employees store a significant amount of articles on (box) pallets inside the assembly department, which reduces the area to perform activities in the assembly department. To improve the efficiency of this process, we must address these three causes. First, Company X does not have a proper replenishment system in place, also they have a significant amount of articles that are not directly assigned to a picking system or a specialized area, and Company X keeps 'inactive' articles in their picking systems.

A solution for the first cause is to alter the current replenishment policy, which we present in Appendix F. With the current policy, the ERP System automatically puts purchase articles on stock upon arrival at the expedition department, which increases the stock level of these articles at their 'standard location' whether they are present on this location. By aligning the policy for the purchase articles with the production articles, the employees have to transfer the articles physically and virtually (with the ERP system) from one location to another. This allows for better monitoring of the location of an article.

A solution for the second cause is to improve the warehouse management application, so the employees can use it to execute the follow-up procedure (choose a 'standard location' for an article). Currently, the employees can only perform the procedure via a 'stand-alone' computer through the ERP system, which also requires a certain level of expertise. By updating the warehouse management application, we reduce the threshold to execute the procedure in terms of time and expertise. So, employees can execute the procedure faster, with more (different) devices, and less skill is required.

A solution for the third cause is to install a formal procedure to keep track and clean up 'old' articles in the picking systems. Currently, after approximately three years of inactivity, project engineers and team leaders review the usefulness of these articles. Unfortunately, Company X does not have an automatic system to check the latest mutation date of these articles, so a lot of items slip through the mesh. By installing a formal procedure, Company X could track and address these articles more efficiently.

5.2 Storage operations

In section 4.3, we explained the bottleneck in storage operations of the assembly department, which is the storage strategy for production and purchase articles in the reserve bulk area. In the following sub-section, we describe a strategy to make this process more efficient.

5.2.1 Bottleneck 2: The storage strategy of the reserve bulk area is not efficient

The inefficiency within the storage strategy is failing to store the production and purchase articles (which are destined) for the assembly department close to its I/O-Point. The management of Company X introduced an informal rule to place the items destined for the assembly department in the aisles AA and AB, the closest aisles relative to their I/O-point. Unfortunately, the proposed storage strategy does not result in the sought-after efficiency, because of these causes: First, the employees can not place all the products destined for the assembly department in the aisles AA and AB (at the preferred height), production and purchase from, other (production) departments articles occupy these slots. Second, Company X keeps 'inactive' articles in the storage systems, with which they occupy sought-after places.

For the first cause, we suggest implementing a class-based storage concept for the aisles AA and AB, which is a hybrid option between random and dedicated storage. We assign production and purchase articles that are intended for the assembly department to these aisles. In addition, we divide every pallet rack in the aisles into two parts, the lower (bottom to 2nd highest ledge) and upper (1st highest to the highest ledge) part. We randomly assign all the purchase and production articles destined for the assembly department to the lower sections of the aisles. The employees can use the upper section for the storage of articles for various departments however, we prioritize articles with a connection to the assembly department in these slots.

For the second cause, we suggest the same solution as present in section 5.1.1, because the same cause is present in the picking process of the assembly department. So, to install a formal procedure to keep track and clean up 'old' articles in the storage systems. Hence, Company X could track and address these articles more efficiently.

5.3 Assembly operations

In section 4.4, we explained the bottleneck in assembly operations of the assembly department, which is the inefficient assembly of large series repeat orders in the assembly department. In the following sub-section, we describe a strategy to make this process more efficient.

5.3.1 Bottleneck 3: The assembly process of large series repeat orders is not efficient

The inefficiency within the assembly of large series repeat orders is the temporary storage of production articles on box pallets in the assembly department during the production course. Currently, Company X set-ups the order once and stores the larger required production articles for the entire series on box pallets, which are placed on an undercarriage or on the floor, to save costly production time. The chosen assembly strategy results in insufficient floor space to execute other operations in the assembly department because of ingested areas with large production articles. To improve the efficiency of this process, we must address these causes: First, the pallet racks in the assembly department do not have sufficient capacity to store all the production articles on (box) pallets for the rest of the series. Second, the ERP system of Company X schedules orders in such a manner, so that it keeps the WIP inventory at a low level, by creating a large series that need to be split into batches for assembly.

A solution for the first cause is difficult to construct because there is no coupling present between the pallet racks within the assembly department and the ERP system. So, they assigned every article which is stored in these pallets racks to a 'general' storage location or a dedicated area of a manufacturer. This implies that the stock which is and was present in the pallet racks is not traceable via data and therefore impossible to analyze. So, for this bottleneck, we focus on the second cause of the inefficient assembly of large series repeat orders. We believe that splitting the series into multiple batches before the assembly department results in no additional storage operations within the assembly department, addressing both causes at once.

We suggest reducing the number of box pallets with larger production articles required during the assembly of the DDC. In addition, reducing the content per (box) pallet to a minimum quantity, so 1 batch instead of the entire series, eliminating temporary storage in the assembly department. The DDC has 10 individual production articles that go through several edits in different production departments. Looking from an economic perspective, we want to separate the articles from the second last production department, which is the paint shop. Here, the employees paint all the articles and separately wrap and store the (box) pallets in the reserve bulk area.

Currently, they create 10 (box) pallets (for each SKU), because these articles do not arrive consecutively at the paint shop in most cases, these articles required different edits and differences in dimensions. The employees gather articles for the entire series on one (box) pallet, as I depict in Figure 22.

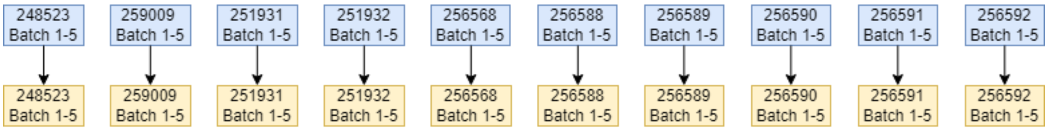


Figure 22: Storage Production articles (DDC) – Current Strategy

By combining the symmetrical production articles in pairs of 2, we reduce the amount of required (box) pallets needed in the assembly department. And by wrapping and storing the quantity for 1 batch per (box) pallet, the employees do not need to store the (box) pallet for the rest of the series within the assembly department. We present the 'new' wrapping and storage schema in Figure 23.

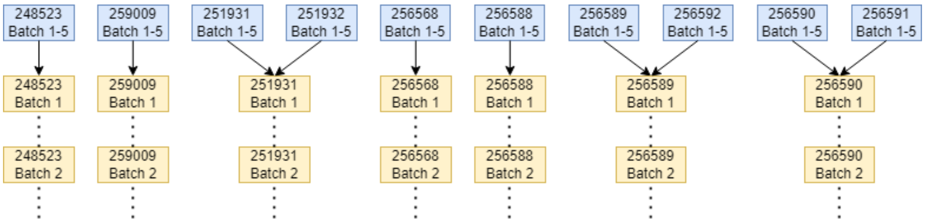


Figure 23: Storage Production articles (DDC) – Suggested Strategy

5.4 VLM

5.4.1 Introduction

Company X bought a VLM, a type of Automated Storage and Retrieval Systems (AS/RS), which is commonly used in warehouses. The VLM has several advantages, such as the usage of less floor space by utilizing the vertical storage of the warehouse more, and an increase in productivity, in contrast to conventional storage systems. With AS/RS, the picker stays in one position and the machine brings the article to the picker, which can save the picking time by 50% (Meller and Klote 2004) (Riedel 2011).

We present an illustration of a single VLM in Figure 24, via this side view, we see the most important hardware of a VLM, such as the trays, and the inserter/extractor system. A VLM comprises trays in the front and back of the machine in storage positions, each tray can store articles. The pick opening is at the front of the VLM, where the picker has direct access to the content of the tray. An inserter/extractor system runs down the center of the VLM, storing and retrieving trays from/to the storage position from/to the pick opening.

In case we want to pick an article, we call a tray via a computer/operator interface, then the inserter/extractor system delivers the tray to the pick opening, so we can gather the articles for our order. After the picking proceedings, the inserter/extractor system retrieves the tray in the pick opening and stores the tray in an empty storage position.

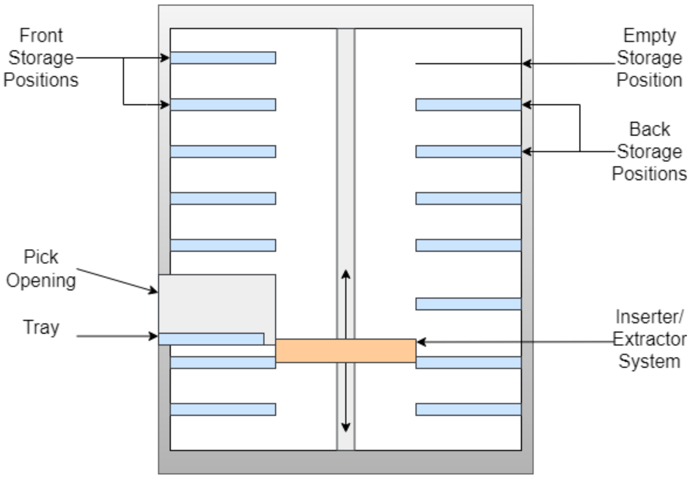


Figure 24: VLM illustration with the most important hardware (side view)

5.4.1.1. Picking Process with a VLM

Order picking is the process of retrieving articles from their storage location (for example, a tray in a VLM) to compile a customer's order. A set of articles represents a (customer) order, each article corresponds to a required amount of pieces for that order. We present the composition of a customer order in Figure 25.

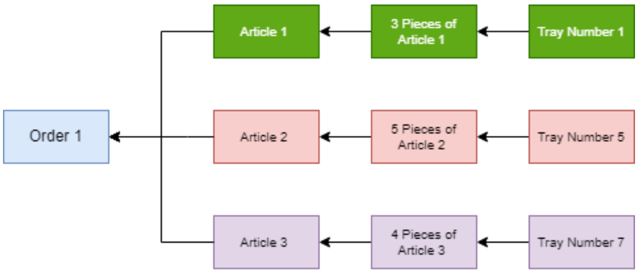


Figure 25: Composition of a Customer Order at Company X

To pick an order with a single VLM unit, we call the first tray that has one or multiple required articles and we pick them from the tray. After the picking, we return the tray to its storage location in the VLM and extract the next tray. We repeat this process until we picked all articles for that order, and finally, we return the last tray to the storage position. So, the completion time to collect the order depends on the picking time for all the articles and the tray retrieval time.

5.4.1.2. Research

(Order) picking operations are very important for warehouse overall performance and represent the majority of operational costs (Tompkins et al. 2010). By picking more orders in a certain amount of time, we achieve a higher (picking) throughput in the warehouse, this is a common objective among warehouse managers (Yu and de Koster 2010).

Company X wants to know how to use the VLM pod (a VLM with multiple units) in the best way possible in alignment with the department processes, which benefits the overall efficiency of the assembly department. The research aim is to minimize the total completion time required to collect a set of customer orders from a VLM pod. The minimization of the total completion time naturally results in a higher (picking) throughput, since we express the throughput as the number of articles picked in a given amount of time.

We discovered that the throughput (and thus the total completion time to collect a set of customer orders) of the VLM is strongly correlated with storage location assignment, and the design of the VLM pod (for example, the number of VLM units) (Meller and Klote 2004) (Mantel et al. 2007).

We can demonstrate the correlation between the storage location assignment and the throughput via an example. The storage location assignment, where we decide which article to place on a tray, plays an important role in the number of tray retrievals for an order. We consider two methods, method A requires us to retrieve 3 different trays from a VLM unit for an order, and the alternative method B needs 5 different trays. Method A requires fewer tray retrievals which results in less waiting time (during the retrieval and storage process), by doing the completion time to collect the order is also less, hereby we achieve higher throughput of the VLM.

Regarding the second factor, the design of a VLM pod. We consider a situation with two VLM units that work together as a pod. Here, the picker can collect items for a given VLM unit while another unit is already extracting the next tray, which results in less waiting time for the picker. This means a reduction of the completion time and an increase in throughput in contrast to the usage of a single VLM unit.

To approach a fitting design for the VLM pod, which yields the minimization of the total completion time required to collect a set of customer orders, we subdivided the research into three parts.

