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How to align storage and order picking in the VMI warehouse

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Management summary

Problem context: VMI and the VMI warehouse

This research has been conducted at the warehouse of VMI Holland B.V., located in Epe (the Netherlands). The VMI Group is a market leader in manufacturing production machinery for the tire, rubber, can, and care industry. VMI wanted to know if their current way of processing materials, based on their storage policy, was still adequate. There are four key reasons for this: developments over the past twelve years, the ERP system, doubts about the adequacy of the current system, and uncertainty about the future. An alternative storage and picking policy should be as effective and efficient as possible, but it should also be robust for changes in the future. This led to the following central research question: *What is an efficient and effective storage and picking policy for the VMI warehouse that can cope with the long-term changing environment?*

The VMI warehouse has to store and receive items, that have to be delivered to production, customers, or other warehouses soon. This delivery is done via production, sales, and warehouse orders. The warehouse currently has five storage zones based on the size of items. Within these zones, two storage policies are applied: 'project' and 'anonymous' storage. In the project storage, items are stored per sales, warehouse, or production order. In the anonymous storage, items are stored per SKU. Currently, anonymous items are picked days in advance if they are needed for a production order soon. In that case, they are picked from the anonymous storage, and put away in the project storage, and stored per order again. To deliver the items to production, a tugger train system is used on which multiple orders are gathered.

Approach: alternative storage policies and simulation modeling

To come to alternatives for the current storage policy, a literature study has been performed about warehousing in general, performance measurement, and the storage location assignment problem (SLAP), which is the problem to appoint incoming products to storage locations such that the number of locations needed and time to put away and pick items is reduced. The SLAP is NP-hard. A storage policy tries to find a solution to the SLAP. In literature, many storage policies are described, which can be divided into three groups: random, dedicated, and shared storage.

Next to a literature study, a brainstorming session was held, a questionnaire has been sent to multiple stakeholders, and interviews have been conducted. In this way, important stakeholders could give their opinion about existing ideas and pose new ideas. Eventually, it was decided to test the following alternatives:

- The current situation (as a benchmark).
- Doing anonymous picks simultaneously with project picks (in contrast to days in advance).
- Storage per SKU.
- Storage per tugger train by which orders are delivered to production.
- Procuring more SKUs anonymously: which means that items are not attached to an order when the item is procured. In this way, more items come in together and are stored together.

These alternatives are tested against a scenario in which the volume increases. Moreover, storage per SKU and the current situation are also tested against a scenario in which more SKUs arrive (while the volume remains the same). To test these alternatives, a simulation model has been built. It is decided to use simulation due to the problem size, system complexity, stochasticity involved, and the number of scenarios and interventions that VMI wishes to test in the model.

Results: quantitative results from the simulation model

Per intervention, the following results are obtained from the simulation model (Table MS 1).

Table MS 1: Summary of all results obtained in this research, separated per intervention.

Intervention	Locations needed*	FTE(s) per day needed*	Savings/losses smaller when volume increases?*	Procuring more items anonymously interesting?	Robust against an increase in SKUs?
Current scenario	*n.a.*	*n.a.*	*n.a.*	No	Yes
Doing anonymous picks simultaneously	-93.99 (≈0.95%)	-0.7	Savings larger	Moderately	Yes**
Storage per SKU	+1107 (≈11.19%)	+0.28	Losses in time become smaller, losses in locations become larger	Yes	No
Storage per train	-454 (≈4.59%)	-0.22	Savings larger	No**	Yes**

** Compared to the current scenario*
*** Not tested in the simulation model*

1. Doing anonymous picks simultaneously

When anonymous items are picked simultaneously with project items (in contrast to days in advance) one pick and put-away step can be saved. As a nice catch, on average 93.99 locations (≈0.95%) in various zones can be saved compared to the current scenario. Moreover, based on the saved pick and put-away time, approximately 0.7 FTE per day can be saved. When volume increases, these savings become larger.

2. Storage per SKU

When storing per SKU, on average, approximately 1107 more locations (≈11.19%) are needed compared to the current scenario. This number increases when the volume of items arriving increases. The total time to put away all items decreases while the total time to pick all items increases. Eventually, this causes that on average 0.28 FTE per day more are needed. When the volume increases, the FTEs needed when storing per SKU or in the current scenario are almost equal. Lastly, if the number of different SKUs that arrive increases (while the volume remains the same), more locations are needed, and picking times increase. The current scenario is robust to this change in the number of different SKUs: it shows barely any difference in results if more different SKUs arrive.

3. Storage per train

When storing per train, approximately 454 locations less (≈4.59%) are needed compared to the current situation. On average, storage per train can save 0.22 FTE per day. When volume increases, these savings only become larger.

4. Buying more SKUs anonymously

For interventions 1 (doing anonymous picks simultaneously), 2 (storage per SKU), and the current scenario, it has been tested what the effect is of procuring more SKUs anonymously. When more SKUs are bought anonymously, more locations are needed for each intervention since the sojourn time of these SKUs is longer. For interventions 1 and 2, fewer FTEs are needed if more SKUs are procured anonymously. This is since put-away time is saved. However, in the current scenario, these items are picked and put away twice. So, in that case, more time is needed to do all the work. Lastly, by procuring more SKUs anonymously, the average dock-to-stock time can substantially be decreased.

Next to these quantitative arguments, multiple qualitative arguments can be formulated for or against each intervention. Think about the complexity of the system, implementation in an ERP system, robustness, etc.

Conclusions and Recommendations

Regarding the quantitative arguments, storage per train or doing anonymous picks simultaneously (or a combination thereof) seems like the best alternative regarding efficiency. Moreover, both are even more efficient when the volume is increased and are likely also robust to an increase of SKUs since they are similar to the current scenario. However, looking at qualitative arguments, storage per train seems like a difficult policy to implement in an ERP. So, the current storage policy and storage per SKU remain.

In the future, a new ERP system will be introduced at VMI. Hence, everything (even the current storage policy) will need to be reprogrammed. This is relatively expensive. Therefore, the cost and savings mentioned above have been estimated to euros per year, by assuming a price for m^2 and FTE per year. Based on this estimation, storing items with the current storage policy saves approximately €*xx,xxx* per year (assuming a volume of 1.5x more orders than in 2020) compared to storing per SKU. If the anonymous picks are done simultaneously this amount becomes approximately €*xx,xxx* per year. In a new ERP system, storage per SKU is the standard, so the costs for implementing this storage policy are much lower. However, next to these costs, multiple other qualitative arguments can be stated for or against storing per SKU or remaining in the current situation. To implement storage per SKU or per order, a road map has been made per policy, which is summarized in Table MS 2 below. This road map consists of six overlapping phases.

Table MS 2: A summary of the road map created to implement the chosen storage strategy (per SKU or the current situation). The road map consists of six phases, in which a key question is answered by performing several tasks.

Phase	**Key question**	**Result**
Decision and forming a project team	*Are we willing to invest in reprogramming the current storage policy in the new ERP system?*	A decision on which storage policy to implement and a project team.
Look for and choose a software provider	*Which software provider can provide the way of storing per SKU or storing per order?*	A strategic software partner that can implement the storage policy in Epe and globally.
Make transition in the current system	*Is our physical process capable of storing items in the preferred way?*	A view on if the new storage policy is feasible in the physical warehouse.
Identify risks and mitigate them	*What are immediate risks that can harm the flow of goods and how can we solve them?*	List of risks and how to mitigate them.
Continuous improvement	*How can the chosen storage policy become more effective and efficient?*	Not applicable, this is an ongoing process.
Make feasible in the new system	*How should the new storage policy be implemented in the new ERP system?*	Implemented storage policy in the new ERP system.

I would recommend VMI to reprogram the current way of working (storage per order) while doing anonymous picks simultaneously due to the following reasons:

- I think the efficiency gains will eventually pay back the initial extra investment into programming the current scenario. I think storage per train is too difficult to implement regarding the qualitative arguments.
- The volume of items arriving … [*information censored for public version].*
- The strategic directions of VMI cause … [*information censored for public version].*
- The road map of storing per order seems to be easier to implement even though extra programming work is needed.
- … [*information censored for public version].*
- A shift towards … [*information censored for public version].*
- The Leszno and Yantai warehouses will probably also use this way of storing, increasing the efficiency gains and relatively decreasing programming costs for VMI globally.

Acknowledgments

In the context of my master's study Industrial Engineering and Management at the University of Twente, I did my graduation project on storage location assignment at the warehouse of VMI Holland B.V., located in Epe (the Netherlands). I look back on a great time in which I learned a lot of new things. Not only regarding the subjects covered in this thesis but also regarding the many aspects the company faces. It is a pleasure to work in such a high-tech environment with more than enough room for innovation.

This thesis would not have been possible without the help of several people. I want to use this opportunity to express my gratitude to everyone who supported me during my thesis and the five years of my bachelor's and master's studies.

First, I want to thank my colleagues at VMI. Many people helped me along the way by explaining things, giving support, and providing feedback. Trying to mention all of them would result in a very long list of names. Moreover, I do not want to risk missing any of them. It is great to see that literately everyone at VMI wants to make time for you and wants to help you progress in your thesis.

"Help will always be given at VMI to those who ask for it."

I want to specifically thank two people: Henk Esveld and Berthold Gerrits. First, I want to thank Henk for allowing me to even graduate at VMI. Moreover, I want to thank him for his support and feedback during my thesis and the feedback on my reports and presentations. I also want to thank him for allowing me to let me involve in other things within VMI, outside the scope of this research. Secondly, I want to thank Berthold for his support and feedback. Moreover, his enthusiasm about warehousing and logistics, in general, is catching. All in all, it is great to have so many sparring partners around at VMI.

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I hope you enjoy reading this report.

Jesper Rensen

Epe, September 24, 2021

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List of abbreviations

		Explained on page
EP	Euro Pallet	*17*
KPI	Key performance indicator	*5*
PO	Production Order	*24*
RB	Red Box	*17*
SCI	Supply Chain Innovation	*1*
SKU	Stock Keeping Unit	*3*
SLAP	Storage Location Assignment Problem	*38*
SO	Sales Order	*24*
SP	Steel Pallet	*17*
ST-EP	Standard Euro Pallet (the anonymous part of the EP zone)	*17*
ST-GB	Standard Grey Bin (the anonymous part of the RB zone)	*17*
ST-LL	Standard Lean Lift	*17*
TKH	Twentsche Kabel Holding (the listed company of which VMI is part)	*1*
WO	Warehouse Order	*24*
ZD	Self-carrying (from the Dutch word zelfdragend)	*17*

1. Introduction

In the framework of completing my master's study in industrial engineering and management, at the University of Twente, I performed research on storage location assignment and order picking at the warehouse and supply chain innovation departments of VMI Holland B.V. located in Epe, the Netherlands. This chapter introduces this research. Section 1.1 outlines the research background. Section 1.2 introduces the problem context, followed by the scope, method selection, and research goal in Section 1.3. The research question is posed in Section 1.4 together with the approach to answering this question with corresponding sub-questions. The final deliverables are given in Section 1.5.