1. We replicate the current situation at Company X for a test subject. So, the use of a single VLM unit with the current storage location assignment for the articles of this test subject. Further, we explain an analytic throughput model to evaluate the completion time for a set of customer orders and the accompanying throughput of the VLM, based on the storage location assignment of the articles from the test subject (Meller and Klote 2004).
2. We extend our research to a situation where we use alternative storage location assignments. To reduce the completion time required to collect a set of customer orders, we need to minimize the objective of the analytic throughput model by varying the positions of the articles in the VLM unit. Unfortunately, this objective is defined complicated, especially in cases with multiple VLM units. So, we use alternative storage location assignments for the articles in the VLM unit, which are strongly correlated with the throughput, to minimize our objective. First, we provide an example of an order picking process with a single VLM, then describe the alternative storage location assignment for the allocation of articles. Finally, we compare these alternative storage locations with the current storage location assignment on their completion time and the accompanying throughput of the VLM unit for a set of customer orders via the analytic throughput model. Thus, we use the throughput model solely to evaluate the completion time for a set of customer orders and the accompanying throughput of the VLM. The completion time decomposes into two mutually independent parts. The first part which represent the expected VLM retrieval time depends on the number of tray retrievals, and the second part which represents the expected picking time depends on the number of picks.
3. We extend our research to a situation where we use multiple VLM units simultaneously. First, we provide an example of an order picking process with multiple VLM units. Also, we explain the adaptation of the OOS method, to distribute the articles over the trays of the VLM units. We compare alternative VLM pod designs (with 1, 2, and 3 VLM units) with the adapted OOS method as their storage location assignment on their completion time and the accompanying throughput of the VLM pod for a set of customer orders via the analytic throughput model.

5.4.2 Current Situation

In this sub-section, we describe the current situation at Company X, the used VLM pod design, and its storage location assignment for articles of the test subject. We also present the analytic throughput model for a single VLM unit with a human order-picker (Meller and Klote 2004), which we use to evaluate the total completion time and throughput of the VLM to collect a set of customer orders.

Currently, the employees of Company X store the consumables in mobile carts and warehouse cabinets, because of frequent usage and their small size. They store the larger articles inside pallet racks in the expedition department because of their size. They place articles that fall in between these categories on (box) pallets inside pallet racks, to avoid the storage on (box) pallets within the department. Unfortunately, the employees do not follow this policy because of the associated effort in terms of travel time to collect these items. Company X wants to place these types of articles in the VLM, to save costly floor space, and increase the productivity in the assembly department. Currently, Company X assigned the first articles that are eligible from shelves with bins to VLM. We use the same shelves in our research, to validate and verify our results.

5.4.2.1. Test Subject Shelf for Client A

For the manufacturer Client A, Company X has four shelves with bins with articles that fall within the category mentioned in the previous paragraph. We present an example of a similar type of shelf in Figure 27. Company X has 197 articles present on these four shelves, which they assigned to trays of VLM.

Figure 26: Example shelf rack with bins (Anon n.d.)

Company X has a VLM pod that consists of two units but they choose to allocate these articles simply at first, by utilizing one VLM unit. They assigned these articles to trays in a quick method (without a train of thought), which we explain below.

Over the years, the employees placed the articles on the shelf in a way that products used together as a 'family' have been 'grouped' together in the same row. So that during (order) picking operations, articles that are likely required together are present close to each other.

They assigned the articles to the tray in the same order as they currently lie on the shelf. Meaning that all the articles from row 1 are assigned to tray 1 of the VLM until they reach the maximum capacity of the tray. The tray capacity is variable by partitioning, however, a fixed capacity of 8 is chosen, so that the capacity of the bin and a single compartment of the tray is equal. Meaning that the same amount of articles fit inside the bin, as in a tray compartment. After allocating every article present in row 1 to the tray(s), they assign the article from row 2 to the first available storage location on a tray and so on. We present the current location assignment used by Company X in Figure 27, to clarify the situation.

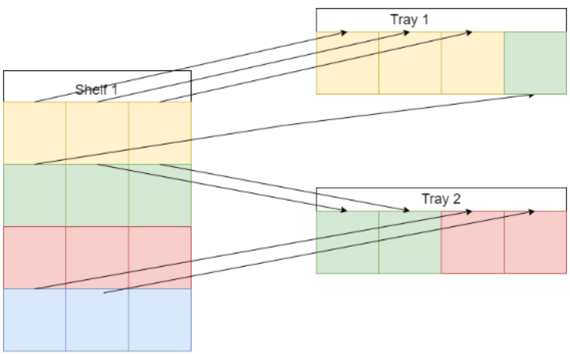


Figure 27: Current Storage Location Assignment Shelves to the Tray of the VLM unit

5.4.2.2. Throughput model

In this sub-section, we present the analytic throughput model for a single VLM unit with a human order-picker (Meller and Klote 2004). We use this model to evaluate the total completion time and the throughput of the VLM to collect a set of customer orders. In this sub-section, we present the parameters and our assumptions and execute a calculation for a test order.

The parameters that we use in this model are all related to the characteristics of the VLM at Company X. First, the height of VLM H represents the total length from the ground level to the top of the VLM. We divide the VLM into three sections, h_1, h_2, and h_3, for the top part, the bottom part, and the pick opening, as illustrated in Figure 28. We assume that, in every section, multiple trays are stored, and the number of trays in each section is proportional to its height. Section h_3 has a typical value of 88 cm, because of the fixed pick opening size on the front side of the VLM, which means that it only contains trays on the back side. Section h_2 has a typical value of 89 cm and contains trays on both sides of the machine. Section h_1 does not have a typical value, but depends on the allowable height of the warehouse. At Company X, this corresponds with a value of 393 cm, this section also contains trays on both sides of the machine.

The second parameter *v* represents the vertical speed of the inserter/extractor system, to move the lift up from the pick opening to Section 1, to store a tray, for example. The associated velocity of this lift is 100 cm/s. The third parameter $t_{a/d}$ is the delay time before the acceleration or deceleration of the lift. So, before the lift moves up or down, it remains idle for 1 *s*. The fourth parameter, $t_{p/d}$ is the time to slide a tray from the lift to the picking opening or storage location and back when the lift is at the desired elevation. We illustrate the parameters in Figure 28.

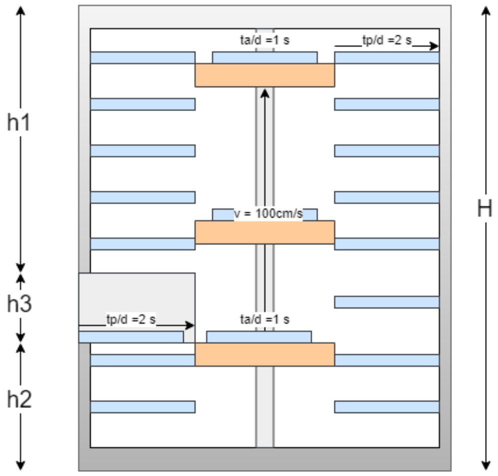


Figure 28: VLM illustration (side view) with the characteristics parameters

Parameters:

$H: height\ of\ the\ VLM = h_1 + h_2 + h_3 = 393 + 89 + 88 = 570\ cm$

$v: velocity\ of\ the\ VLM\ inserter/extractor\ (crane\ ) =\ 100\ cm/s$

$t_{a/d}: delay\ time\ per\ VLM\ trip\ to\ accelerate\ and\ decelerate = 1\ s$

$t_{p/d}: delay\ time\ to\ pickup\ or\ deposit\ a\ tray = 2\ s$

A VLM performs one of these commands, a Single Command (SC) task such as the retrieval or storage of a tray in the VLM, or a Dual Command (DC) task when these two SC are combined in a single operation. In Figure 29, we illustrated the intermediate steps of a DC task. We store a tray by executing operations 1, 2, and 3 consecutively, to retrieve a tray in the VLM, we execute operations 5, 6, and 7, consecutively. By connecting these commands with operation 4, we execute a Dual Command. Hereby, we store the ‘old’ tray (depicted with the blue arrow) and retrieve the next tray (depicted with the red arrow) from the VLM unit, the green arrow connects these commands.

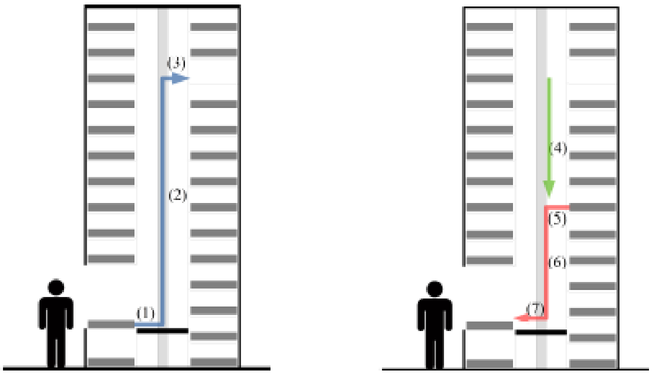


Figure 29: Tasks in a Dual Command VLM Operation

The first step in determining the throughput of the VLM is to calculate the expected travel time for the lift, from the picking opening to a certain section *i*. This situation corresponds with operation 2, displayed in Figure 29. We assume that a tray is randomly stored in the VLM by the computer, which means that the tray has no fixed position, unlike a carousel. During this calculation, we use the average height of a section. For example, the expected travel time for the lift from the pick opening to section h_1, the top part of the VLM is an addition of the height of picking opening h_3, plus the half-height of h_1, divided by the velocity *v* of the crane; $t_{01} = \frac{h_3 + \frac{h_1}{2}}{v} = \frac{88 + \frac{393}{2}}{100} = 2.85\ s$

We can calculate the other expect travel times of the lift from/to the picking opening to/from section *i* as t_{0i}, in a similar manner with; $t_{01} = \frac{h_3 + \frac{h_1}{2}}{v} = 2.85\ s$, $t_{02} = \frac{\frac{h_2}{2}}{v} = 0.45\ s$, $t_{03} = \frac{\frac{h_3}{2}}{v} = 0.44\ s$

In the same way, we can calculate the expected travel time of the lift from/to section *i* to/from section *j*. This situation corresponds with operation 4, displayed in Figure 29. We denote the expected travel time as t_{ij}; $t_{11} = \frac{\frac{h_1}{3}}{v} = 1.31\ s$, $t_{12} = t_{21} = \frac{\frac{h_1}{2} + h_3 + \frac{h_2}{2}}{v} = 3.29\ s$, $t_{22} = \frac{\frac{h_2}{3}}{v} = 0.30\ s$, $t_{13} = t_{31} = \frac{\frac{h_1}{2} + \frac{h_2}{2}}{v} = 2.41\ s$, $t_{23} = t_{32} = \frac{\frac{h_2}{2} + \frac{h_3}{2}}{v} = 0.89\ s$, $t_{33} = \frac{\frac{h_3}{3}}{v} = 0.30\ s$

The accompanying probability that we store a tray in section *i* during an SC task is; $p_1 = \frac{2h_1}{(2H - h_3)} = 74.70\ \%$, $p_2 = \frac{2h_2}{(2H - h_3)} = 16.90\%$, $p_3 = \frac{h_3}{(2H - h_3)} = 8.30\%$

We express the probability that we store a tray in section *i* and retrieve the next tray in section *j* during a DC task by multiplying p_i with p_j, for example; $p_{12} = p_1 * p_2$

Now, we calculate the expected VLM crane travel time for the lift for an SC and DC task, by summing the probability multiplied by the expected travel time with;

$$E[SC] = \sum_{i=1}^{3} 2 t_{0i} p_i = 4.48\ s \tag{1}$$

$$E[DC] = \sum_{i=1}^{3} \sum_{j=1}^{3} (t_{0i} + t_{ij} + t_{0j}) p_i p_j = 6.38\ s \tag{2}$$

Ultimately, we can define the expected VLM crane cycles time, which includes the delay time for the VLM trip acceleration/deceleration and the pickup or deposit of a tray as;

$$T[SC] = E[SC] + 2t_{a/d} + 2t_{p/d} = 10.48\ s \tag{3}$$

$$T[DC] = E[DC] + 3t_{a/d} + 4t_{p/d} = 17.38\ s \tag{4}$$

The equation for expected completion time to pick *n* articles in a VLM with *m* trays decomposes into two mutually independent parts. The first part which represent the expected VLM retrieval time depends on the number of tray retrievals, and the second part which represents the expected picking time depends on the number of picks.

$$E^V[T(n,m)] = E^V[R(m)] + E^V[P(n)] \tag{5}$$

The equation for the expected VLM retrieval time to retrieve trays in a VLM with *m* trays comprises three sections. The first section, is the expected crane cycle for a single command to get the first tray. The second section is based on the number of stops to pick articles in a VLM, in the case of 1 stop, we will not execute any dual commands. The last section is the expected crane cycle for a single command to return the last tray to a storage location within the VLM.

$$E^V[R(m)] = T[SC] + (E[Stops] - 1)T[TDC] + T[SC] \tag{6}$$

We can calculate the expected picking time to pick *n* articles in a VLM, by multiplying the number of articles to pick with the time to pick an article *p* of 5 seconds, which we assume is a deterministic parameter.

$$E^V[P(n)] = np \tag{7}$$

We can calculate the throughput expressed in items/min with the following equation:

$$Throughput = \frac{n}{E^V[T(n,m)]/60} \tag{8}$$

We now consider an example order that requires visiting 4 trays on the VLM and picking 3, 4, 2, and 4 articles on the given trays, respectively. The VLM has 50 *m* trays stored within the unit, and the time to an article *p* is equal to 5 seconds.