1.1. Background

This part introduces the VMI group. The problem is placed within the organization with the aid of an organogram.

1.1.1. Introduction to the VMI and TKH group

The VMI Group is a market leader in manufacturing production machinery for the tire, rubber, can, and care industry. VMI stands for Veluwse Machine Industrie. It was founded in 1945 by Jan de Lange. Back then, it helped to rebuild the Dutch railways after the Second World War. From the 1960s onwards, VMI started to focus on manufacturing systems for the rubber and tire industry and later expanded with machines for the can division (1973) and care industry (2009). In 1985 VMI became fully part of the Twentsche Kabel Holding (TKH) Group (VMI Group, 2020). The TKH Group is a listed company, who internationally creates and supplies innovative telecom, building, and industrial solutions. In 2019, the TKH group had a turnover of approximately 1.5 billion euros realized with 5890 employees (TKH Group NV., 2019).

VMI's headquarters is located in Epe, the Netherlands. Currently, VMI employs approximately 1000+ employees of which approximately 500+ employees work in Epe. These numbers fluctuate quite a bit over the years. It has nine facilities on four continents. The company's constant effort lies in developing innovative products and solutions for its markets. This is reflected in the slogan: "technology meets success" (VMI Group, 2020). Two of its products are displayed in Figure 1.1, the VMI ACE-500 cotton machine (left) and the VMI MAXX tire assembly machine (right).

Figure 1.1: Two of VMI's products: the VMI ACE-500 on the left and the VMI MAXX on the right (VMI Group, 2020).

1.1.2. Company structure

To place this research into the right context, the company's structure is given. To start, VMI can be placed in the industrial solutions segment of the TKH Group. VMI itself can be divided into nine locations: the Netherlands, Germany, Brazil, Poland, China, USA, Malaysia, Thailand, and Russia. The first five locations are manufacturing facilities, whereas the latter four locations are mainly support and service locations. The locations in Brazil and Germany are minor production locations with, for example, some assembly, whereas the locations in Leszno (Poland), Yantai (China), and Epe (the Netherlands) are the main production locations. VMI also stores items in the TKH Group warehouse in Haaksbergen, which is a warehouse that stores items for multiple companies that are part of the TKH Group. However, this warehouse also has some external customers. The production location in Leszno only has a warehouse that receives big parts or picked parts from the Haaksbergen or Epe warehouses. So, Yantai and Epe are the only production locations that fully operate a warehouse. This research is performed at the warehouse and Supply Chain Innovation (SCI) departments of VMI Holland B.V. The (abbreviated) organogram of VMI Holland is displayed in Figure A 1 in Appendix A.1. The warehouse and SCI departments are part of the logistics department, which in itself is under the supervision of the Chief Operating Officer (COO).

The warehouse is the facility that temporarily stores parts that are needed to build the VMI machines. The inbound department of the warehouse processed approximately *xxx* thousand purchasing order lines in 2020, whereas the outbound processed approximately *xxx* thousand order lines in 2020. The difference is because certain purchasing order lines are split into multiple production orders and because some lines are picked twice. A floor plan of the warehouse can be found in Figure 1.2. The supply chain innovation department, as its name suggests, is responsible for continuously improving the internal and external supply chain of VMI.

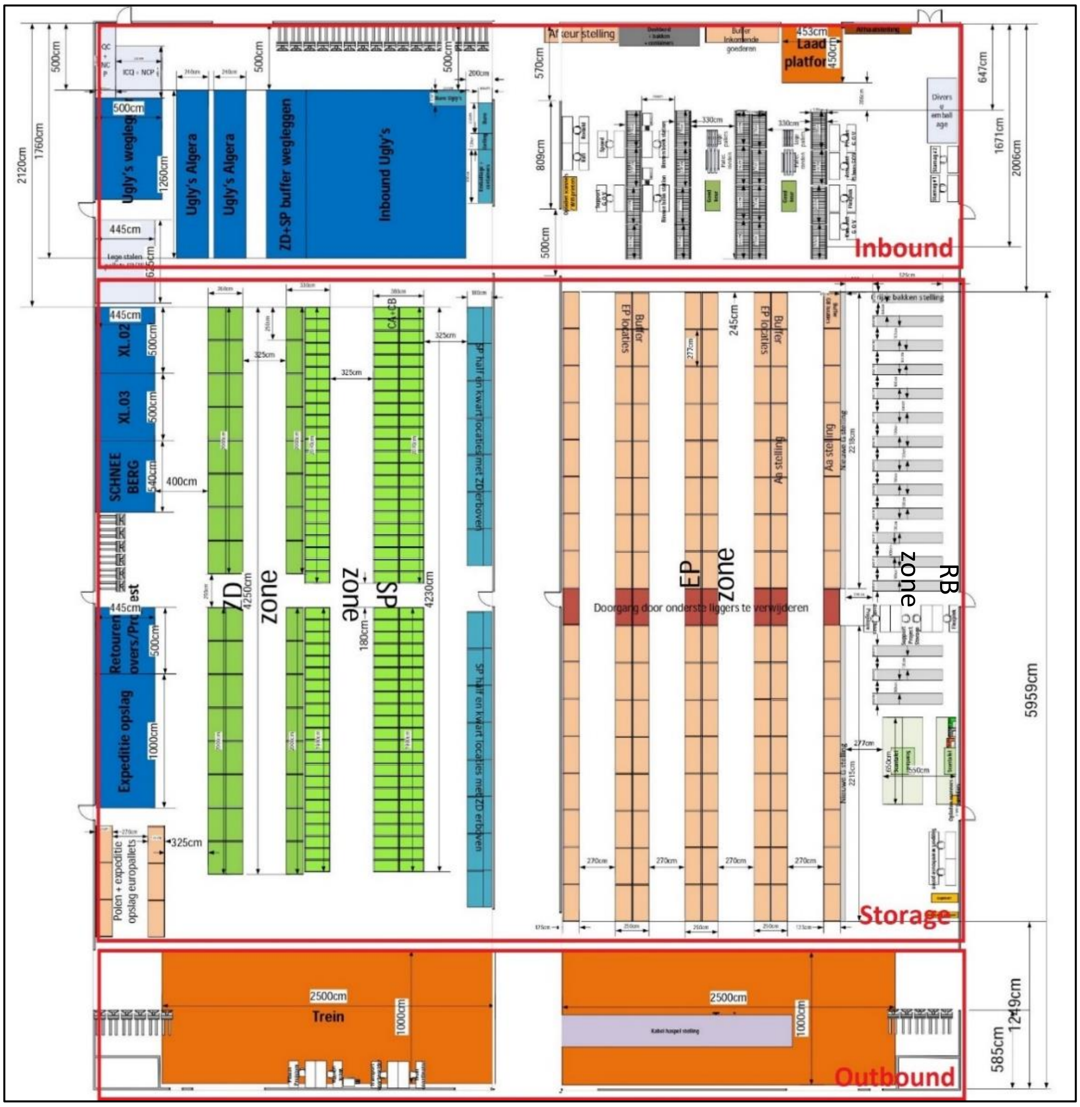


Figure 1.2: Floor plan with corresponding dimensions of the warehouse at VMI Holland B.V. Four storage zones are indicated: red box (RB), euro pallet (EP), steel pallets (SP), and self-carrying (ZD). Moreover, a division is made between the inbound (top), storage (middle), and outbound (bottom) side of the warehouse.

1.2. Problem context

This section introduces the processes at VMI, with a focus on the warehouse process and storage policy. Next, the formal definition of a storage policy is given. After this, the history of the current storage policy, causes of the action problem, and performance criteria are outlined.

1.2.1. Overview of the warehouse processes and storage and picking policy

VMI is a project-oriented organization. Its customer order decoupling point is between engineer-to-order and make-to-order. VMI attains orders for new machines from customers, after which the production of the machines starts. This production is done in phases, each phase consisting of several modules. The customer could have particular wishes to change some modules: by adding parts, size requirements, etc. The engineering department has to change the drawings to incorporate these changes, hence the engineer-to-order elements. Work preparation translates the engineering's bill of material into production orders by making make or buy decisions, doing hour calculations, and determining the routing. The machine modules consist of multiple production days, which subsequently consist of multiple production orders (POs). More information about the product structure is outlined in Section 2.1. Work preparation is also responsible for planning these POs, according to the project plan made by operations control. After work preparation, purchasing can start buying all parts needed for the POs. These individual parts arrive in the VMI warehouse.

A flowchart of the warehouse processes is displayed in Appendix A.2. A more detailed description of the current process is outlined in Sections 2.3 and 2.4. The inbound department of the warehouse receives and checks parts that arrive from suppliers. After this, they put the parts away into either the anonymous storage or the project-based storage. An item goes to the anonymous storage if it is not attached to an order yet. These are items that have: a high demand, a cheap price, a minimum order quantity (MOQ), a safety stock, a price agreement with the supplier, or ordering costs reduction when ordered together. These items are stored per stock keeping unit (SKU) in the anonymous storage, where each SKU has its own location. An SKU is an item type with a unique code and is "completely specified as to function, style, size, color, and, often, location" (Silver et al., 2017, p. 28). Items go to the project storage if they are attached to a project of a customer via an order. These orders have their own storage location in the project storage.

The VMI warehouse currently has roughly five storage zones: red box (RB), euro pallet (EP), steel pallets (SP), self-carrying (ZD), or lean lift (LL). Pictures of these storage zones are displayed in Appendix A.3. A more detailed description of these zones is given in Section 2.2. Based on the size and weight of an item, it is determined to which zone it should be allocated. Project-related items can go to either the RB, EP, SP, or ZD zones. Anonymous items are either stored in the RB zone, EP zone, or the lean lift. The EP and RB zones are in the warehouse itself, whereas the lean lifts are located at the expedition in a separate hall. Anonymous items are picked by the outbound department from the anonymous storage and put away by the inbound department in the project storage when they are needed for an order soon. Items from the lean lifts are picked three working days before production needs the order, whereas the other anonymous items are picked six working days before production needs the order.

Items are needed in production with a PO. A PO consists of several parts. When this PO is needed, all parts are picked from the project locations. The PO is put together on a steel pallet or a rack for items in the RB, EP, or SP zone. These racks and pallets are delivered to the needed production department using a tugger train system. Items stored in the ZD zone are individually delivered to production using pallet trucks. The task of the VMI warehouse is to compose the POs for production on time and complete. If this is not achieved, production cannot start on time or efficiently. The goal of the warehouse is to reach their task as efficiently as possible.

After the warehousing process, production mechanics start assembling POs and the machine is gradually built. After this, the machine is dismantled and shipped to the customer where it is installed. VMI's operations are summarized in Figure 1.3.

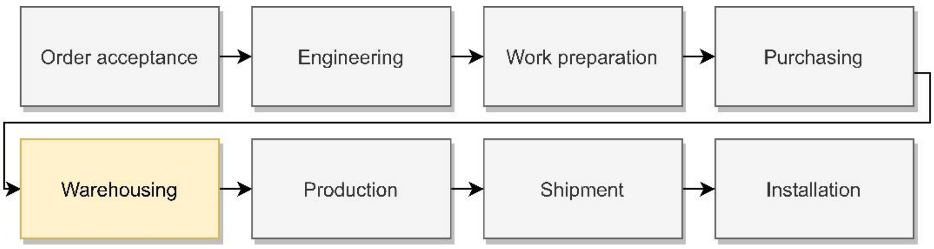


Figure 1.3: VMI's operations, summarized in eight steps.

1.2.2. Action Problem and Storage policy

The initial acquired action problem of the organization is: *is the way of processing materials based on our storage policy adequate?* In this section, the term "storage policy" is outlined. A storage policy is "the decision of which physical storage addresses to assign to which items" (Malmborg, 1998, p. 3459). In literature, three main types are mentioned (Rouwenhorst et al., 2000):

- **Dedicated storage:** which dedicates SKUs to fixed locations.
- **Shared storage:** which dedicates no location slots to SKUs.
- **Class-based storage:** allocates SKUs to classes, where classes have fixed locations, but within classes shared storage is used.

Within these three main types, multiple alternatives exist, like closest-open location assignment, object-oriented slotting, family grouping, etc. A more detailed description of storage policy literature is outlined in Section 3.1.2.

As mentioned, VMI uses anonymous storage and project storage. The anonymous articles are stored according to a dedicated storage policy on a location in the EP and RB zone. When VMI moved into the warehouse in Epe, SKUs were allocated logically by putting fast-movers on picking height or putting tools that are often needed together close to each other. The lean lift zone has its own storage policy, which can be described as a random storage policy. If an SKU is already in a certain location, a new arriving item of this SKU should be allocated to that location. If this location is full, it should be placed in another location of the same size or all items that are already in the lean lift should move to one larger location together with the new items. If no SKU of this new arriving item was already stored, it can be allocated to any empty location. The operator needs to determine the size of the location that is needed.

The project storage can be classified as a random storage policy: when an order is picked, it is free for another order to be stored. However, this is not on item level like in the lean lift, but on order level. Project locations are prioritized using a sort of ABC classification. How the current storage policy exactly works, is identified in Section 2.2.

When talking about storage policies in literature, performance is only measured on mainly two variables: the space reserved for material allocation and the time required for handling materials (Bahrami et al., 2019). The material handling time includes the put-away time and order picking time. Next to these main variables, a storage policy influences many other aspects like maintainability, the affinity of order pickers with locations, congestion in aisles, etc. More about this can be found in Section 3.1.3.

1.2.3. History of the current storage policy

The current storage policy was introduced around the economic crisis of 2009. Back then, an unrealistic goal was set for the warehouse management: use half of the people, use half of the square meters, and double the turnover. This was an unrealistic goal that was not attained, however, by setting this goal the entire warehouse system had to change. This would, for example, not happen if the goal were to improve the efficiency by 5%. Another factor back then was the ERP transition from Baan to Infor.

Before 2009, the warehouse only consisted of stacked steel pallets on which POs were collected. The turnover of VMI was also not as high as it currently is. If material came in that did not have a PO pallet yet, it was temporarily stored somewhere else and picked when a project pallet was prepared. Back then, the entire PO consisted of one machine module, that was delivered to production. In the ERP system, the entire warehouse was just one location. So, materials could not be traced except for the fact that it was somewhere in the warehouse. Therefore, a lot of product knowledge was needed from the people working in the warehouse. When materials were delivered to production, everything was checked. Because an entire module was shipped, this checking took quite some time. Moreover, if parts were missing you had to search in the entire warehouse. When the module was delivered in production, the mechanics received a lot of material in one go. So, during production, they could again start searching in this big pile.

Around 2009, VMI changed its warehouse entirely. The first idea was to make a fully automatic warehouse with automated storage and retrieval systems. However, the investment costs for these were too high. Moreover, a restriction was that the warehouse should be easily movable. So instead, the current warehouse resources were purchased: the pallet racks and bin racks. The steel pallets were kept for storing larger parts that do not fit in the pallet and bin racks, but at the same time are too small to store on the floor. Second, locations were created within the warehouse together with a scan application that was programmed next to Infor (the ERP system). The software of this scan application was programmed by VMI itself, with the aid of an external company. In this way, an operator did not need a lot of material knowledge, but most knowledge is stored in the system. In this way, your workforce can relatively easily be increased and decreased. Third, the project storage remained instead of, for example, storage per SKU like you often see in warehouses. The idea behind not storing per SKU is that VMI wants to move items as little as possible. When items are stored together in a project location, items only have to be put away once when they arrive and retrieved once when they are needed for production. Also, when picking a PO, you only have to move to a few project locations instead of completing an entire picking route across SKU locations. From this transition onwards, there was already a separate part in the warehouse for the anonymous storage. These items are picked from the anonymous storage when they are needed for an order soon. After this pick, they are put away in the project storage. So, in a way, the anonymous storage can be seen as an internal supplier for the project storage.

From 2009 onwards, with the new system in place, quite some things changed. First, the way items are delivered to production has been changed by work preparation. At first, all items of a complete machine module were delivered to production. One machine module consists of several POs. Now, not all items of an entire module are delivered to production, but POs are delivered. Therefore, the number of items that are delivered to production in one go is smaller, decreasing picking time, checking, and searching by the mechanics when items arrive. This allowed picking to start closer before the parts are needed by production. Second, the number of items that come into the warehouse has increased significantly due to the increase in turnover over the last twelve years. Third, the tugger train is used to deliver POs to the production. The train was not present when the new system was introduced.

So, in 2009, VMI went to a more professional and sophisticated warehouse which was a big improvement regarding the situation before. However, since then, much has changed. The focus on designing this new warehouse has been on the picking process. The entire PO is currently picked by only visiting the designated PO locations. At that time, it was believed that this was the best storage policy for VMI. Other alternatives like, for example, storage per SKU, were not seen as interesting alternatives because of the longer picking times.

1.2.4. Causes for the acquired action problem

The question arises, why is the acquired action problem, a problem now? Why does VMI currently want to know if their storage policy is still adequate? To identify the causes for this problem, a fishbone diagram is drawn in Figure 1.4. The causes can be divided into roughly four topics.

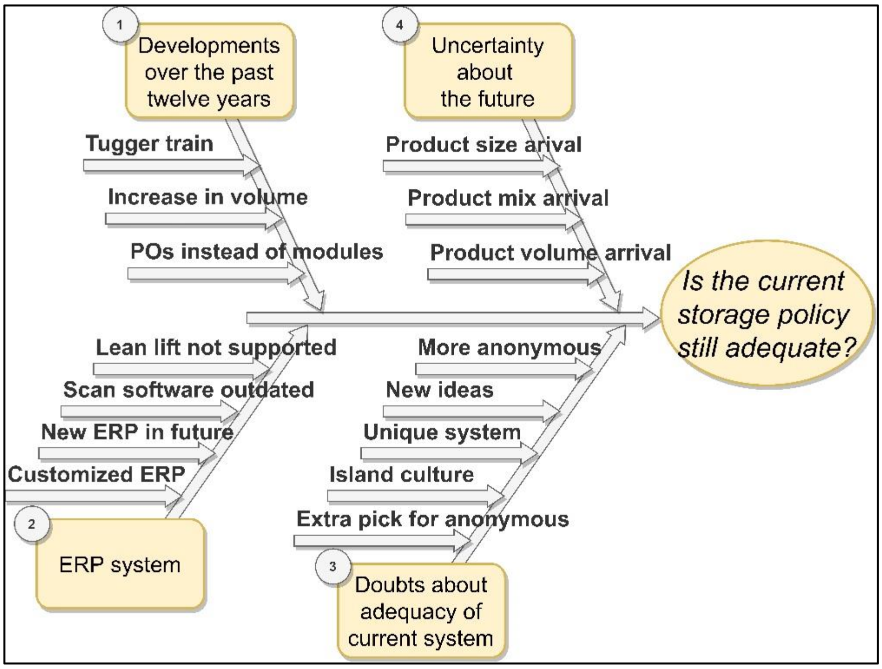


Figure 1.4: Causes for the action problem, displayed in a fishbone diagram. Four key causes are indicated, which can be subdivided into smaller sub-causes.

1. Developments over the past years

In the previous section, multiple developments from 2009 until now have been outlined. When the new storage policy was implemented in 2009, the storage policy was tested for the conditions at that time. However, the developments raise the question if the current storage policy is adequate for this situation. The increase in the volume of items that arrive and smaller deliveries to production heavily changed the warehousing process. Also, the tugger train was introduced which changed the order picking process and delivery to production. Of course, VMI already made use of some of these changes. For example, picking a PO is only done one day before the PO is needed in production. However, the storage policy has never been reconsidered while incorporating the new situation in which VMI currently is.

2. The ERP system

The ERP system changed with the warehouse in 2009. However, currently, this system is already quite old and VMI has made plans to replace the system in the coming years. The scan software was programmed as such, such that it suited the VMI warehouse and could work together with the new ERP system. Hence, it was heavily customized by VMI. The costs of this customization are quite high. So, this is not something that VMI wishes to do if not necessary. Furthermore, the current system was set up by an employee of VMI who unfortunately passed away. With him, a lot of knowledge about the system went away. So, if the system should have a malfunction in the future, quite some problems could occur. Also, the current lean-lift software, in which some anonymous items are stored, is not supported anymore. This ERP transition, just like twelve years ago, allows rethinking the storage policy, without having to change the entire system to this new policy since it can be made from scratch.

3. Doubts about the adequacy of the current storage policy

A few other problems were identified which can be classified as doubts about the adequacy of the current system:

- VMI believes that few (or perhaps no) companies use this storage policy, which raises the question if this way of working is that good. Perhaps, there are also other ways of working which might suit VMI better.
- It was identified that there is quite some ‘island culture’ at VMI. There are a lot of individual departments. Each department optimizes its own ‘island’. Moreover, some research is done about the optimization of individual departments in the VMI warehouse. However, it could be questioned if all this local optimization benefits the overall performance. To mention an example, currently, the inbound department puts away the articles as close as possible to their location at the one side of the warehouse. However, the outbound department will need to walk further since they start at the other side of the warehouse.
- Some new ideas and other storage policies have raised the attention of the warehouse management team. For example, at the Haaksbergen warehouse of the TKH Group, they use storage per receipt.
- In the current warehouse system, anonymous items that come in are stored and subsequently picked when needed for production soon. In this way, items are picked and received two times. It is a step that is maybe inefficient, but it also secures more complete and correct deliveries to production. What would happen if this step were removed and combined with when POs are picked? And what is needed to make this work?
- VMI also wishes to acquire insight into if more parts would be bought anonymously. This can save time when putting away parts since you can put multiple parts away in one go if they come into the warehouse together. More anonymous parts also bring advantages for the purchasing department since ordering cost reductions can be obtained.