For this order, we need to perform a total of 4 tray retrievals or 4 stops. With the first SC, we retrieve the first tray of 4, after this, we need to perform three more tray retrievals with DC, finally, we store the last tray in the VLM. The expected retrieval time for the order is displayed in the equation below.

$$E^V[R(50)] = T[SC] + (E[Stops] - 1)T[TDC] + T[SC] = T[SC] + 3 * T[DC] + T[SC] = 73.10\ s$$

For this order, we pick a total of 13 articles from 4 different trays. The expected picking time for the order is displayed in the equation below.

$$E^V[P(n)] = np = (3 + 4 + 2 + 4) * 5 = 65\ s$$

The expected completion time to pick *n* articles in a VLM with *m* trays is displayed in the equation below. By adding the expected retrieval time with the expected picking time for the order. We present an illustration of the completion time for the example order in Figure 30.

$$E^V[T(n,m)] = E^V[R(m)] + E^V[P(n)] = 73{,}1 + 65 = 138.10\ s$$

Figure 30: Illustration of completion time for the example order

The corresponding throughput of the VLM expressed in items/min is displayed in the equation below.

$$Throughput = \frac{n}{E^V[T(n,m)]/60} = \frac{13}{138{,}1/60} = 5.65\ items/min$$

5.4.3 Experiment with alternative storage location assignment

With the storage location assignment, we decide which article to assign to which tray in the VLM unit. As stated before, the throughput of the VLM is strongly correlated with storage location assignment

(Meller and Klote 2004). To improve the throughput of the VLM, we need to reduce the completion time for picking orders, which is our goal. We investigate the methods COI and OOS as alternative decisions for the storage location assignment and test their influence on the completion time and throughput of VLM for a set of customer orders via experiments.

In this section, we introduce these storage location assignment models and also provide an example of an order picking process with alternative storage location assignments. Concluding we provide the set-up for our experiments to evaluate the performance of these models.

Lastly, we investigate the influence of additional VLM units in a VLM pod on the completion time and throughput of VLM for a set of orders via experiments.

5.4.3.1. Order picking with alternative storage location assignments

In this paragraph, we describe the picking process with a single VLM unit via an example. We consider an example order that requires 8 different articles, article number 1, 3, 4, 5, 7, 8, 9, and 12. We use two different storage location assignments to allocate these articles to the trays of the VLM unit. Method A considers the order composition (of all possible order sets) during the allocation of articles to trays. Method B allocates the articles based on their overall popularity to the trays. We present the allocation of the required articles on the trays of the VLM unit with both storage location assignments in Figure 32; we require the green articles for this order.

Method A requires us to visit 3 trays on the VLM and pick 3, 2, and 3 articles on the given trays, respectively. Method B requires us to visit 5 trays on the VLM and pick 1, 2, 2, 1, and 2 articles on the given trays, respectively.

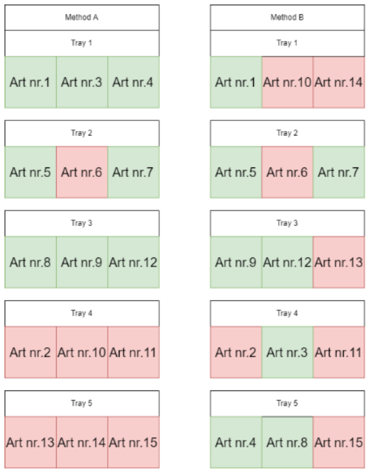


Figure 31: Allocation of the articles to the trays for the example order; Method A (left), Method B (right)

We use the analytic throughput model to evaluate the completion time and throughput of the VLM unit for the example order. Our VLM has 50 *m* trays stored within the unit, and the time to an article *p* is equal to 5 seconds.

The expected tray retrieval time for the order is displayed in the equation below.

$$Method\ A: E^V[R(50)] = T[SC] + (E[Stops] - 1)T[TDC] + T[SC] = T[SC] + 2 * T[DC] + T[SC] = 55.72\ s$$

$$Method\ B: E^V[R(50)] = T[SC] + (E[Stops] - 1)T[TDC] + T[SC] = T[SC] + 4 * T[DC] + T[SC] = 90.48\ s$$

The expected picking time for the order is displayed in the equation below.

$$Method\ A = Method\ B: E^V[P(n)] = np = 8 * 5 = 40\ s$$

The expected completion time to pick *n* articles in a VLM with *50* trays is displayed in the equation below. By adding the expected retrieval time with the expected picking time for the order.

$$Mehod\ A: E^V[T(n,m)] = E^V[R(m)] + E^V[P(n)] = 55.72 + 40 = 95.72\ s$$

$$Method\ B: E^V[T(n,m)] = E^V[R(m)] + E^V[P(n)] = 90.48 + 40 = 130.48\ s$$

The corresponding throughput of the VLM expressed in items/min is displayed in the equation below.

$$Method\ A: Throughput = \frac{n}{E^V[T(n,m)]/60} = \frac{8}{95.72/60} = 5.01\ items/min$$

$$Method\ B: Throughput = \frac{n}{E^V[T(n,m)]/60} = \frac{8}{130.48/60} = 3.68\ items/min$$

We see that the storage location assignment and the throughput of a VLM unit are strongly correlated. The storage location assignment, where we decide which article to place on a tray, plays an important role in the number of tray retrievals for an order. Method A requires fewer tray retrievals which results in less waiting time (during the retrieval and storage process), by doing the completion time to collect the order is also less, hereby we achieve higher throughput of the VLM.

5.4.3.2. Mathematical formulations storage location assignment

In this sub-section, we present the mathematical formulations for the method OOS and COI, which we use to assign the article to the trays. With OOS, we can assign the articles in such a way that the amount of tray retrievals needed to order-pick is minimized, given a certain set of orders (Mantel et al. 2007). Since tray retrieval operations in the VLM take in a large proportion of the expected completion time of an order, we want to minimize the tray retrievals in the VLM unit. The OOS problem is an NP-hard combinatorial optimization problem, but we can solve the problem optimally with a CPLEX solver, because of our small problem size. I present the ILP-formulation of the OOS model below:

Sets:

$i = \ SKU\ number$	$i = 1, 2, 3, \dots, I$
$k = order\ number$	$k = 1, 2, 3, \dots, K$
$p = tray$ number	$\mathrm{p} = 1, 2, 3, \dots, \mathrm{P}$
$O_k = Order\ sets$	$i \in O_k$

Parameters:

$C_p =$ number of storage points in tray p

$multi_k =$ order frequency for order number k

Decision variables

$$Z_{kp} = \begin{cases} 1\ if\ order\ k\ is\ located\ in\ tray\ p \\ 0\ otherwise \end{cases}$$

$$X_{ip} = \begin{cases} 1\ if\ SKU\ i\ is\ located\ in\ tray\ p \\ 0\ otherwise \end{cases}$$

Optimal value function

$$min \sum_{k=1}^{K} multi_k \left(\sum_{k=1}^{K} \sum_{v=1}^{V} Z_{kp} \right) \qquad 9$$

One tray per SKU assignment constraint

$$\sum_{p=1}^{P} X_{ip} = 1 \qquad \forall i \qquad 10$$

Tray Capacity constraint

$$\sum_{i=1}^{I} X_{ip} \leq C_p \qquad \forall p \qquad 11$$

Connect SKU to Order constraint

$$X_{ip} \leq Z_{kp} \qquad \forall, k, i \in O_k \qquad 12$$

Binary constraint

$$X_{ip}, Z_{kp} \in \{0,1\} \qquad \forall i, k, p \qquad 13$$

Next to experimenting with the OOS model, we test one other storage location assignment method called COI, which was proposed by Company X. With the COI index policy, we can allocate optimal SKUs for the single command storage. We order the articles in ascending order, so the lowest score (most popular) is placed at the top of the list. I allocate the articles in the same order of the list to the trays of the VLM unit, so placing the ‘fast-movers’ together to the maximum extent. We calculate the COI score with the equation below, which was first introduced by Heskett (1963).

$$COI = \frac{\#\, required\ storage\ loactions}{\#\, trips\ in\ or\ out\ of\ storage\ per\ period} = \frac{S_j}{T_j} \qquad 14$$

In case, we have 6 articles with a T_j value of 10, 15, 20, 25, 30, and 40, respectively, and a constant S_j value of 1, because Company X stores these articles in a single bin. This results in a COI score of 0.10, 0.07, 0.05, 0.04, 0.03 and 0.03, respectively. Imagine, we choose a tray capacity of three articles, we categorize the last three articles of the list as 'fast-movers', and place these together on the same tray.

5.4.3.3. Experiment storage location assignment

In this sub-section, we describe the setup of our experiments. As mentioned before, Company X furnished four shelves with bins with articles that are used in different combinations in orders, for Client A. We use the 197 articles present in this storage system for our experiments.

Company X has an average of 25 orders per day for Client A, which requires articles from the aforementioned shelf. We derive these 25 orders from a bulk of distinctive 234 order sets. From these order sets, we randomly sample problem instances for our experiments, according to the desired setting. The setting is a set of parameters for the sample. In the following paragraph, we explain these parameters.

First, we create a basic setting to replicate the current situation accordingly. The first parameter presents the number of unique orders that we will use per created problem instance. We choose a value of 25 unique orders because that is the average number of orders per day at Company X. We define the second parameter, tray capacity as the maximum amount of unique articles that could be present on a single tray. This value is constant for every tray in the VLM, we choose a value of 8 for the tray capacity, this allows the same volume for the articles as in the current situation. In addition, we assign every article from the shelf to a single storage location, because of limitations with the ERP system of Company X, which does not allow us to fragment unique articles over multiple trays. The third parameter presents the maximum multiplicity per unique order in a problem instance. We choose a value of 10, which is much in line with the current situation at Company X. For the fourth parameter, the number of VLM units, we choose a value of 1, because they currently use a single VLM unit. In Table 6, we present the basic setting for the experiments.

Setting	The number of (unique) orders	Tray Capacity	Maximum Multiplicity of an order	Number of VLM units
Basic	25	8	10	1

Table 6: Basic Setting for the experiments storage location assignment

In these experiments, we evaluate the performance with the analytic throughput model, using alternative decisions for the storage location assignment for a single VLM unit. During the experiments, we track a few KPIs to measure the performance. For every order, we calculate the number of tray retrievals and the completion time for that order. After picking every order sequentially, which means we do not batch pick, we sum up these values. From this, we get 2 KPIs the total number of tray retrievals and the total completion time for the set of customer orders. We divide the number of articles required for the orders by the total completion time to obtain our 3^{rd} KPI, the throughput of the VLM unit.

We created 7 scenarios (with different settings) for each storage location assignment, hereby creating 21 experiments. Each experiment comprises 10 problem instances, meaning that we replicate each experiment 10 times, with random numbers. We use the same random numbers per scenario to compare the storage location assignments with each other. We start the experiments by using scenario 1, and the current storage location assignment, to allocate the articles. Hereinafter, we compare the results with the alternative methods of COI and OOS, using the same scenario. Then, we investigate how the performance of the VLM is influenced by the following the parameters:

- Number of (unique) orders: [25, 50, 75]
- Tray Capacity: [8, 10, 12]
- Maximum Multiplicity of an order: [10, 5, 30]

- Number of VLM units: [1]

We present an overview of the scenarios in Table 7. Our goal is to minimize the total completion time required to collect a set of customer orders.

Scenario	Storage Location Assignment	Number of (unique) orders	Tray Capacity	Maximum Multiplicity of an order	Number of VLM units
1 (Basic Setting)	Current Situation/COI/OOS	25	8	10	1
2	Current Situation/COI/OOS	50	8	10	1
3	Current Situation/COI/OOS	75	8	10	1
4	Current Situation/COI/OOS	25	10	10	1
5	Current Situation/COI/OOS	25	12	10	1
6	Current Situation/COI/OOS	25	8	5	1
7	Current Situation/COI/OOS	25	8	30	1

Table 7: Overview scenarios for the experiments alternative storage location assignments

5.4.4 Experiment with multiple VLM units

The throughput of the VLM is strongly correlated with the design of the VLM pod, elements such as the number of VLM units we use for picking (Meller and Klote 2004). To improve the throughput of the VLM pod, we need to reduce the completion time for picking orders. First, we provide an example of an order picking process with multiple VLM units, hereinafter we provide an adaptation of the OOS method to distribute the articles over the trays over the given VLM units. Lastly, we investigate the influence of additional VLM units in a VLM pod on the completion time and throughput of VLM for a set of orders via experiments.

5.4.4.1. Order picking with multiple VLM units

In this paragraph, we describe the picking process with a VLM with three units via an example. We rank the VLM unit with the most tray retrievals for an order, as unit 1. We number the other VLM units, in a descending order following their required tray retrievals for that order. Order picking with multiple VLM units happens in rounds, we always start picking at unit 1, and continue picking at the VLM units in ascending order, after which we return to unit 1.

We have an example order that requires visiting 4 trays on the first VLM unit, and picking a single article on each of the trays. We have to visit 3 trays on the second VLM unit picking 2, 1, and 2 articles on the trays, respectively. We have to visit 2 trays on the third VLM unit, picking 2 articles on each of the trays. The results in four rounds of picking proceedings.

With multiple VLM units, the picker can work under ‘masked’ time. The picker can collect items for a given VLM unit while another unit is extracting a tray, which results in less waiting time for the picker. This means that the completion time to collect the order depends on the picking time for all the articles, the walking time between VLM units, and the tray retrieval time, while the picker stands in front of the VLM units.

In the first round of picking proceedings, the VLM pod starts with an SC (*E[SC])* to retrieve all the trays in the pick opening of the VLM units. At VLM unit 1, we pick (*P)* a single article, hereinafter this unit executes a DC, to retrieve the next tray. Meanwhile, we walk (W*)* to VLM unit 2, where we pick (*P)* 2 articles from the tray that already is present, hereinafter this unit executes a DC (*E[DC])*, to retrieve the next tray. Meanwhile, we walk to VLM unit 3, where we pick (*P)* 2 articles from the tray that already is present, hereinafter this unit executes a DC (*E[DC])*, to retrieve the next tray. This results in the expected completion time of: E[SC]+P+W+P+P+W+P+P, which we present in Figure 32.

After we picked 2 articles at VLM unit 3, we walk back to VLM unit 1, where we find the next tray. At this unit, we pick a single article, hereinafter this unit executes a DC, to retrieve the next tray. Meanwhile, we walk to VLM unit 2, where we pick 1 article from the tray that already is present, hereinafter this unit executes a DC, to retrieve the next tray. Meanwhile, we walk to VLM unit 3, where we pick 2 articles from the tray that already is present, hereinafter this unit executes an SC, to store the tray because we do not need to pick more items at this unit. We can call this the second round of picking proceedings. This results in the expected completion time of: W+P+W+P+W+P+P, which we present in Figure 32.

After we picked 2 articles at VLM unit 3, we walk back to VLM unit 1, where we find the next tray. At this unit, we pick a single article, hereinafter this unit executes a DC, to retrieve the next tray. Meanwhile, we walk to VLM unit 2, where we pick 2 articles from the tray that already is present, hereinafter this unit executes an SC, to store the tray because we do not need to pick more items at this unit. We can call this the third round of picking proceedings. This results in the expected completion time of: W+P+W+P+P, which we present in Figure 32.

Now we walk back to VLM unit 1, where we arrive simultaneously when the DC is completed. We pick 1 article, hereinafter this unit executes an SC, to store the tray because we do not need to pick more items at this unit. We can call this the fourth round of picking proceedings. This results in the expected completion time of: W+P+E[SC]. We present an illustration of the completion time for the example order in Figure 32, which we present in Figure 32.

Figure 32: Illustration of completion time for the example order with multiple VLM units

5.4.4.2. Mathematical formulation for multiple VLM units

In this sub-section, we present the mathematical formulations for the adapted OOS method, which we use to assign the article to the trays of a given VLM unit. We cannot use the current storage location assignment and COI to assign the articles to the tray of the given VLM unit, because these methods are not suited, to allocate articles to multiple VLM units.

With the original OOS method, we can assign the articles in such a way that the amount of tray retrievals needed to order-pick is minimized, given a certain set of orders (Mantel et al. 2007). For a single VLM unit, this objective function results in a decrease in the completion time of an order, which comprises two factors. The first factor, the picking time, is composed of the number of articles multiplied by the picking time. The second factor, the tray retrieval time, is composed of the number of trays required multiplied by tray retrieval time. This means that the objective of the OOS method leads to a reduction in order-picking time.

With multiple VLM units, the picker can work under 'masked' time. The picker can collect items for a given VLM unit while another unit is extracting a tray, which results in less waiting time for the picker. To calculate the completion time for this case is much more complex, as we showed in the example order in the previous sub-section. If we use the completion time function as an objective function for our model, it leads to a very complex non-linear model that does not have a closed-form solution (Nicolas, Yannick, and Ramzi 2018).

Nicolas et al. (2018) showed that there is a positive correlation between the completion time and the sum of the number of trays visited by the VLM unit that requires visiting the largest number of trays (VLM unit 1). So, we alter the object function of the OOS method to minimize the sum of the number of trays visited by the VLM unit that requires visiting the largest number of trays (VLM unit 1). This objective allows the picker to work more under 'masked' time, decreasing the time waiting on trays in front of the VLM unit, thus reducing the completion time to pick given a set of orders. We present the adapted OOS model below.

Sets:

$i = \ SKU\ number$ $i = 1, 2, 3, \ldots, I$

$k = order\ number$ $k = 1, 2, 3, \ldots, K$

$p = tray$ number $p = 1, 2, 3, \ldots, P$

$v = VLM$ unit $v = 1, 2, 3, \ldots, V$

$O_k = Order\ sets$ $i \in O_k$

Parameters:

C_{pv} = number of storage points in tray p of VLM unit v

$multi_k$ = order frequency for order number k

Decision variables

$$Z_{kpv} = \begin{cases} 1\ if\ order\ k\ is\ located\ in\ tray\ p\ in\ VLM\ unit\ v \\ 0\ otherwise \end{cases}$$

$$X_{ipv} = \begin{cases} 1\ if\ SKU\ i\ is\ located\ in\ tray\ p\ in\ VLM\ unit\ v \\ 0\ otherwise \end{cases}$$

$$Y_{kp} = \begin{cases} 1\ if\ order\ k\ is\ located\ in\ tray\ p \\ 0\ otherwise \end{cases}$$

Optimal value function

$$min \sum_{k=1}^{K} multi_k \left(\sum_{k=1}^{K} \sum_{p=1}^{P} Y_{kp} \right) \quad (15)$$

One tray per SKU assignment constraint

$$\sum_{v=1}^{V} \sum_{p=1}^{P} X_{ipv} = 1 \qquad \forall i \quad (16)$$

Tray Capacity constraint

$$\sum_{i=1}^{I} X_{ipv} \leq C_{pv} \qquad \forall p, v \quad (17)$$

Connect SKU to Order constraint

$$X_{ipv} \leq Z_{kpv} \qquad \forall p, k, v, i \in O_k \quad (18)$$

Max Order in Tray constraint

$$Y_{kp} \geq Z_{kpv} \qquad \forall p, k, v \quad (19)$$

Binary constraint

$$X_{ipv}, Y_{kp}, Z_{kpv} \in \{0,1\} \qquad \forall i, k, p, v \quad (20)$$

5.4.4.3. Experiments multiple VLM units

In this sub-section, we describe the setup of our experiments. For these experiments, we use the same four shelves with bins with articles that are used in different combinations in orders, for Client A. In addition, we replicate the basic setting for the first scenario as a start case for the other scenarios, which we present in Table 8.

Setting	The number of (unique) orders	Tray Capacity	Maximum Multiplicity of an order	Number of VLM units
Basic	25	8	10	1

Table 8: Basic Setting for the first scenario in the experiments with multiple VLM units

In these experiments, we evaluate the performance with the analytic throughput model, using the adapted OOS method as storage location assignment for single and multiple VLM units. During the experiments, we track a few KPIs to measure the performance. For every order, we calculate the number of tray retrievals and the completion time for that order. After picking every order sequentially, which means we do not batch pick, we sum up these values. From this, we get 2 KPIs, the total number of tray retrievals and the total completion time for the set of customer orders. We divide the number of articles required for the orders by the total completion time to get our 3rd KPI, the throughput of the VLM unit(s).

We created 3 scenarios (with the same settings), each experiment comprises 10 problem instances, meaning that we replicate each experiment 10 times, with random numbers. The first scenario represents the current situation at Company X, with a single VLM unit. Here, the model functions as a regular OOS, because it cannot choose between units to minimize the tray retrievals. In the second and third scenarios, we describe a situation where we use 2 and 3 VLM units simultaneously. We present an overview of the scenarios in Table 9. Our goal is to minimize the total completion time required to collect a set of customer orders.

Scenario	Storage Assignment	Number of (unique) orders	Tray Capacity	Maximum Multiplicity of an order	Number of VLM units
1 (Basic)	Adjusted OOS	25	8	10	1
2	Adjusted OOS	25	8	10	2
2	Adjusted OOS	25	8	10	3

Table 9: Overview scenarios for the verification

5.5 Conclusion

In this section, we summarize Chapter 5 and draw conclusions on which strategies create a more efficient flow of the material through the assembly department. We answer the following research question in this section:

“What are possible strategies to create a more efficient flow of materials through the assembly department?”

Picking Process

We propose the following three solutions to improve the efficiency of the picking process. First, Company X needs to align the policy regarding the stock transfer for the production and purchase articles, which allows for better monitoring of the location of an article. Second, we need to update the warehouse management application to make the ‘standard location’ change easier and more accessible for all employees. Lastly, Company X needs to install a formal procedure to keep track and clean up ‘old’ articles in their picking systems.

Storage Process

We propose the following two solutions to improve the efficiency of the storage process. Company X needs to implement a dedicated storage concept for the aisles AA and AB, which are intended for the assembly department. In these aisles, the employees can store and pick articles for the assembly department to the lower sections, and use the upper section for various departments (including the assembly department). Also, Company X needs to install an automatic system to keep track and clean up ‘old’ articles in their storage systems.

Assembly Process

We propose the following solution to improve the efficiency of the assembly process of large series repeat orders. Company X needs to split the large series into multiple batches in the production department before the assembly department. First, by reducing the amount (box) of pallets (with unique production articles) required during the assembly of the product. Second, by reducing the number of production articles on a box (pallets) to the amount required for a single batch.

VLM

Company X wants to know how to use the VLM in the best way possible in alignment with the department processes, which benefits the overall efficiency of the assembly department. Company X wants to place the articles in the VLM in such a way that we minimize the total completion time required to collect a set of customer orders, thereby increasing the (picking) throughput in the assembly department. The completion time to collect the order depends on the picking time for all the articles, the walking time between VLM units, and the tray retrieval time, while the picker stands in front of the VLM units.

First, we replicate the current situation at Company X, the use of a single VLM unit with their current storage location assignment. We explain an analytic throughput model to evaluate the completion time and throughput of VLM for a set of customer orders (Meller and Klote 2004). Hereinafter, we provide an example of an order picking process with a single VLM unit and alternative storage location assignments. Then, we describe alternative storage location assignments such as COI and OOS for the articles in the VLM and compare these alternatives on the number of tray retrievals, the completion time, and throughput of VLM for a set of customer orders via experiments. Last, we extend our research to a situation where we use multiple VLM units simultaneously. We provide an example of an order picking process with multiple VLM units and explain an adaptation of OOS storage location assignment, to distribute the articles over the trays over the VLM units. We conduct experiments to check the influence of multiple VLM units on the number of tray retrievals, completion time, and throughput of VLM for a set of customer orders.

6. Results

In this chapter, we describe the results of the proposed strategies to improve the efficiency of the picking, storing, and assembly operations in the assembly department. Also, we discuss the results of the proposed methods to pick and store articles in the VLM efficiently. In this chapter, we answer the following research question:

"What is the influence of the chosen strategy on the operations in the assembly department?"

We evaluate the results of the strategies chosen to improve the inefficient picking, storage, and assembly processes in the assembly department in sections 6.1, 6.2, and 6.3, respectively. Section 6.4 describes the results of methods chosen to optimize the VLM to pick and store articles efficiently.