4. Uncertainty about the future

Twelve years ago, VMI did not know what developments the future would bring. Currently, VMI does also not know this. However, what can be done, is to test how a potential storage policy would be influenced by different scenarios. The most important scenarios that VMI wants to test are changes in the arrival of products regarding their volume, mix, and size. What this exactly includes is outlined in the next section.

1.2.5. Performance criteria

The considered storage policies are judged on two main criteria:

- **Efficiency and effectiveness**
  Should be as good or better as the current situation, where:
  - *Effectiveness* is the maximum value for stakeholders.
  - *Efficiency* is to accomplish something with the minimum amount of money, time, effort, etc.

  What the right key performance indicators (KPIs) are to measure the effectiveness and efficiency are identified in Sections 3.1.3 and Section 4.4.4.
- **Can it cope with the long-term changing environment?**
  The policy should still work when the situation changes. Especially the following three changes are considered:
  - *Peaks in the workload:* what happens if the volume of items decreases or increases?
  - *Mix of items:* what happens if a lot of the same items (series production) or a lot of individual items (one-offs) arrive?
  - *Size of items:* what happens if the arrival of large/small items increase or decrease?

These scenarios do not come out of the blue. In the past, the VMI warehouse had busy and less busy periods (volume). Periods in which a lot of the same machines were sold and periods in which a lot of different machines were sold (mix). Periods in which mainly smaller machines (for example car tire machines) were sold and bigger machines (for example truck tire machines) were sold. Hence, the discussed scenarios.

As mentioned, the current system is difficult to implement in the new ERP system. However, it is not a hard restriction that this should not be true for an alternative storage policy. For example, when the current storage policy is more efficient and robust than another storage policy, but more difficult to implement in the ERP system, this could be a worthwhile investment.

1.2.1. Previous research at the VMI Warehouse

VMI has had multiple graduation assignments at the SCI and warehouse departments. Not all of them are described here but some that are closely related to this research are:

- Luigjes (2020) researched the allocation of stock to the red boxes or the lean lift. He advised allocating more anonymous stock to the lean lifts to save space and processing time.
- De Rooij (2020) researched the use of lean lifts. It was recommended that the four lean lifts should be replaced with newer lean lifts.
- Veldhuis (2016) analyzed the euro pallet zone. His advice was to halve the pallet locations on the first and second row.
- Marijn Bastiaannet (2018): researched optimization possibilities at the inbound department of the warehouse. He made a complete value stream map of the inbound process.
- Brummelhuis (2016) researched optimization possibilities at the inbound department and performance measurement for the VMI warehouse.

1.3. Research Scope and Goal

In this section, the research scope of the research is defined. Also, the method to assess potential solutions is chosen. To summarize this part, the research goal is stated.

1.3.1. Scope

The article of Rouwenhorst et al. (2000) is used to clearly define the scope and position of this research. In this article “a reference framework and a classification of warehouse design and control problems” (Rouwenhorst et al., 2000, p. 1) are given. The chosen scope can be seen in Table 1-1. The table shows that the problem scope is on a strategic and tactical level. The storage policy itself is a strategic decision, whereas the dimensions of the resources are mainly tactical decisions.

Table 1-1: The scope of this research, defined with the aid of Rouwenhorst et al. (2000).

Include in scope	Exclude from scope
Processes - Item arrival - Receiving - Storage - Picking - "Shipping"/Train loading: items are put on the train and delivered to production Organizational - Storage policy - Locations needed - Number of personnel Resources - The resources currently in place	Processes - Purchasing - Work preparation - Production Organizational - Considering automation - Dimensions of the warehouse itself - Sorter lane assignment (not present) - Dock assignment - Procurement decisions next to buying more SKUs anonymously - Layout - Process flow - Picking process in itself Resources - Storage unit, storage system, pick equipment, computer systems, order pick auxiliaries, and sorter systems - No other systems than currently in place, but dimensions may be expanded

The VMI warehouse in Epe has multiple outgoing product flows: warehouse orders (26%), production orders (73%), and sales orders (1%). These percentages are based on the outbound data from 2020. This research focuses on all three types of flows. Furthermore, in the inspection step, it could be that item quantities are not right, products are damaged, etc. This rejection flow is not considered. Hence this research only focuses on the main flow of products from arrival to production.

All warehouse processes are included. From the arrival of an item until an item is picked for an order and loaded on the train. The receiving and shipping steps are only included superficially, whereas the storage is considered in detail. The put-away and picking process is considered because it is heavily influenced by the storage policy. However, this research does not go into the optimization of routes itself. This could be a topic for further research. Other processes, like work preparation, production or purchasing are not considered. It is assumed that items come into the warehouse, either anonymous or project-based. These items are needed at some time in production.

Regarding the organizational dimension, only the storage policy is considered together with the dimension of resources. Other organizational issues are left out of the scope.

Regarding the storage resources, only the resources that are currently in place are considered. The locations that are considered are the red box (RB), euro pallet (EP), steel pallets (SP), self-support carriers (ZD), and lean lift (LL). The floor stock is excluded. An external company takes care of this stock. Moreover, 'exclusive stock' like the tubes and cables on rolls, calibration, and some others (for example in a container outside, etc.) are excluded.

Lastly, the warehouse of the production location in Yantai is excluded. However, this can be considered by also testing their item characteristics. For example, in Yantai, larger parts come in. With a simulation model, this can relatively easily be changed by generating more larger items. In this way, the performance of other storage policies can also be tested for this location.

1.3.2. Method selection

There are multiple ways to study a system (Law, 2015):

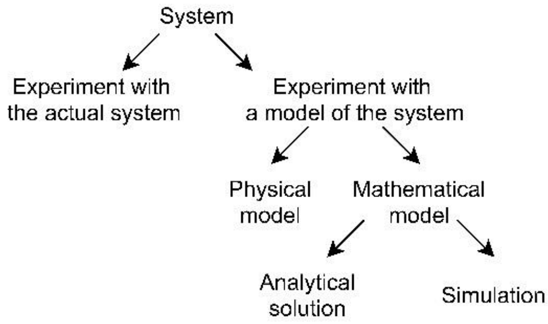


Figure 1.5: Ways to study a system (Law, 2015).

However, based on the problem size and complexity, an experiment with the actual system or physical model is not suitable. Hence, to analyze the performance of several storage policies based on robustness, efficiency, and effectiveness, simulation is used as an operations research technique. Simulation can be defined as "a technique that imitates the operation of a real-world system as it evolves over time" (Winston, 2004, p. 1145). Preferably, an analytical model would be used. However, Frazelle (1989) classifies the problem as NP-hard. In the case of VMI, the problem size is quite big due to the many items coming in and going out of the warehouse. Also, the real-life situation has quite some exceptions: VMI does not have the most straightforward warehouse, items come in with different numbers, sizes, and attributes, storage options are different, etc. Hence, it would be difficult to analyze this analytically, without making (too) many simplifications and assumptions. The problem at hand also involves quite some stochasticity, think about the arrival of items and processing times. A simulation model can incorporate this stochasticity well even if the (assumed) distributions are different. With other models, this is difficult. Lastly, VMI wishes to look at multiple scenarios (change in product mix, size, and volume) and interventions (storage policies). Also for this, a simulation model is well-suited. If the simulation model is set up, these new interventions can be implemented and immediately be tested. An alternative could be that VMI tests this in a real-world experiment, which is too costly.

Of course, simulation has its disadvantages. First, it is not an optimization method. Beforehand, multiple interventions should be thought of which can subsequently be tested in the model. Even though simulation can be used for optimization, it is relatively slow. Second, it is quite time-consuming to build a simulation model. Third, the output of a simulation model is random since its inputs are also random. Hence, the output is only one point estimate of system performance. Therefore, it should be repeated multiple times. Furthermore, statistical tests should be used to compare alternatives. Lastly, at times there is some tendency to put too much confidence in the study's results (Law, 2015; Winston, 2004).

Despite the disadvantages of simulation, it is still chosen to continue with this approach due to the problem size, system complexity, stochasticity involved, and the number of scenarios and interventions that VMI wishes to test in the model.

1.3.3. Research Goal

To summarize the aforementioned: the goal of this research is to provide the management of VMI insight into an efficient and effective storage policy for the VMI warehouse. However, this also heavily influences the picking process. In addition, some alternatives, like picking anonymous items simultaneously with project items, only change the way items are picked, not stored. Hence, the order picking policy is also considered. This is done by describing the current situation at VMI. Next to that, other alternatives are generated. The current and alternative policies are tested based on efficiency and effectiveness. Which KPIs are needed to evaluate this, is determined in a literature study. The policy should be robust to the changes that could occur in the future. A simulation model is a good tool to test the policies against different scenarios. With simulation, it can be analyzed how the different interventions behave under different scenarios. Which alternatives, scenarios, and KPIs are tested in the simulation model, are determined with the relevant stakeholders. Based on the analysis of the results of the simulation model, recommendations are given to VMI.

1.4. Research question(s) and research design

To answer the action problem and fulfill the research objectives mentioned above, the following research question is formulated:

*What is an **efficient and effective storage and picking policy** for the VMI warehouse that can cope with the **long-term changing environment?***

The keywords are displayed in bold. The (current) storage and picking policies are explained in Section 1.2, together with the meaning of efficiency, effectiveness, and what is included in the long-term changing environment. The latter has been mentioned separately since the storage policy should be able to cope with the changing environment and, preferably, it should be more efficient and effective than the current situation. This question is answered in five steps (see Figure 1.6). In each step, research questions are answered, which subsequently contain several sub-questions.

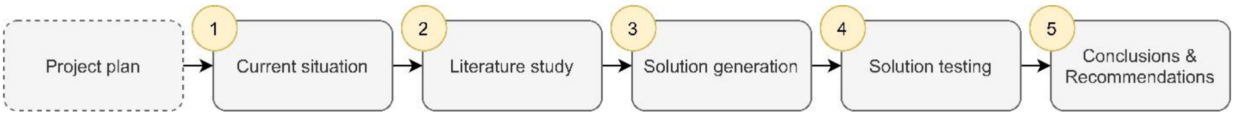


Figure 1.6: The five steps that are followed to answer the main research question.

Step 1: Current situation/data gathering (Chapter 2)

The main question in this phase is about the current situation at the VMI warehouse.

1. *What are the characteristics of the current warehousing process at VMI?*
   1.1. What is the product structure of a VMI machine?
   1.2. How are items currently stored?
   1.3. What are the characteristics of the items that arrive?
   1.4. How are items requested by production?
   1.5. What do orders in the warehouse look like?
   1.6. What other resources are present in the warehouse?
      1.6.1. What does the tugger train look like?
      1.6.2. Which ERP system(s) is/are used in the warehouse?
      1.6.3. What are the working hours in the warehouse?
      1.6.4. What happens when all locations in the warehouse are occupied?
   1.7. What are the throughput times at each relevant process (receiving, storage, picking, and shipping)?

The first step is about getting to know the VMI warehouse in detail. Question 1.1 briefly outlines the product structure of VMI machines, which determines the item arrival in the warehouse. Question 1.2 outlines the current storage zones, the dimensions of these zones, and the current storage policy. In question 1.3 the item arrival is investigated. In what quantities do they arrive? How is it determined to which storage option an item is assigned? What makes an item anonymous? How is this determined? These questions are covered here. Question 1.3 dives into the arrival process of these particular items whereas Question 1.4 looks at the other side: how are items requested and picked? Question 1.5 looks closer at the demand for production orders, warehouse orders, and sales orders. Question 1.6 looks at the tugger train, the ERP system, the working hours in the warehouse, and what happens when an item cannot be stored in its destined zone because all locations are occupied. Question 1.7 is needed to determine the process times of separate stages in the VMI warehouse. This is important for the simulation model described in step 4. Data is gathered via interviews, the ERP system (with the attached SQL server), reading through documents, and observation.

Step 2: Literature study (Chapter 3)

In this step, two questions are answered, regarding warehousing and simulation literature.

2. *What are alternative storage policies for the VMI warehouse?*
    2.1. What are the characteristics of a warehouse?
    2.2. Which alternative storage policies does literature suggest?
        2.2.1. What are the (dis)advantages of these policies?
    2.3. What are relevant KPIs to measure the effectiveness of a warehouse process?
    2.4. What are relevant KPIs to measure the efficiency of a warehouse process?

The second step consists of consulting literature to acquire knowledge about the relevant topics for this research. First, the warehouse function is outlined, together with its activities, and resources. This is done to get a proper overview of what a warehouse includes and what its function should be. Second, alternative storage policies are investigated. Third, it is determined which KPIs describe the efficiency and effectiveness of a warehouse. The results from this literature study are used in the next step.

3. *How should a proper simulation study be conducted?*
    3.1. What types of simulation can be used?
    3.2. What steps should be followed in a sound simulation study?
    3.3. How can the simulation model be verified?
    3.4. How can the simulation model be validated?
    3.5. How should experiments be set up with a simulation model?
    3.6. How can results from the simulation model be analyzed?

Question 3 (and its sub-questions) are needed to perform a proper simulation study. By identifying this in an early stage, it is observed if all needed data was present and which steps had to be followed such that it was clear what still had to be done. By also already outlining the techniques used to compare alternatives and results from the simulation model, it is clear how results are obtained.

Step 3: Solution generation (Chapter 4)

In this step, solutions are generated and selected. So, this step includes two questions.

4. *What are interesting alternatives and scenarios to test in the simulation model?*
    4.1. Who are the important stakeholders to be included in the decision-making?
    4.2. Which KPIs does VMI currently use in the warehouse?
    4.3. Which alternative storage policies does VMI have in mind?
    4.4. To which scenarios should the storage policies be tested?

This step mainly consists of generating solutions, opposed to selecting them. Important stakeholders for this research are identified here. They are involved in the solution generation and decision-making.

In step 2, several KPIs have been considered to analyze the system. Here, this is compared to the KPIs actually in use at VMI. Next to that, alternative storage policies are formulated. These storage policies should be robust to certain scenarios. So, these scenarios are also formulated here. To acquire the right input from each stakeholder, multiple meetings are planned to acquire input from each stakeholder together with gathering opinions via a questionnaire.

5. *What are the scenarios and interventions that should be tested in the simulation model?*
   5.1. Which interventions should be tested in the simulation model?
   5.2. Which scenarios should be tested in the simulation model?
   5.3. Which KPIs does VMI want to include in the research to measure the efficiency and effectiveness of the warehouse?

In the fifth question, the relevant stakeholders select alternatives that are interesting for VMI. The same goes for relevant scenarios and KPIs on which the storage policies are tested. In this step, a lot of meetings are planned to gather enough opinions and to come to a consensus between all stakeholders.

Step 4: Solution testing (Chapters 5 and 6)

In this step, the selected solutions are tested using a simulation model. Again, two questions are posed.

6. *What does the simulation model of the VMI Holland warehouse look like?*
   6.1. What does the conceptual simulation model of the VMI warehouse look like?
   6.2. What does the simulation model of the VMI warehouse look like?
   6.3. To what extent is the simulation model verified?
   6.4. To what extent is the simulation model valid?
   6.5. How should experiments be set up?
   6.6. Which experiments should be run?

In this part, the techniques discussed in Question 3 are used. Here, the actual simulation model is created. For this, the steps in Figure 1.7 are followed. First, a paper model is created. The relevant stakeholders first have to accept this paper model. When the model was accepted, the computer model was programmed. Verification is about how the paper model is implemented into the computer model. Validation is about how accurately the computer model describes the real-world situation. The experimental setup is important to determine the warm-up period or initial conditions, together with the run length and the number of replications. Lastly, based on the results from the fifth question, it is outlined which experiments are run with the model.

7. *What are the results from the simulation model?*

Finally, the simulation model results are outlined and analyzed. This is done using tables and visualizations. The results are not only posed but they are also analyzed and discussed such that there is no doubt about why these results come out of the simulation model. In this way, mistakes are spotted if it turns out that output does not make sense.

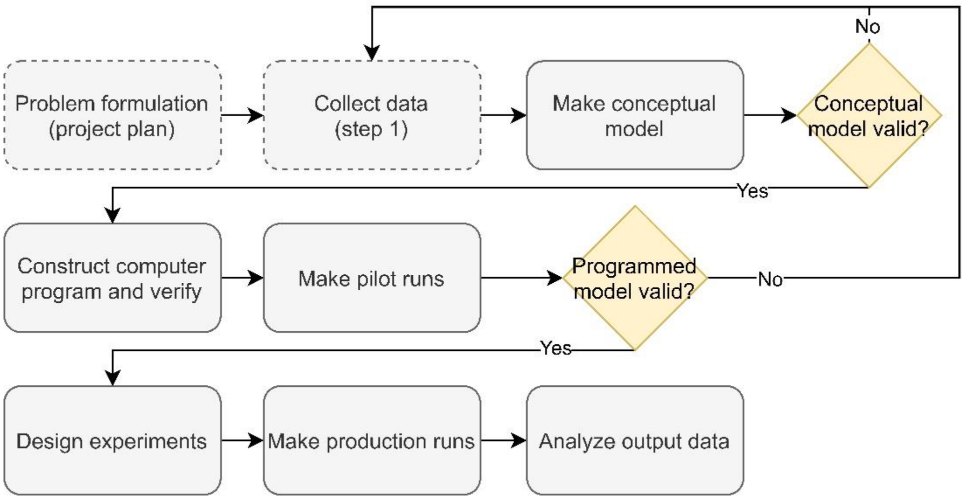


Figure 1.7: Steps followed in a simulation study (Law, 2015, p. 67).

Step 5: Conclusions and recommendations (Chapter 7)

Lastly, based on the results, conclusions can be drawn and discussed using the following question.

8. *Based on the results from the simulation model, which storage policy is most efficient and effective while being able to cope with the long-term changing environment?*
   8.1. Which storage policy is the best alternative for the VMI warehouse?
   8.2. What are the limitations of this research?

Based on the analysis in step 7, conclusions are drawn, and recommendations are given to the board of VMI. The best alternative is recommended, together with outlining what is needed for this alternative to work. Lastly, the limitations of the entire research are discussed together with its contribution to literature and practice.

1.5. Deliverables

Based on the plan of approach, the following deliverables are provided to VMI at the end of this research:

1. An analysis of the warehouse processes at VMI that are included in the scope.
2. An overview of alternative storage policies in literature.
3. An assessment of the alternative storage policies based on stakeholder's opinions.
4. A simulation model of the current VMI warehouse.
5. An analysis of the results from the simulation model.
6. Recommendations regarding the best storage policy/policies for VMI, based on the results of the simulation model.
7. An implementation plan for the best storage policy/policies.

1.6. Summary: key points from Chapter 1

At the end of each chapter, the key points of that chapter are summarized.

- This research is performed at the supply chain innovation (SCI) and warehouse departments of VMI Holland B.V.
- The acquired action problem was: given the current situation, is the way of processing materials based on our storage policy adequate?
- This problem appears due to four main causes: developments over the past twelve years, the ERP system, doubts about the adequacy of the current system, and uncertainty about the future.
- An alternative storage policy should be efficient, effective, but also robust against possible future developments.
- It is decided to use a simulation model to study the VMI warehouse due to the problem size, system complexity, stochasticity involved, and the number of scenarios and interventions that VMI wishes to test in the model.
- The central research question of this research is: *What is an **efficient and effective storage and picking policy** for the VMI warehouse that can cope with the **long-term changing** environment?*
- This research question is answered in five steps: describing the current situation, doing a literature study, generating alternative solutions, testing these solutions, and giving recommendations. During these five steps, one/two research question(s) is/are answered that can be subdivided into multiple sub-questions.

2. Data Gathering and Analysis

This chapter outlines the current situation at VMI. It starts by outlining the product structure of VMI machines, the current assignment policy, zones, and locations. This is followed by a description of the arrival (put-away) and demand (picking) of items. The chapter ends with some general resource descriptions and a discussion about throughput times.

2.1. Product structure

The product structure of a VMI machine is displayed in Figure 2.1. This is briefly explained to describe the origin of the demand and supply side of the VMI warehouse.

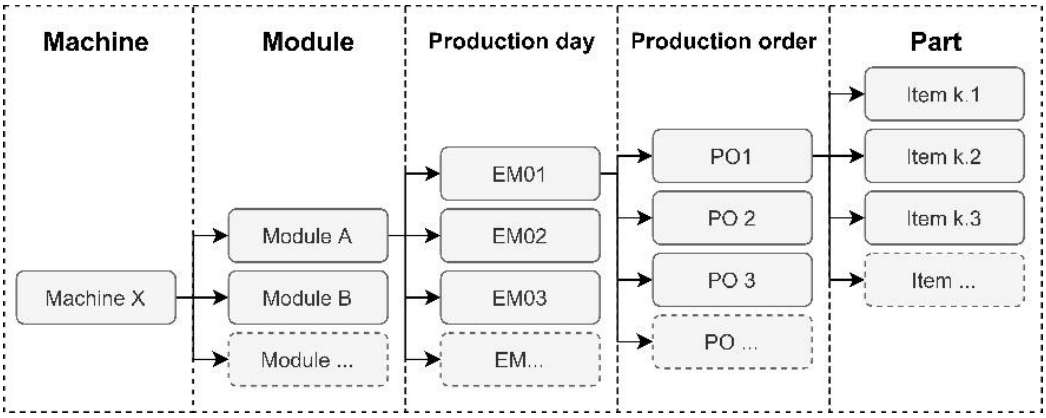


Figure 2.1: The product structure of a VMI machine, based on Brummelhuis (2016). The figure shows that a VMI machine can be subdivided into four sub-layers: modules, production days, production orders, and parts.