6.1 Picking operations

In section 5.1, we described a strategy to make the inefficient put-away process in the assembly department more efficient, with the help of Lean Six Sigma principles (Theisens 2016). We discuss the result of the proposed strategy in the following sub-section.

6.1.1 Bottleneck 1: The put-away process is not efficient

To improve the causes of the inefficient put-away process, we proposed the following three solutions. For the replenishment policy in the assembly department, we suggested aligning the put-away policy for purchase articles with the production articles. With this new policy, all articles have to be transferred physically and virtually from one location to another. The new policy allows better monitoring of the location and stock of an article by the employees of the assembly department, the chance that an article is present at a different location (than depicted in the ERP system) is reduced. The disadvantage of the proposed solution is that the employees now need to execute an extra operation for the put-away of purchase articles.

For the poor execution of the procedure (choose a 'standard location' for an article), we suggested making the procedure easier for the employees of the assembly department, by enabling the procedure via the warehouse management application. By doing so, we lower the threshold (time and expertise) to execute the procedure. This results in a reduction of articles that are not directly assigned to a picking system or a specialized area, a situation that causes them to remain on boxes/ (box) pallets around the department.

For the storage of 'inactive' articles in the picking system inside the assembly department, we suggested installing a formal procedure to keep track and clean up 'old' articles in their picking systems. So, the project engineers and team leaders could review the articles at fixed times, as part of the 5S cycle. With this solution, Company X creates the possibility of storing new articles in the picking system or increasing the capacity of an existing article in the system. By creating new storage locations, the roaming of boxes with stock will decrease inside the assembly department, which they now store on (box) pallets, and on top of mobile carts.

6.2 Storage operations

In section 5.2, we described a strategy to make the inefficient storage of articles in the reserve bulk area more efficient. We discuss the result of the proposed strategy in the following sub-section.

6.2.1 Bottleneck 2: The storage strategy of the reserve bulk area is not efficient

To improve the mentioned causes for the inefficient storage strategy in the reserve bulk area. We suggested implementing a class-based storage concept for the aisles AA and AB. We assign production and purchase articles which are intended for the assembly department to these aisles. The lower parts are solely intended for these articles, with the higher parts the articles linked to the assembly department are prioritized over other (production) departments.

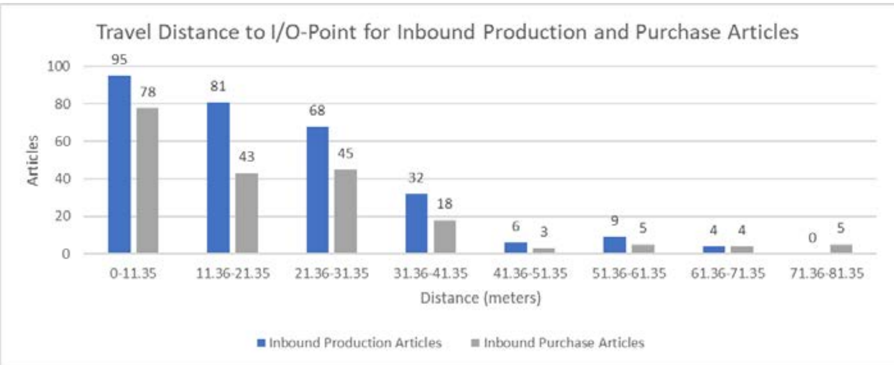


Figure 33: Travel Distance to I/O-Point for Inbound Production and Purchase Articles (new storage strategy)

In Figure 33, we present a histogram of the travel distance per type of articles per type with the 'new' strategy. The majority (93%) of the articles destined for the assembly department are stored in the aisles AA and AB, at a travel distance of less than 32m. The travel distance between all the inbound articles in the expedition area and the I/O-point of the assembly department is 4092.35 m and 5924.85 m for the inbound purchase articles and inbound production articles, which results in a decrease in the travel distance of 50% and 52% compared to the old strategy, respectively.

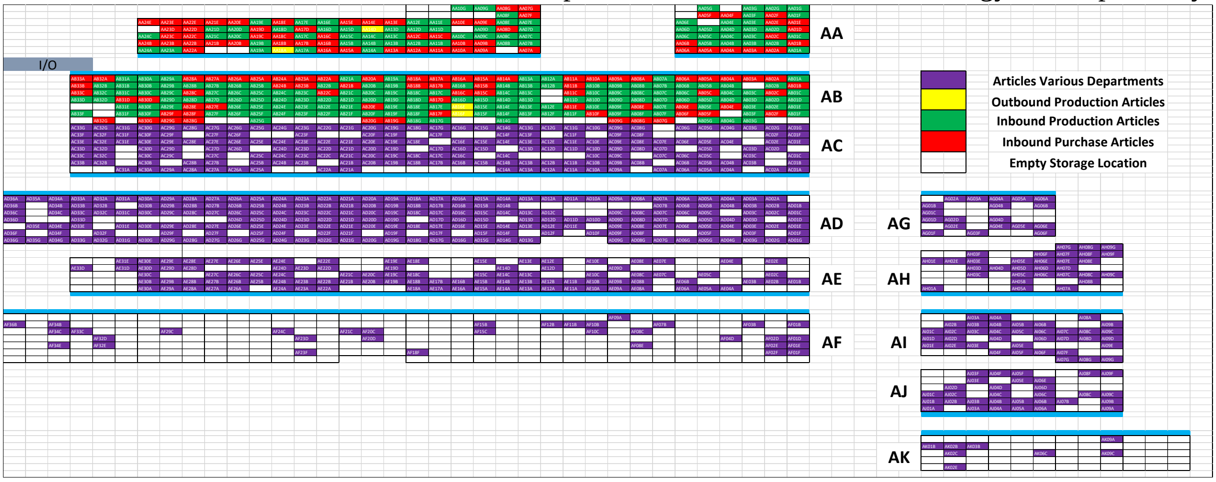


Figure 34: Layout Expedition Area categorized on article type (new storage strategy)

In Figure 34, we present the layout of the expedition area, with all the articles that originate or are destined for the assembly department, we present an enlarged layout in Appendix K. The proposed strategy yields a very high storage utilization (close to 100%) in the dedicated aisles, so there are almost no free storage possibilities in the lower and upper sections of the dedicated aisles.

For the second cause, the storage of 'inactive' articles in the reserve bulk area, we suggested installing a formal procedure to keep track and clean up 'old' articles in their storage systems. With this solution, Company X creates the possibility of storing articles destined for the assembly department in the storage locations near the I/O-point. In addition, the storage utilization of the dedicated aisles is reduced. The employees can more likely place articles in the lower part of the dedicated aisles, needing no help from the employees of the expedition department is less likely to be needed.

6.3 Assembly operations

In section 5.3, we described a strategy to make the inefficient assembly of large series repeat orders in the assembly department more efficient. We discuss the result of the proposed strategy in the following sub-section.

6.3.1 Bottleneck 3: The assembly process of large series repeat orders is not efficient

To improve the causes for the inefficient assembly of large series repeat orders. We suggested splitting the series into multiple batches before the assembly department, which will result in no additional storage operations within the assembly department. With the new strategy, we reduce the amount (box) of pallets (with unique production articles) required during the assembly of the product. In addition, we only store the number of production articles on a box (pallets) for a single batch.

By creating three pairs of two production articles, we need 3 fewer (box) pallets to set up the assembly for the DDC. Looking at the dedicated area for the DDC, the storage space utilization with the proposed strategy is 11.3/75 = 15.06%. This results in a decrease of utilized floor space by 24% compared to the old strategy.

Fortunately, these changes appear to have no or little impact on the hours spent per edit in the paint shop, where the employees need to perform additional acts, to combine the symmetric articles and split the series. The assembly of the DDC takes more time (+12%) comparing the pilot and the historic data. We present an overview of the NACA hours of the pilot and the historic data in Table 10.

Production Department	Edit	NACA Hours (Historic data: 2021-2022)	NACA Hours (Pilot)	Discrepancy Hours Historic Data-Pilot
Paint Shop	W091 Lakken	2.22	2.17	- 0.05
Paint Shop	W092 Ontvetten	0.11	0.13	+ 0.02
Paint Shop	W093 Handwerk lakkerij	4.00	4.42	+ 0.42
Paint Shop	W096 Kitten	1.19	0.67	- 0.62
Sub Total		**7.52**	**7.39**	**- 0.13**
Assembly Department	W101 Monteren	24.25	27.24	+ 2.99

Table 10: NACA Hours

The biggest disadvantage of the proposed strategy is the increase in the required storage locations in the reserve bulk area because the production articles are now stored per batch instead of the entire series on one (box) pallet.

6.4 VLM

In section 5.4, we described alternative decisions for two sub-problems, the storage location assignment, and the number of VLM units. The objective of our project is to minimize the total completion time required to collect a set of customer orders from a VLM pod. We created two separate experiments for each of the sub-problems, to evaluate the performance of the alternative decisions. We measured the performance of the VLM under various conditions via three KPIs: the completion time of the set of orders, the throughput of VLM unit(s), and the number of tray retrievals during picking operations. We present the results of the proposed methods in this section.

6.4.1 Results storage location assignment experiments

We conducted numerical experiments which totaled 210 problem instances spread over 7 scenarios. We used three storage location methods to assign the articles to the trays of the VLM unit, the currently used storage location assignment method, the COI method, and the OOS method. For each scenario per storage location assignment, we created 10 problem instances.

We used the CPLEX solver (version 22.1) within AIMMS, an optimization modeling system, to evaluate the performance of the OOS method. We executed all the experiments with the OOS method on a computer with Intel Core i7-6700HQ 2.60 GHz four-core CPUs and 2x8GB RAM. We solved every of these problem instances optimally. In Table 11 and Table 12, we present an overview of experiments and their summarized results, such as the number of tray retrievals and the CPU time.

From Table 11, we observe that the OOS method provided us with a better solution in every scenario, with fewer tray retrievals ranging from 27% to 36% and 24% to 31% compared to the COI method and the current storage location assignment, respectively. We completed the order in the least amount of time, and gain the largest throughput in the VLM unit, following the OOS method. The current storage location assignment provides us with a slightly better result than the COI method.

From Table 11 and Table 12, we observe that an increase in the number of unique orders results in a larger objective value for all methods. This also accounts for the parameter, maximum multiplicity of an order, where the same phenomenon is visible. The object value shows that an increase in tray capacity results in a better result. Looking at the solution time of the OOS method, we see that an increase in the number of unique orders makes the problem more difficult to solve. On the other hand, an increase in the tray capacity, and the max multiplicity of an order make the problem easier to solve.

Scenario	Number of (unique) orders	Tray Capacity	Maximum Multiplicity of an order	Current Storage Location Assignment	COI-method	OOS-method		Gap COI - OOS %	Gap Current Storage Location Assignment - OOS %
				Tray Retrievals (pcs.)	Tray Retrievals (pcs.)	Tray Retrievals (pcs.)	CPU Time (sec)	Tray Retrievals	Tray Retrievals
				Average	Average	Average	Average	Average	Average
1	25	8	10	198.00	218.60	139.30	5.77	-36%	-30%
2	50	8	10	369.10	403.10	271.80	9.15	-33%	-26%
3	75	8	10	632.90	632.90	438.40	34.53	-31%	-31%
4	25	10	10	187.10	194.40	141.50	0.94	-27%	-24%
5	25	12	10	171.50	179.30	128.90	0.88	-28%	-25%
6	25	8	5	110.40	116.10	78.00	1.79	-33%	-29%
7	25	8	30	542.20	602.60	401.50	1.06	-33%	-26%

Table 11: Results Experiments Storage Location Assignment (Solution time and Number of Tray Retrievals)

Scenario	Number of (unique) orders	Tray Capacity	Maximum Multiplicity of an order	Current Storage Location Assignment		COI-method		OOS-method	
				Completion Time (sec)	Throughput (articles/min)	Completion Time (sec)	Throughput (articles/min)	Completion Time (sec)	Throughput (articles/min)
				Average	Average	Average	Average	Average	Average
1	25	8	10	6370.75	2.49	6715.14	2.37	5257.41	2.85
2	50	8	10	11751.53	2.44	12319.94	2.33	9788.35	2.71
3	75	8	10	19557.73	2.38	19557.73	2.38	15777.33	2.76
4	25	10	10	5931.16	2.39	6053.20	2.35	5058.04	2.67
5	25	12	10	5534.76	2.47	5665.16	2.42	4713.57	2.74
6	25	8	5	3477.26	2.42	3572.56	2.36	2872.89	2.82
7	25	8	30	17439.67	2.48	18449.43	2.35	14595.45	2.75

Table 12: Results Experiments Storage Location Assignment (Completion Time and Throughput)

6.4.2 Results multiple VLM units experiments

We conducted numerical experiments which totaled 30 problem instances spread over 3 scenarios. We used the adapted OOS method to assign the articles to the trays of the VLM unit(s). For each scenario, we created 10 problem instances.

We used the CPLEX solver (version 22.1) within AIMMS, an optimization modeling system, to evaluate the performance of the adapted OOS method. We executed all the experiments with the OOS method on a computer with Intel Core i7-6700HQ 2.60 GHz four-core CPUs and 2x8GB RAM. We solved every of these problem instances optimally. In Table 13, we present an overview of experiments and their summarized results, such as the number of tray retrievals and the CPU time.

From Table 13, we observe that an increase in VLM units provides us with an increase in tray retrievals in the VLM pod. The use of 2 and 3 VLM units resulted in 20% and 47% more tray retrievals, compared to a single VLM unit. The completion time to pick a set of orders decreases by 28%, while we increase the number of VLM units from 1 to 2. We see an increase of 15% in the completion time, our objective when we increase the number of VLM units from 2 to 3.

We also observe that an increase in VLM units provides us with an increase in throughput in the VLM pod, which results from the decreased completion time for the second and third scenarios. Looking at the solution time of the adapted OOS method, we see that an increase in the number of VLM units makes the problem easier to solve. It should be noted that a maximum CPU time of 6 sec over the scenarios is negligible.

Scenario	Number of (unique) orders	Tray Capacity	Maximum Multiplicity of an order	Number of VLM units	Adapted OOS			
					Tray Retrievals (pcs.)	Completion Time (sec)	Throughput (articles/min)	CPU time (sec)
					Average	Average	Average	Average
1	25	8	10	1	139.30	5257.41	2.85	5.77
2	25	8	10	2	167.60	3787.71	3.84	1.53
3	25	8	10	3	204.10	4360.35	3.57	1.80

Table 13: Results Experiments with multiple VLM units

6.5 Conclusion

In this section, I summarize Chapter 6 and draw conclusions based on the results of the proposed strategies to create a more efficient flow of the material through the assembly department. I answer the following research question in this section:

"What is the influence of the chosen strategy on the operations in the assembly department?"

Picking Process

The result of the proposed solutions to improve the efficiency of the picking process is threefold. The new replenishment policy allows the employees of the assembly department to better monitor the location and stock of an article. The update of the warehouse management application to make the 'standard location' change easier and more accessible for all employees results in a reduction of articles that are not directly assigned to a picking system or a specialized area. With the formal procedure to keep track and clean up 'old' articles in their picking systems, Company X creates the possibility of storing new articles in the picking system or increasing the capacity of an existing article in the system. By creating new storage locations, the roaming of boxes with stock will decrease inside the assembly department, which they now store on (box) pallets, and on top of mobile carts.

Storage Process

The result of the proposed solutions to improve the efficiency of the storage process is twofold. The new dedicated storage concept for the aisles AA and AB result in a decrease in the travel distance for the inbound purchase articles and inbound production articles and the I/O-point of 50% and 52% compared to the old strategy, respectively. With the formal procedure to keep track and clean up 'old' articles in their storage systems, Company X creates the possibility of storing articles destined for the assembly department in the storage locations near the I/O-point. In addition, the storage utilization of the dedicated aisles is reduced.

Assembly Process

The result of the proposed solution to split the large series into multiple batches in the production department before the assembly department is less stock transfer (with a forklift) by the expedition department. In addition, we reduced the storage space utilization of the dedicated area for the DDC by 24% compared to the old strategy. Also, we require no additional storage operations within the assembly department for the rest of the batch. These changes appear to have no or little impact on the hours spent per edit in the paint shop, and assembly department during testing.

VLM

We experimented with alternative decisions for two sub-problems: the storage assignment and the number of VLM units. The experiments totaled 210 and 30 problem instances equally spread over 7 and 3 scenarios, respectively. For the storage location assignment, we experimented with three methods, the current storage location assignment, COI, and OOS, to allocate the articles on the trays. The OOS method provided us with a better solution in every scenario, with fewer tray retrievals ranging from 27% to 36% and 24% to 31% compared to the COI method and the current storage location assignment, respectively. This also expressed itself in less completion time for the orders and a higher throughput of the VLM unit.

For the experiments with the number of VLM units, we allocate the articles on the trays via the adapted OOS method. The use of 2 and 3 VLM units resulted in 20% and 47% more tray retrievals, compared to a single VLM unit. The completion time to pick a set of orders decreases by 28%, while we increase the number of VLM units from 1 to 2, and increases by 15% when we increase the number of VLM units from 2 to 3. We also observe that an increase in VLM units provides us with an increase in throughput in the VLM pod, which is the result of the decreased completion time.

7. Discussion, Conclusion, and Recommendations

In this chapter, we evaluate our research findings and discuss the significance and implication of our results. Furthermore, we state the answer to the main research and summarize and reflect on the research. Also, we make recommendations for future work on this topic. In this chapter, we answer the following research question:

"How can Company X *implement the suggested improvements for the processes in the assembly department?"*

7.1 Discussion

Picking operations

The data suggest that our qualitative solution in terms of policy changes, new procedures, and software improvements woud result in less roaming of the boxes in the assembly department and an increase in the capacity of the picking systems of Company X. During this thesis, we partly implemented the proposed method. We could visually confirm that fewer articles were stored on (box) pallets in the area, which meant there was also more room to engage in (assembly) proceedings. In addition, the employees could find articles easier, because the articles were stored inside the picking systems instead of on (box) pallets. So the employee does not have to search for an article in an unlabeled shelf rack, (box) pallet, or a box within the area, thereby saving picking time.

This result lies in line with the theory of Lean Six Sigma, which supports that our solution ensures a more consistent, timely, and repeatable process (Theisens 2016). Unfortunately, we cannot quantify the discrepancy between the 'old' and 'new' strategy, in terms of the picking time for the employees. The employees of the assembly department do not track their picking time, therefore no conclusion can be made from these picking times.

Storing operations

The results indicate that a class-based storage concept for the aisles AA and AB would result in a reduction of 50% and 52% in travel distance for the inbound purchase articles and inbound production articles, compared to the 'old' strategy.

The majority (93%) of the articles destined for the assembly department are stored in the aisles AA and AB, at a travel distance of less than 32m. We expected that we could store all the aforementioned articles within this distance. We discovered that the rest of the articles are present at a relatively large travel distance because they stored these articles together with items from other (production) departments at a single storage location. This means that in order to minimize our travel distance, we should take articles from other production departments into account while implementing a storage concept.

Company X currently assigns both normal (box) pallets and oversized pallets to a single storage location. For example, an oversized pallet could occupy 3 spots while being assigned to 1 in the ERP system. By doing so, the reliability of the storage utilization is affected, because the value of this KPI may be higher. We found a very high storage utilization (close to 100%) in the aisles AA and AB after we allocated the articles via the 'new' storage concept. This means that the employees might not find a suitable storage location if they would like to store articles here, because the storage utilization might be 100%.

Assembly operations

The results indicate a decrease of used floor space by 24% compared to the old strategy, because we need 3 fewer (box) pallets to set up the assembly for the DDC, by altering the assembly strategy of large series repeat orders. This means less stock transfer (with a forklift) by the expedition department, and less set-up time for the employee in the assembly department.

The assembly of the DDC takes more time (+12%) comparing the pilot and the historic data of the repeat order. Conversely, we could only execute a single order for the DDC during this research, which does not allow us to state whether the NACA hours are significantly worse or better because of insufficient replications.

VLM

The results of the storage location assignment experiments indicate that the OOS method provides us with the least completion time for a set of orders, and the largest throughput of the VLM unit in every scenario. This lies in the line of expectation, because with the OOS method, we take order composition into account, in contrast to the COI method, which is intended for the single command storage and does not take order compositions into account, hence the inferior result. With the current storage location assignment, they placed a part of the articles on the trays with the order composition of Client A in mind, hence the slightly better result.

With the OOS method, we had fewer tray retrievals ranging from 27% to 36% and 24% to 31% compared to the COI method and the current storage location assignment, respectively. These results build on existing evidence of Meller and Klote (2004), that the throughput of the VLM unit (and thus the total completion time to collect a set of customer orders) of the VLM is strongly correlated with storage location assignment.

We observe that an increase in the number of unique orders results in a larger completion time for a set of orders with all storage location assignments. More unique orders guarantee more articles, so we need more (different) trays, thus more tray retrievals, which hurt the objective value. This reasoning also accounts for the parameter, the maximum multiplicity of an order. In these experiments, we did not consider batch picking, so if we have to pick the same order twice in sequentially, we need to retrieve the tray(s) twice, which hurt the objective value. The objective value also shows that an increase in tray capacity results in a better result, which is a logical outcome. A large capacity means that we can store more articles on a single tray, thus reducing the total amount of trays in the VLM, so fewer tray retrievals are required for an order.

The results of the number of VLM unit experiments show that 2 VLM units provide us with the least completion time for a set of orders. Our objective, decreases by 28%, while we increase the number of VLM units from 1 to 2. We see an increase of 15% in the completion time when we increase the number of VLM units from 2 to 3. This result did not lie in the line of expectation, but can be substantiated. The objective function of the adapted OOS method balances the number of tray retrievals over the VLM units, allowing the possibility of working more under 'masked' time. The model assigns the articles more scattered over 150 trays (in 3 VLM units), instead of 100 trays (in 2 VLM units), which results in fewer articles per tray. As a result, we need more tray retrievals (to pick the same articles), more walking time (between the VLM units), and less waiting time (in front of the VLM unit) during picking proceedings. To minimize the completion time for a set of orders, we need to balance these factors.

Next, we address a few limitations regarding the VLM. First, the adapted OOS model does not take the walking time between the VLM units into consideration. Therefore, the solution seems to get worse if the number of VLM units are excessively increased. We calculate the completion time (picking time, waiting time, and walking time) for a set of orders based on this storage location assignment afterwards, which explains the aforementioned result. Second, we did not consider batch picking during our experiments. We sequentially picked the orders, which may lead to visiting the same tray multiple times during a set of orders. This hurts the objective value and decreases the throughput of VLM unit(s).

Third, we did not consider the possibility of fragmented storage of the articles over the trays of the VLM unit(s). Currently, the ERP system of Company X does not allow fragmented storage in the warehouse, which means that a single article only has one location. We believe that by creating duplicate VLM units and allowing fragmented storage, the completion time for a set of orders could be reduced. At last, we used a fixed tray capacity for the articles that is equal on every tray in the VLM unit, because these articles came from a picking system with a fixed capacity per location. In reality, not every article does not take up the entire space of the location in the picking systems. Since the tray capacity is variable by partitioning, so we could increase or decrease the capacity per article. This would allow us to place more articles per tray, where fewer tray retrievals are resulting in a better objective value.

7.2 Conclusion

This thesis project focuses on the assembly department of Company X, of which the proceedings have been increasing over the years. The assembly department has a fixed amount of floor space, which bulges with (assembly) items, thus reducing productivity, and accessibility in the department and creating safety concerns. By improving the efficiency of the department, Company X hopes to meet the rising demand in the future. This thesis describes improvements in the picking, storing, and assembly operations, which improve the flow of material overall, hence increasing the efficiency of the assembly department.

Picking operations

By observing and taking part in project activities in the picking operations in the assembly department, we identified and measured the efficiency of the process with the help of the DMAIC improvement cycle. We used a Swimlane flowchart to identify the problems, data analysis to support our claim, and a Fishbone diagram to find the causes. We found that the assembly department failed to store articles (put-away process) within their picking systems. This inefficiency lead to a reduced area to perform activities in the assembly department, which limited the overall assembly capacity of the department. For this inefficiency, we created a qualitative solution, in terms of policy changes, new procedures, and software improvements, that ensures a more consistent, timely, and repeatable process. As a result, the employees need less time to pick, the roaming of boxes is reduced, and the capacity of the picking system is increased.

Storing operations

Via a data analysis of the storage statistics of the reserve bulk area of Company X, we discovered two inefficiencies: the storage concept of the area and inventory control of Company X. These inadequacies result in large travel distances and a lack of storage possibilities in the reserve bulk area. We investigated the impact of a hybrid storage concept on this area to allocate articles in this area, in combination with a policy change to manage the inventory better. The new dedicated storage concept for the aisles AA and AB result in a decrease in the travel distance for the inbound purchase articles and inbound production articles and the I/O-point of 50% and 52% compared to the old strategy, respectively. By utilizing the policy change, we created more storage possibilities near the I/O-point of the assembly department, reducing the travel distance.