VMI machines are subdivided into several modules. Each module consists of several production days (also referred to as a 'pluk'), which in itself contain multiple POs. These POs consist of one or multiple items. At the VMI warehouse, individual items arrive at the inbound department, either anonymous or project-related. Items are requested by production via a PO. The outbound department of the warehouse picks these POs. Hence, the individual items that arrive at different moments in time, need to be consolidated to a PO somewhere in the warehouse. Next to POs, the warehouse has to deliver a few different types of orders, which also consist of one or several items. More about these orders in Section 2.4.

2.2. Current storage zones, locations, and storage policy

This section outlines the current storage zones, locations, and assignment policy in use at the VMI warehouse. The storage location assignment problem (SLAP) is the main part of this research, hence, it should first be identified what the current storage policy is. The storage zones and locations determine the capacity of the warehouse. The capacity needed is partly determined by the storage policy. Hence, the storage zones and locations are identified here.

2.2.1. Storage zones

VMI has five main storage zones in its warehouse, with the codes given in the parentheses. In this section, pictures of some storage options in the red box (RB), lean lift (LL), euro pallet (EP), and steel pallet (SP) zones are shown. However, pictures of all storage options in each zone are displayed in Appendix A.3.

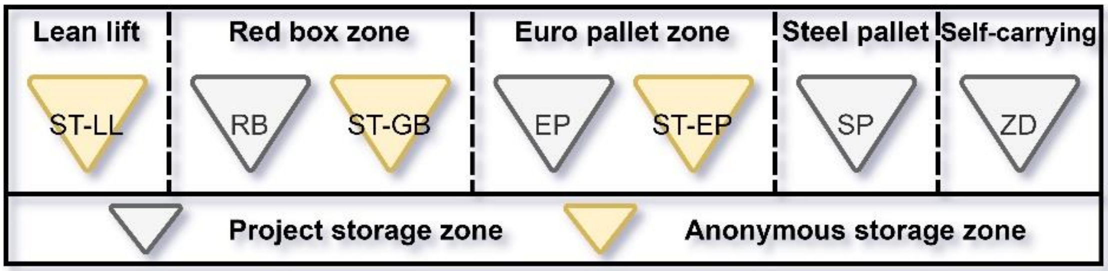


Figure 2.2: An overview of all five storage zones at VMI, subdivided into seven sub-zones indicated with codes, dependent on if it stores anonymous or project-related items.

Table 2-1: Data about the five storage zones at VMI (March 2021). The table contains data about the red box (RB), euro pallet (EP), steel pallet (SP), self-carrying (ZD), and lean lift (LL) zones.

Zone	RB	EP	SP	ZD	LL
Max. surface size of item (cm)	35x26	115x75	175x60	> 175x60	35x26
Max. height of item (cm)	12	40	70	> 70	12
Max. weight of item (kg)	18	> 18	> 18	> 18	1[1]
Number of locations (#)	6440	3830	615	128	9301
Number of project storage locations (#)	4000	1863	615	128	0
Number of anonymous storage locations (#)	2440	1967	0	0	9301

1. Red box (RB) zone

The RB zone consists of grey plastic boxes stored in bin racks, also see Figure 2.4 (or Figure A 5). An item is allowed in a grey box if its surface is less than 35x26cm and the item height is less than 12cm. For ergonomic reasons, a grey box may not weigh more than 18 kilograms. The RB zone consists of 4000 project storage and 2440 anonymous storage locations. The project locations within the RB zone are indicated as the "RB zone", whereas the anonymous storage locations in the RB zone are indicated as the "ST-GB zone". "ST" stands for standard and "GB" for grey bin (also see Figure 2.2 above). The question arises: why is this zone called "red box" if it only contains grey boxes? This is since these boxes used to be red. Lastly, in the ERP system, the RB zone indicates more locations since some 'special locations' are also part of the RB zone, like for example lockers. These are not considered in this research.

2. Euro pallet (EP) zone

The EP zone consists of euro pallet locations stored in a pallet rack, also see Figure 2.3 (or Figure A 6). The size of a euro pallet is 120x80cm, however, due to the pallet collars, items of at most 115x75cm can be stored in the EP zone. The item height can at a maximum be 40cm. There is an exception though. Since anonymous items are only stored in the RB or EP zone, a problem occurs for anonymous items with a larger surface than 115x75 or a bigger height than 40cm. These items are stored in the "AJ" locations. The AJ location is a pallet rack location in a separate area in the warehouse, also see Figure A 7. This rack is a bit further away from the wall. Moreover, the number of floors is smaller allowing higher items to be stored.

[1] Not a hard restriction

Of the 3830 pallet locations, 1967 locations are anonymous locations (the AA-AD and AJ locations), and 1863 locations are project locations (AD-AH locations). Of these locations, 2754 locations (project 1242 locations, anonymous 1512 locations) are ½ pallet locations, whereas 1005 locations (project 621 locations, anonymous 384 locations) are full pallet locations. The other 71 locations are the "AJ" locations. The project locations within the EP zone are indicated as the "EP zone", whereas the anonymous storage locations in the EP zone are indicated as the "ST-EP zone" (also see Figure 2.2 above).

Figure 2.3: Pallet locations in the EP zone (Pannekoek, 2020).

Figure 2.4: Grey boxes in the RB zone (Pannekoek, 2020).

3. Steel pallet (SP) zone

The SP zone consists of steel pallets and storage compartments in a euro pallet rack, also see Figure 2.5 (or Figure A 8 and Figure A 9). Of the 615 project locations, 135 locations are floor locations for steel pallets and 480 are pallet rack compartments. Steel pallets are 180x80cm. Though, due to the stacking posts, items allowed on steel pallets are at most 175x60cm. The maximum allowed item height is 70cm. The stacking height is dependent on if steel tubes are used to stack the pallets or not. This consequently depends on the item's height. On one floor location, multiple projects may be stored.

The pallet rack in the SP zone is for project items that would fit in an EP based on their height and width, but not on their length, like bars, tubes, etc. The pallet rack is a bit further from the wall, allowing longer items to be stored than in the EP zone. The pallet rack compartments are subdivided into twelve 'sections'. One section has a width of three euro pallets. Of the 480 pallet rack locations, 192 locations have the width of 1/16 section, whereas 288 locations have the width of 1/8 section.

4. Self-carrying (ZD) zone

The ZD zone consists of large steel pallets, cantilevers, floor locations (XL), and pallet rack locations, also see Figure A 10, Figure A 11, Figure A 12, and Figure A 13. Of the 128 project locations, 72 locations are within the pallet rack, 48 locations are large steel pallet locations, 5 locations are cantilever locations, and 3 locations are floor locations.

Large steel pallets are 140.5x102.5 cm. The stacking height is dependent on if steel tubes are used to stack the pallets or not. Cantilevers are used for items that, for example, arrive in long wooden boxes (also see Figure A 11). Floor location items are items that cannot be stored on anything else and can carry themselves like large frames, electrical cabinets, etc. One pallet rack location in the ZD zone has the size of one euro pallet location. Items going to this zone are project-related items, with the surface of a pallet location but with a height higher than an SP location.

5. Lean lift (LL)

The lean lift data is based on Luigjes (2020). The lean lift is shown in Figure 2.6 (or Figure A 3 and Figure A 4). Currently, VMI has four lean lifts. Each lean lift has 80 different trays. The number of locations per tray differs (and hence differs per lift). The sizes of these locations together with how often they occur can be found in Appendix A.4. In total there are 9301 locations in the lean lift. Roughly 7178 locations have the size of half a grey bin, whereas 2123 locations have the size of a full grey bin (Luigjes, 2020). Since the lean lift only contains anonymous items, it is often indicated as “ST-LL” (standard lean lift, also see Figure 2.2 above).

There is not a particular separation between items that are allowed in the RB zone and items that are allowed in the lean lift. However, some items that are currently in the RB zone are not in the lean lift since the software cannot deal with their item codes. Also, items that are quite heavy cannot be stored in the lean lift since trays have a maximum allowed carrying weight. This is not a hard restriction per item but based on the total tray weight.

Figure 2.5: Stacked steel pallets in the SP zone (Pannekoek, 2020).

Figure 2.6: Lean lifts in use at VMI (Pannekoek, 2020).

2.2.2. Current storage assignment

VMI currently has two storage assignment policies, dependent on the item type and in which zone it is stored.

Project storage

Project-related items, items that, when they arrive, are already attached to an order, are stored per order. These orders are stored in one or multiple project storage locations in the RB, EP, SP, or ZD zone. In this way, the entire order is composed while items are being put away. This benefits the picking process who can subsequently pick the assigned locations when an order is needed. When an order location is full, but not all items of the order have already been put away, a location nearby (preferably next to it) is filled. In the ERP system, locations have infinite capacity. When an order is picked, the location becomes free again and any new order can be stored in that location.

Underlying the project storage in the RB, EP, and SP zones is a location prioritization. The ZD zone does not have prioritization since putting away items in this zone is mainly dependent on their size. The prioritization is on a scale of 1 to 999, where locations with 1 have the highest prioritization and locations with 999 have no prioritization. The employee who puts away the articles gets advice for the location with the highest prioritization that is not occupied if it is the first item of a new order. Items close to the inbound department, on picking height (e.g. storage height 2 and 3) are filled first. For example, in the EP zone, first, the AE.02.02 is filled, then AE.02.03, then AF.02.02, AF.02.03, then AG.02.02, etc. So first, the locations close to the inbound department are filled, in different aisles. The goal of this is to prevent congestion in the aisles when orders are picked. If already one item of an order has been put away, the system instructs the employee to put away the other items of the order in the same location. This prioritization raises the question: does the prioritization disbenefit the outbound department who have to walk further to the other side of the warehouse to pick all items? This is true, however, the inbound has to put away multiple items at once, whereas the outbound department only has to pick the order locations which are usually fewer than the inbound has to put away.

To classify this storage, it can be classified as a random storage policy. The closest open location (COL) is filled first and when a location is emptied, it is opened for other orders. However, this random storage policy is not on item level but order level. Also, not exactly 'the closest' open location is filled first since items are also distributed over the aisles, however, the extra walking distance in comparison to the closest open location policy is small.