Assembly operations

By observing and taking part in project activities in the assembly operations in the assembly department, we discovered the efficiency of this process. Company X currently stores production articles of large repeat orders on box pallets in the assembly department, for the entire series. They produce the order in batches leaving the remaining articles on the job, which limits the overall (production) capacity of Company X. We created a pilot for the DDC, where we altered the assembly strategy of large series repeat orders. Following this strategy, Company X needs less time and space to set up for the assembly of the order, because fewer transport movements are required for these articles. This results in a decrease in used floor space in the dedicated area of the DDC by 24% compared to the old strategy during the assembly operations. In addition, we required no temporary storage of production articles inside the department for the rest of the series. These changes have no impact on the hours spent per edit in the paint shop, and assembly department.

VLM

Company X bought a VLM to reduce the usage of floor space and increase productivity in the assembly department. We investigated how to improve the (picking) throughput of VLM with the alternative storage location assignment decisions, and the usage of multiple VLM units. The objective of the project is to minimize the total completion time required to collect a set of customer orders from a VLM pod. For the storage location assignment experiments, we found that the OOS method provided us with the best solution in every scenario, with fewer tray retrievals ranging from 27% to 36% and 24% to 31% compared to the COI method and the current storage location assignment, respectively. This also resulted in the best completion time for an order and throughput for the VLM unit. For the experiments with the number of VLM units, we discovered that the usage of two VLM units provides the best option regarding the completion time for a set of orders, our objective.

7.3 Recommendations

As mentioned, we could not quantify the discrepancy between the 'old' and 'new' strategies, in terms of the picking time for the employees. However, by the partial implementation, we saw the results of the proposed method. We suggest that Company X investigates the actual picking time for an order inside the department by collecting real-time data. With this data, they could determine other inefficiencies with the picking operations. Furthermore, they could test a different picking strategy, such as batch picking, to improve these operations further. As order picking comprises the majority of the operational costs, this seems worth it to us.

Based on the conclusion of the proposed storage concept, Company X should consider implementing this storage concept at all (production) departments, hereby lowering the travel distance between the articles and the departments. In addition, Company X could extend their research to other storage concepts. For this, Company X must track data regarding the size (width and height) of a pallet. The benefit of this is that someone could develop a method for the automatic allocation to storage location based on certain preferences.

The proposed strategy for large series production order resulted in a decrease of used floor space, and less set-up time for the employees. Unfortunately, further research is needed to determine whether the NACA hours are significantly worse or better because of insufficient replications. To use this method for these types of orders, Company X should investigate the 'new' strategy more extensively. First, they need to replicate the pilot more often to examine the NACA hours if the proposed strategy is significantly better or worse in terms of labor hours. Based on these results, Company X needs to decide whether to adjust the proposed strategy or not. Hereinafter, they need to extend the proposed method to other large series repeat orders to check if the thought process applies here as well. Lastly, they need to compile a framework for the assembly of further products of that type to create a generic solution that works.

Based on these conclusions for VLM, Company X should consider using two VLM units for picking operations, and to assign the articles to the tray with the OOS method. This provides considerable advantages over the settings currently used. To further improve the performance of the VLM pod, Company X could extend their research to fragmented storage in the warehouse. Currently, the ERP system of Company X does not allow fragmented storage in the warehouse, which means that a single article only has one location. We believe that by creating duplicate VLM units and allowing fragmented storage, the completion time for a set of orders could be reduced. Also, Company X currently does not consider batch picking for orders, for the VLM and other picking systems. Batch picking could dampen the number of tray retrievals, by picking the required articles for multiple orders at once, instead of at separate moments.

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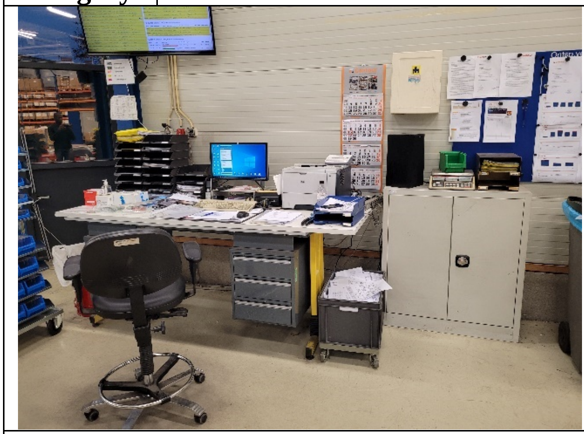
Appendix A: Layout of the assembly department

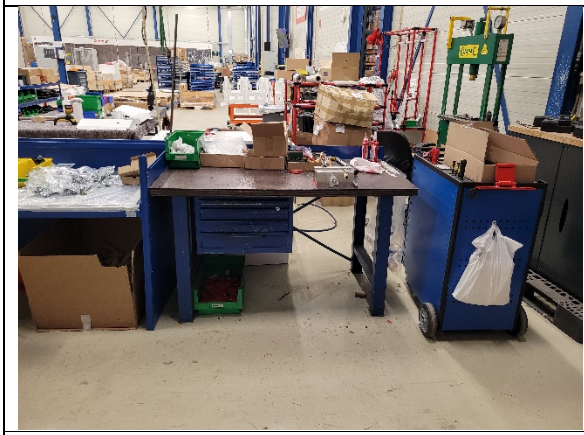
Figure 35: Layout of the assembly department

Appendix B: Resources assembly department

Category	General warehouse tools
	
Kaercher Scrubbing Machine	
Category	Office desk
	
Office table (supervisor)	Office table
Category	Consumables
	
Container distilled water	Glue closet (left)

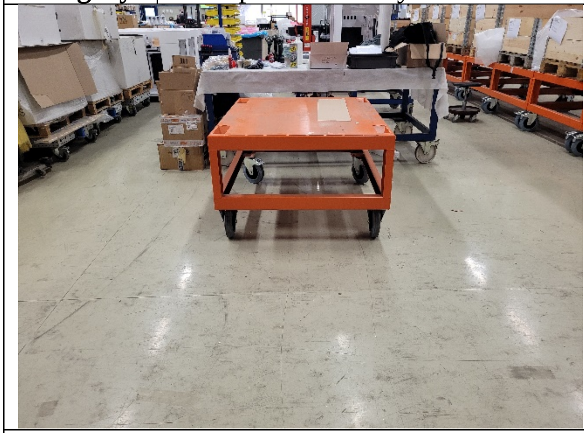
	
Europallet packaging material	Europallet packaging material
Category	Picking/Storage system static
	
Fabory warehouse Cabine	Mobile shelf rack eurobox
	
Overtoom low shelf rack	Overtoom high shelf rack

	
Pallet rack	VLM
Category	Picking/Storage system dynamic
	
Mobile cart	Pipe and joint shelf
Category	Assembly Workstation Static
	
Cleanroom	ESD table

	
Worktable medium	Worktable orange/blue
	
Worktable small	
Category	Assembly Workstation Dynamic
	
Pipe and joint worktable	Worktable basic

	
Worktable kit operations	Worktable medium
	
Worktable small	
Category	Assembly Tools Static
	
Compressor	Lift table

	
Tool closet (right)	Workshop press
Category	Assembly Tools Dynamic
	
Pallet jack	Tool trolley type 1
	
Tool trolley type 2	

Category	Transport/Assembly Tools
	
Pallet undercarriage (Transport)	Pallet undercarriage (Assembly)
	
Trolley	Trolley with vice (right)
Category	QA/QC
	
Control box	

Appendix C: Routing plan for articles in the factory

Materiaal: 234226 Sheet AISI 304-2B 2.5 mm L: 3.000 B: 1.500 **Geleideblad (OHW)**

[redacted]

App gebruiker: APPDEFAULT

Cluster:

Orderaantal **250**

Routing	Aantal Producten Pallets	Kwaliteit akkoord Pers.nr.		Aantal Producten Pallets	Kwaliteit akkoord Pers.nr.
~~W950~~			W113		
~~W034~~			W111		
~~W048~~					
W038					
W041					
W075					
W062					
W065					

Figure 36: Routing plan for articles in the factory

Appendix D: Storage plan in the assembly department

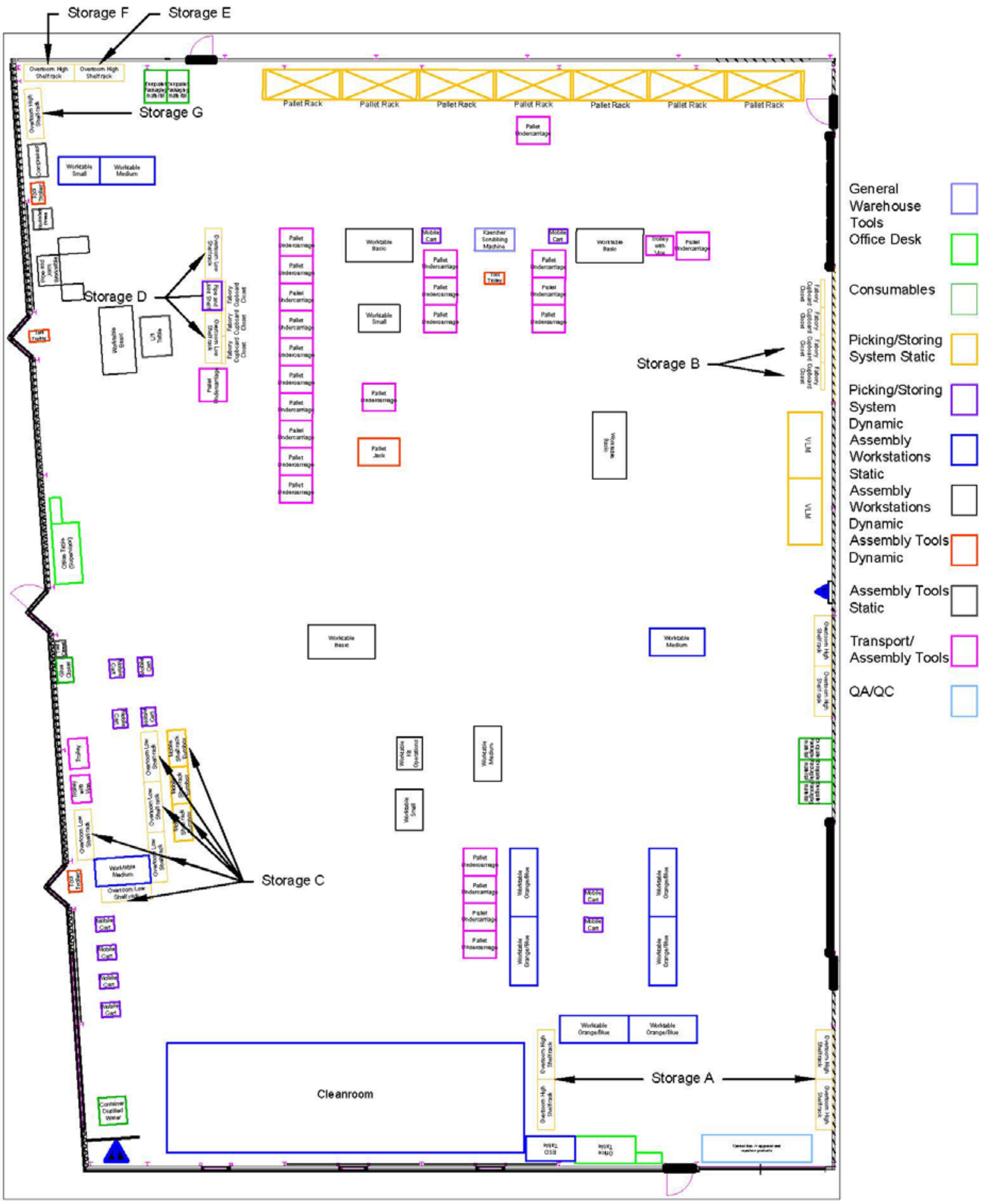


Figure 37: Storage plan in the assembly department

Appendix E: Dashboard for the orders in the assembly department

Figure 38: Dashboard for the orders in the assembly department

Appendix F: Swimlane Flowchart for current replenishment policy

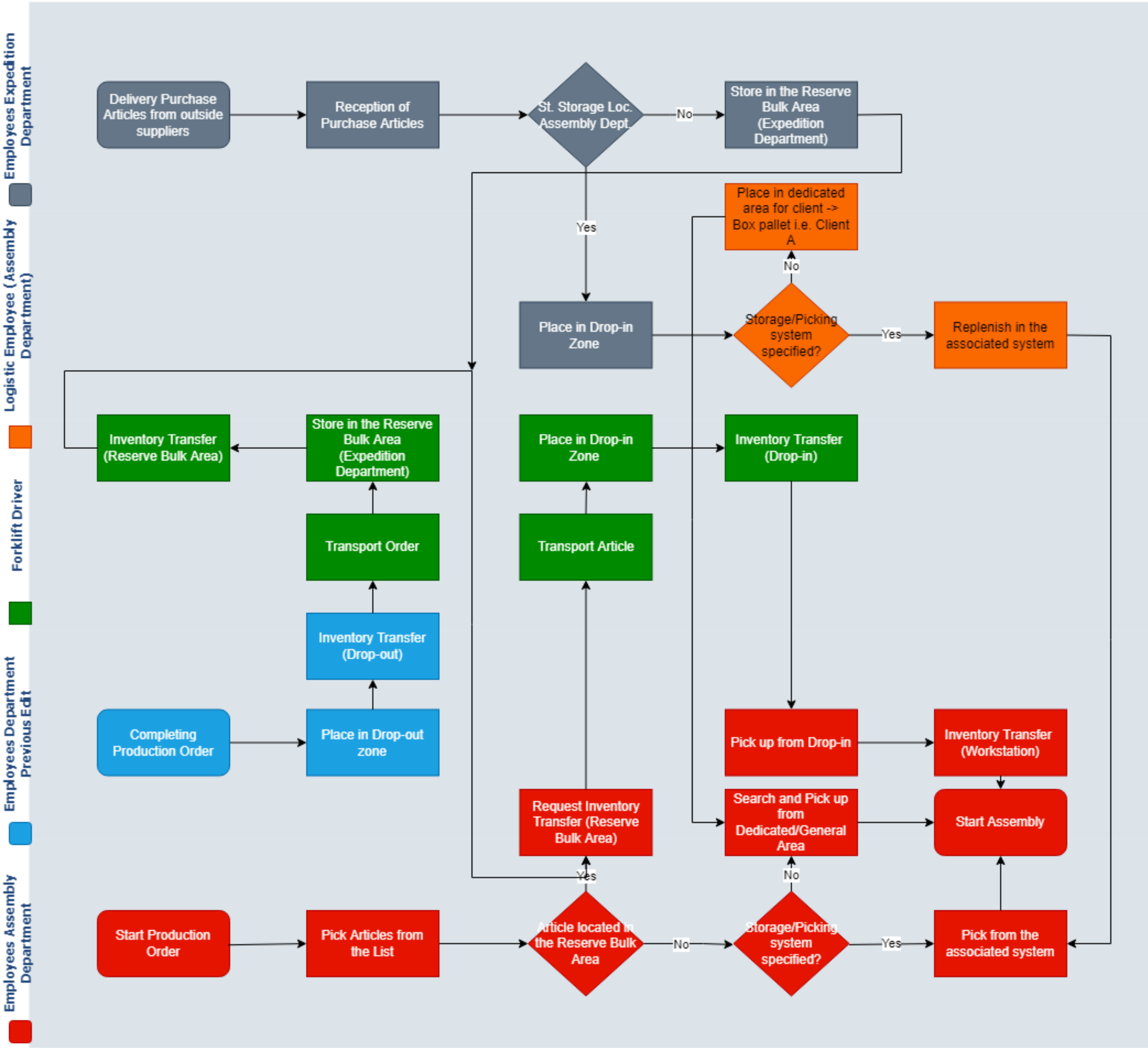


Figure 39: Swimlane Flowchart for current replenishment system

Appendix G: Fishbone diagram (root cause analysis) for the inefficient put-away process

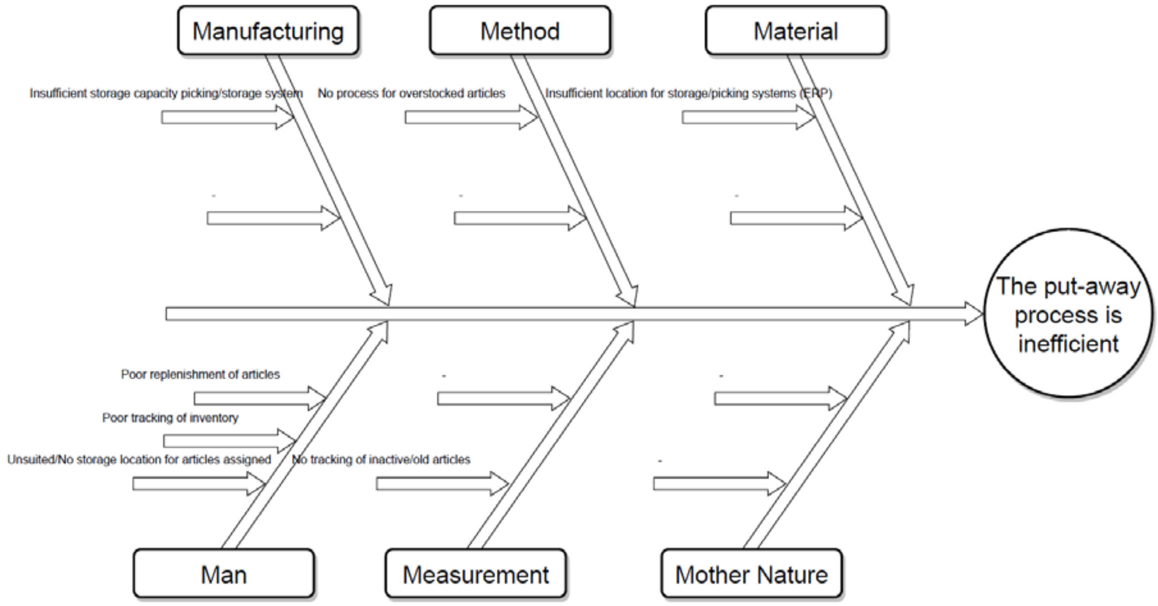


Figure 40: Fishbone diagram (root cause analysis) for the inefficient put-away process

Appendix H: Layout Reserve bulk Area (Expedition)

Figure 41: Layout Reserve bulk Area (Expedition)

Appendix I: Layout Expedition Area categorized on article type

Figure 42: Layout Expedition Area categorized on article type

Appendix J: Layout Expedition Area categorized on mutation date

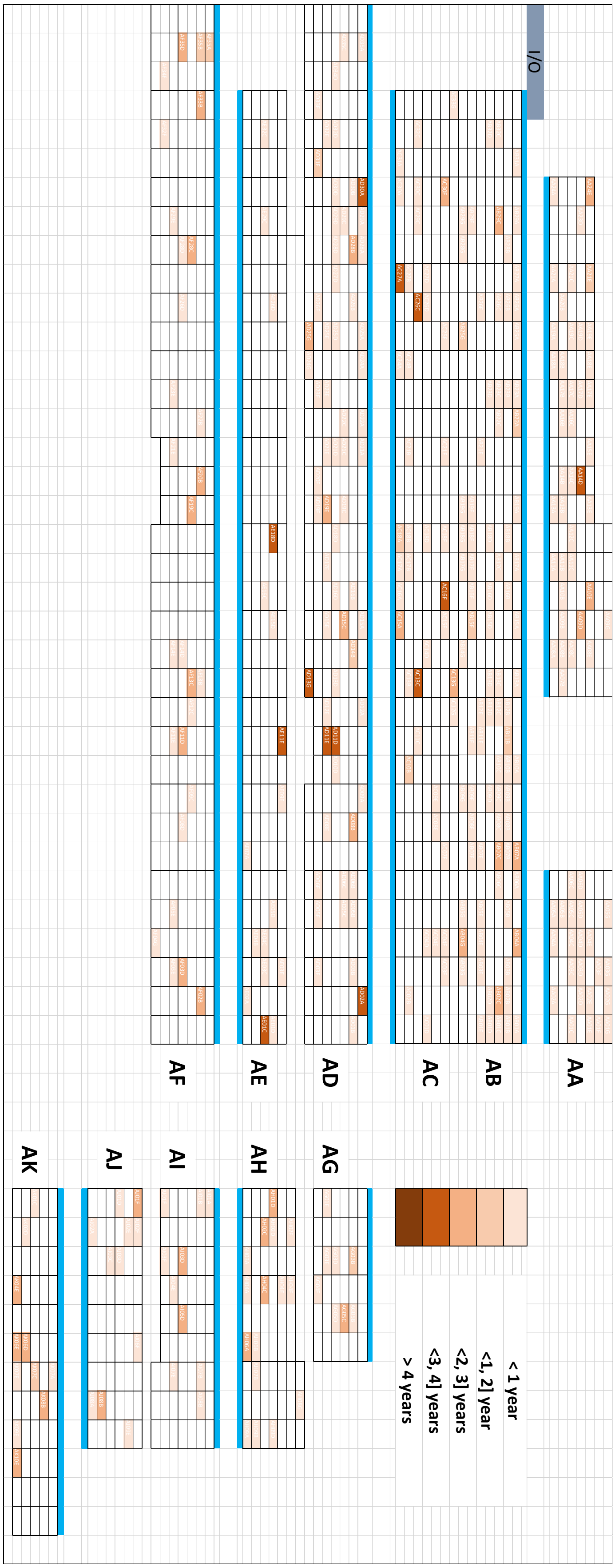


Figure 43: Layout Expedition Area categorized on mutation date

Appendix K: Layout Expedition Area categorized on article type new strategy

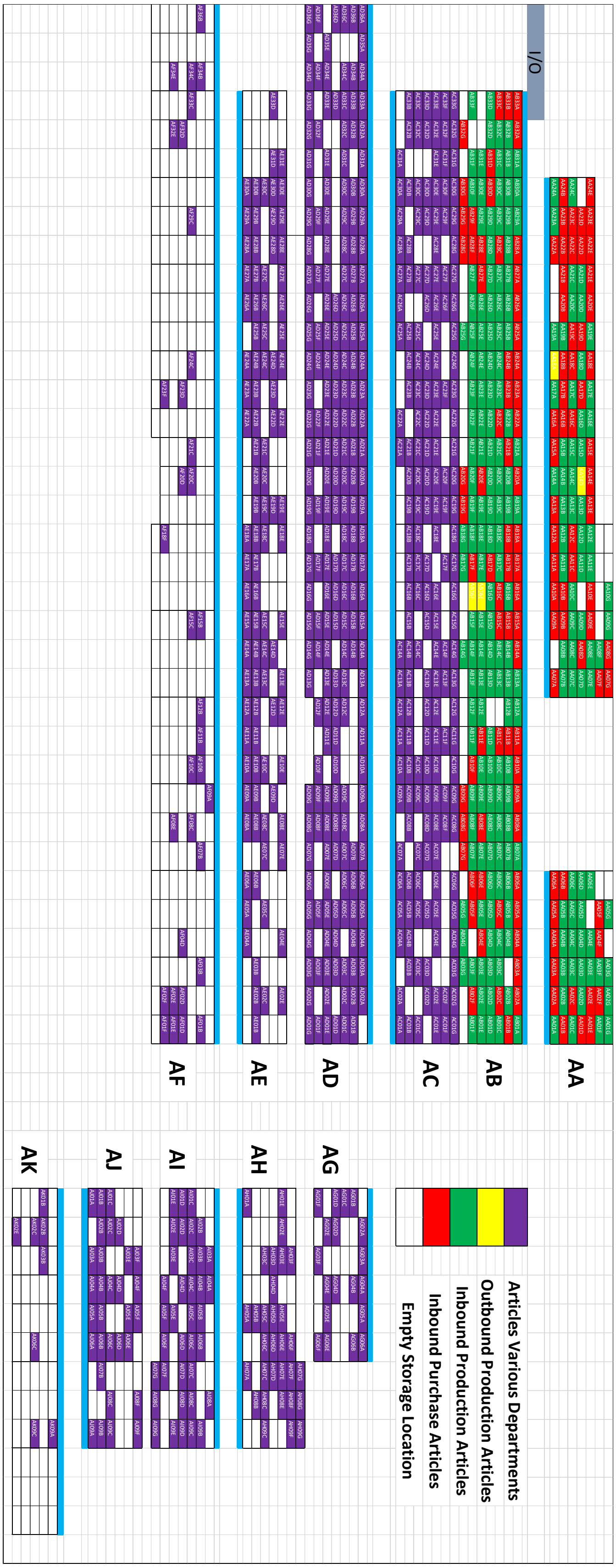


Figure 44: Layout Expedition Area categorized on article type new strategy