Anonymous storage

Anonymous storage is for items that are not attached to an order when they arrive. These anonymous items are stored in the anonymous locations in the RB zone, EP zone, or lean lift. Also called respectively the ST-GB, ST-EP, and ST-LL zones (also see Section 2.2.1). In the anonymous storage, storage per SKU is used: each item code has its own location. A fixed location might be removed when the physical stock is zero at a certain moment in time, such that other SKUs can use that location. Though, when this SKU comes in again, it gets a new fixed physical location. To maintain this, control reports are printed and checked. In the ERP system, the lean lift is seen as one location on which multiple items can be stored whereas the anonymous euro pallet and red box zone are divided into individual locations per SKU like for example AA.52.03 or BT.13.10. If all items of this type that should be stored do not fit into one location anymore, a new open location is searched, preferably as close as possible to the other SKU location.

Within the lean lift (ST-LL), a random storage policy is in use. When an item is already in the lift and a new package of this item arrives, the lift assigns the new package to the locations that are already occupied by this item. If the new package does not fit into this location, the lift searches for a new location somewhere else in the lift, of the same size. If the operator of the lean lift is busy, he or she puts the new package in this new location. The operator could also choose to pick all items from the current location and assign a larger location to the new package and the items that were already in the lift, which takes more time. If an item does not have a location yet, it can be stored in any open location. The operator needs to determine the size of the location he/she wants if the item is completely new to the system. If the item has already been in the lean lift before, the system remembers the location size it used to have. If a location is emptied, it becomes free for any other item. Within the lift, no class-based storage is used.

Within the ST-GB and ST-EP zone, dedicated storage with ABC classification is used. ABC storage is used such that items that are often needed are put away on and picked from ergonomically favorable locations. However, the warehouse employees also consider the fact that items that look alike are separated. When anonymous items are picked by the outbound department, they are put away behind the tracks at the inbound department. The inbound department subsequently puts away the items in the project storage. So, in a way, the anonymous part of the warehouse can also be seen as an internal supplier for the project storage.

The aforementioned is summarized in Table 2-2. VMI uses a hybrid form between storage per project and per SKU. In general, it can be said that the current storage policy suits the order picking process since the outbound department only has to pick the project storage locations when an order is requested. The storage policy is capable of processing both flows (anonymous/project) of material. A big disadvantage is the extra pick and put-away step between the anonymous and project storage.

Table 2-2: A summary of the storage policies at VMI, together with the advantages and disadvantages of these policies.

<table>
<tr><th>VMI name</th><th>Zones</th><th>Storage policy</th><th>Advantage</th><th>Disadvantages</th></tr>
<tr><td>Project storage</td><td>RB, EP, SP, and ZD</td><td>Random storage on order level with COL</td><td>Consolidation of orders per storage benefits the picking process.
Prevention of congestion in aisles.
Fast put-away regarding prioritization.</td><td>Slow put-away since items need to be sorted over multiple locations.
Prioritization disbenefits the outbound department.</td></tr>
<tr><td rowspan="2">Anonymous storage</td><td rowspan="2">RB (ST-GB), EP (ST-EP), and LL (ST-LL)</td><td rowspan="2">Dedicated storage with ABC classification for RB and EP, random storage in LL</td><td colspan="2">Moderate picking times due to class-based storage with dedicated storage.
Moderate space utilization due to maintenance of dedicated storage.</td></tr>
<tr><td>Good space utilization in lean lift due to random storage.</td><td>No clustering of items due to random storage, increasing picking times.</td></tr>
</table>

Note that the locations of these storage zones are displayed on the warehouse map in Section 1.1.

2.3. Item arrival and characteristics

Since the storage zones, locations, and policies are known, it is time to zoom in on the items that arrived in the warehouse and the processes these items go through. This item arrival determines the locations and handling needed in the warehouse, which is again influenced by the storage policy.

2.3.1. The inbound process

Items arrive at the inbound department, as mentioned, either anonymous or project-related. If items arrive, they are placed in front of the inspection tracks. First, they are booked-in, where packing lists are checked on quantities, articles numbers, and order numbers. When items are booked, items are ready to be inspected and are allocated to transport carriers. This transport carrier is a unique bar-code. The assigned transport carrier is done based on the weight and size of the item. However, when items are anonymous, they are allocated to the ST-GB zone, ST-EP zone, or lean lift (ST-LL). When items are project-related, they are stored in the RB, EP, SP, or ZD zone. An employee behind the inspection tracks puts away the articles in the destinated zone, after which the items are stored. An overview of all processes in the inbound department is displayed in Appendix A.2.

2.3.2. Number of incoming lines and anonymous items

Over the last four years the number of arriving items was as follows:

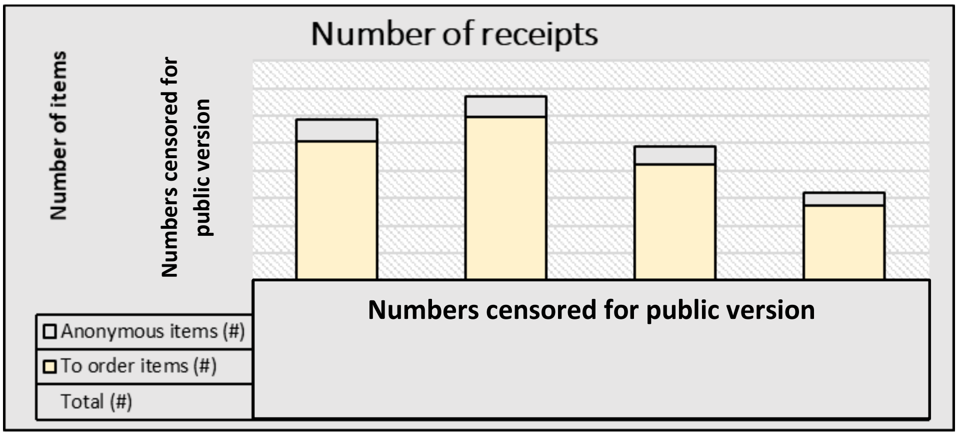


Figure 2.7: The number of arriving items over the years. A distinction is made between project and anonymous items (ERP, Location Transaction History, 20xx-20xx).

In 2020, of the arriving purchasing orders, 14.6% is anonymous and 85.4% is project-related. An anonymous item can be anything, from small stickers to even frames. So, what determines an anonymous item? Anonymous items have one or more of the following characteristics:

- A high demand
- A minimum order quantity (MOQ)
- A safety stock (due to long lead times or uncertainty in demand)
- A price agreement with the supplier
- Ordering costs reduction when ordered together

Zooming in a bit closer, anonymous items were divided as follows over the three anonymous storage zones:

Table 2-3: Division of anonymous items over anonymous storage zones (ERP, Location Transaction History, 2020).

Anonymous storage	Anonymous items (#)	Anonymous items (%)
ST-GB	A	22.0%
ST-EP	B	32.5%
ST-LL	C	45.5%

And the following division can be made for project-related items:

Table 2-4: Division of items over project storage zones (ERP, Location Transaction History, 2020).

Project storage	Put-away of items from suppliers		Put-away from the anonymous storage	
	Items (#)	Items (%)	Items (#)	Items (%)
RB	A	61.2%	A	90.9%
EP	B	27.6%	B	8.1%
SP	C	5.7%	C	0.6%
ZD	D	5.5%	D	0.4%

Figure 2.8: One red box (RB) or grey bin (GB).

Anonymous items are picked from the anonymous storage when needed for a production order soon. These picked items are subsequently placed behind the inspection tracks, after which they are put away in the project storage. Anonymous items from the lean lift and ST-GB zone are put away in the RB zone, whereas anonymous items from the ST-EP zone are put away in the EP-zone. The lean lift and ST-GB items are collected per order in an RB. Hence, they are also subsequently put away per RB. If the entire RB fits in the already existing order location, all items are added to that location. If the entire collected RB does not fit or the order does not have a location yet, it is added to a new open location. ST-EP items are picked and subsequently put away item by item.

When summing the numbers in Table 2-3 and Table 2-4 and comparing these to Figure 2.7, a discrepancy can be observed. This is because one incoming line can be allocated over multiple locations in the project and anonymous storage. One reason for this is space constraints, for example, if the entire receipt does not fit into one location. Another reason is the fact that one receipt can be broken down for multiple orders, resulting in multiple put-aways.

2.3.3. Seasonality

Lastly, the seasonality of arriving items is investigated. By summing all incoming orders from 2017 to 2020 per day of the week and month of the year, Figure A 14 and Figure A 15 were obtained, displayed in Appendix A.5. Interestingly, on Fridays, average arrivals are lower. This is done deliberately by the warehouse management, who rescheduled a lot of supplies on Friday to the other weekdays. The reason for this is two-fold: 1. In this way, there is time for the inbound department to solve all backlogs of previous days. By doing so, after each week, it can almost certainly be said that everything has been put away at the end of the week. This makes the traceability of items easier. 2. On Friday, the outbound department used to be busier with picking. In this way, inbound department employees could help there. The arrivals per month of the year indicate a seasonality regarding holiday months.

2.4. Order types and Order picking

The previous section covered the arrival of items in the warehouse. This section covers the way items are picked from the storage zones. Just like the put-aways of items, the way items are picked from the storage locations is partly determined by the storage policy in use. The storage policy can influence the handling needed, the locations that need to be visited, the search time needed, etc. Hence, order picking is investigated here.

2.4.1. Production, warehouse, and sales orders

In the simulation model, production orders (POs), warehouse orders (WOs), and sales orders (SOs) form the basis for the item arrival. How this is used in the simulation model is explained in Section 5.5. This section zooms in on POs, WOs, and SOs: what are these, how big are these, what do these contain?

As displayed in the product structure tree in Section 2.1, a PO can be seen as a part of a VMI machine. One machine consists of multiple modules, which contain several production days. One production day contains several POs. A WO is an order that needs to be transported to one of the other warehouses of VMI, for example, in Haaksbergen or Leszno. An SO is a request for parts by a customer. These orders are directly shipped to the customer. Each PO, WO, or SO, contains at least one, but usually, multiple items, as displayed in Figure 2.9. When these individual items for an order arrive at the warehouse, it is already known to which order they belong for items in the RB, EP, SP, and ZD zones.

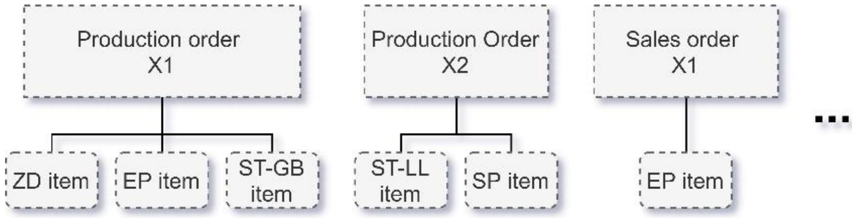


Figure 2.9: Examples of what production, warehouse, or sales orders can look like.

2.4.2. Order picking

When an order is needed, this triggers multiple pick actions. First, the anonymous items on this order are picked. Items from the lean lifts are picked three working days before production needs the order, whereas the other anonymous items are picked six working days before production needs the order. This is done with pick lists. These anonymous items are stored in a project-storage location, together with the project-related items of that order (if present). Second, one day before production needs the order, the project locations corresponding to the order are completely picked. These are loaded on the tugger train (see Section 2.5), which subsequently brings the items to the right production halls. An overview of all processes in the outbound department is displayed in Appendix A.2.

When picking all orders for a train, first, the SP items are picked, after which the EP items, and eventually, the RB items are picked. The train is used to bring the orders to production, more about the train in Section 2.5.1. This is done since the EP and RB items can, at times, be added to the steel pallets, such that no extra racks are needed on the train, saving space. ZD items are delivered to production one by one using the pallet trucks. Picking routes for project items are based on the location code. This is done per row, where the 'lowest' locations are picked first. To give an example, in the EP-zone, first, location AD.01.01 is picked, then AD.47.06, then AE.01.01, AE.96.01, etc. until row AH. In the other zones, this works similarly. When picking anonymous items, the same routing is used, however, this is divided per order. For example, if two orders need to be picked, order one from the locations AA.01.01, AB.02.01, and AC.05.02 and order two from the locations AA.02.02, AB.03.05, the routing becomes AA.01.01-AB.02.01-AC.05.02 for order one and then AA.02.02-AB.03.05 for order two. Orders are not batched. The question arises if this routing can be improved, however, this is beyond the scope of this research.

2.4.3. Orders and Items picked

The number of orders picked, with corresponding lines picked are displayed in Figure 2.10. Note that the number of anonymous lines is added twice, once when the items are picked from the anonymous storage and once the order itself is picked. For example, a lean-lift item is first put away in the lean lift. Then, three days before production needs the order, this item is picked from the lean lift. It is subsequently put away in the project storage, in the RB zone. One day before production needs the order, the item is picked from the project storage.

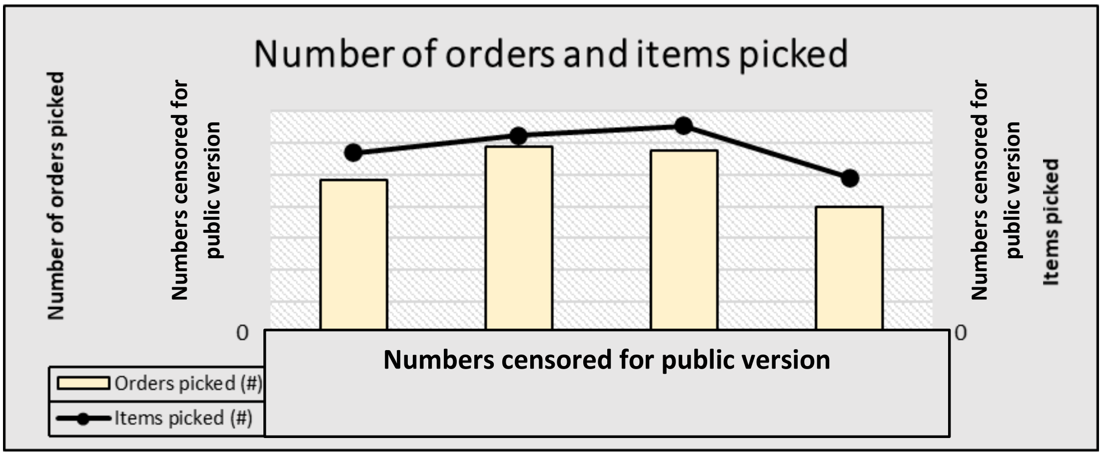


Figure 2.10: Number of orders and items picked per year (ERP, transaction history, 2020).

The figure shows that 20*xx* was a relatively quiet year. Also note that in 20*xx*, more orders were picked, than in 20*xx*, but the number of items picked was higher in 20*xx*. This is possible since on average the order size in 20*xx* could be smaller than in 20*xx*. Zooming in on these numbers for 20*xx*, the following division for the types of orders can be made:

Table 2-5: Orders picked, items picked, and the average and standard deviation of items per order (ERP, transaction history, 2020), subdivided per order type (PO, SO, or WO).

Type	Orders (#)	Orders (%)	Items picked (#)	Items picked (%)	Avg. items per order (#)	Stdev. items per order (#)
PO	A	73.4%	A	95.7%	A	A
SO	B	1.0%	B	0.3%	B	B
WO	C	25.6%	C	4.0%	C	C
Total	**D**	**100.0%**	**D**	**100.0%**	**D**	**D**

The POs are responsible for the larges part of the item arrival. Furthermore, approximately, an SO is four times smaller than a PO, whereas a WO is ten times smaller than a PO. The distribution of the number of items per order is displayed in Appendix A.6. The distribution shows that approximately 30% of all orders only consist of only one item. It also shows that the order size varies a lot. Items from orders can be allocated over multiple storage zones. Per zone, the following division can be made. The lines picked from the project storage include the lines from the anonymous storage (since these are picked again):

Table 2-6: Orders, items, and locations picked per zone. The top side includes the project storage, the bottom side the anonymous storage (ERP, inventory transaction history, 2020).

Project storage						
Zone	**Orders (#)**	**Orders (%)**	**Items picked (#)**	**Items Picked (%)**	**Locations picked (#)**	**Locations picked (%)**
RB	A	54.1%	A	76.8%	A	56.9%
EP	B	28.8%	B	16.7%	B	24.8%
SP	C	8.3%	C	3.2%	C	9.2%
ZD	D	8.8%	D	3.3%	D	9.1%
Total	**E**	**100.0%**	**E**	**100.0%**	**E**	**100.0%**
Anonymous storage						
ST-GB	A	18.6%	A	11.3%	A	22.9%
ST-EP	B	35.8%	B	23.6%	B	47.3%
ST-LL	C	45.6%	C	65.1%	C	29.8%
Total	**D**	**100.0%**	**D**	**100.0%**	**D**	**100.0%**

When comparing the numbers in Table 2-5 to Table 2-6, it can be observed that the numbers do not completely correspond. This is since some of the anonymous items also leave to different zones than the zones considered in this research. These are special zones like dangerous goods or windable items. Also included in the total lines in Table 2-5 (and not in Table 2-6) is floor stock, which are small items like bolts and nuts. Floor stock is stored within the production halls, which is taken care of by an external company. In total, this special total stock corresponds to 8% of the items, whereas already 3% of this 8% can be allocated to floor stock. Note that in both tables, picks from the anonymous storage are added twice: once when an item is picked from the anonymous storage, and once an item is picked from the project storage (as explained above). Finally, the number of orders is double-counted over zones in Table 2-6. For example, an order can have an item in the RB zone and the EP zone, hence the order is counted once for the RB zone and once for the EP zone.

Comparing Table 2-3 and Table 2-4 to Table 2-6, a few remarks can be made. First, *xx* anonymous items come in, which are divided into *xx* picking lines, meaning, that, on average, one incoming anonymous line is broken down into 5.6 order lines. Second, the number of items picked differs from the number of put-aways for the project storage (Table 2-4). A reason for this is the addition of anonymous items to the project storage. Third, some of the anonymous order lines are directly shipped and did not end up in the project storage. This is not a standard process at VMI, however, it could be that this was done because there was some urgency in shipping the items. Lastly, there is always a little time difference between the put-away and picking of items.

2.4.4. Seasonality in order picking

In the inbound department, a seasonality is observed (see the previous section). This is also checked for the outbound department in Appendix A.5. No seasonality per day of the week is observed. However, per month of the year, the figure indicates a seasonality regarding holiday months.

2.4.5. Orders per day: fitting a distribution and checking for independence

In the simulation model, the orders per day are used as input for the model. How this is done is explained in Section 5.5. This section zooms in on Table 2-5. Here, the focus is only on orders that were eventually stored in the ZD, SP, EP, or RB zones (in contrast to Table 2-5). The average orders per day are displayed in Table 2-7. The numbers in this section are based on the 249 working days in 2020.

Table 2-7: Average and standard deviation of orders per day, subdivided into averages for the first half of 2020 and the second half of 2020 (ERP, location transaction history, 2020).

Order type	**Average per day**	**Standard deviation**	**Average per day (first half of 2020)**	**Average per day (second half of 2020)**
Production orders	A	A	A	A
Warehouse Orders	B	B	B	B
Sales Orders	C	C	C	C
Total	**D**	**D**	**D**	**D**

The table indicates quite a large difference in average orders per day between the first and second half of 2020. The distribution of the total number of orders per day is displayed in Figure 2.11. This can be subdivided into distributions for the number of warehouse, sales, and production orders per day, which is done in Appendix A.5.

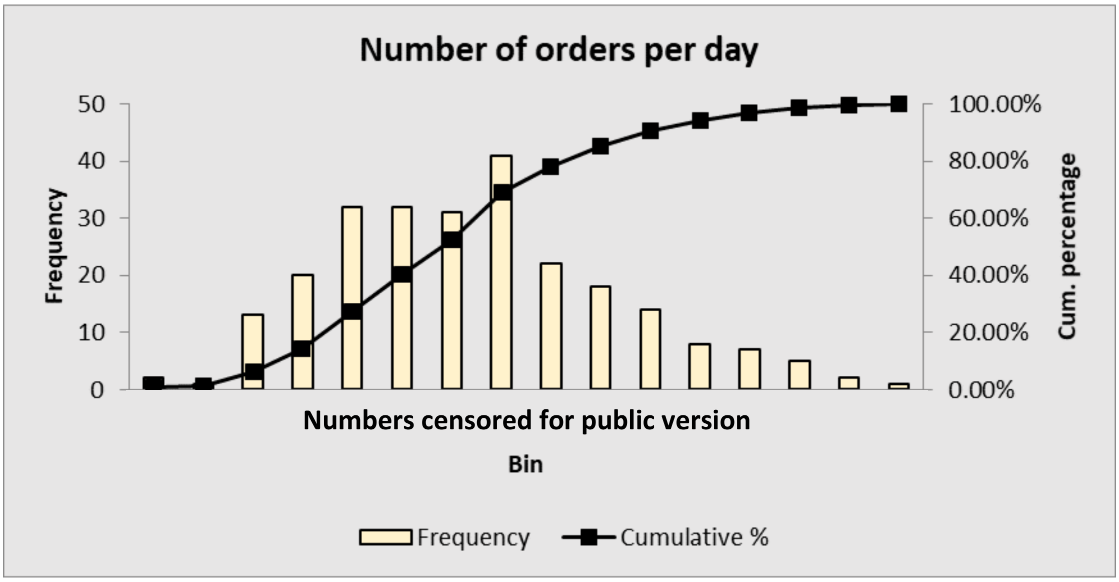


Figure 2.11: Distribution of total orders per day in the VMI warehouse.

Independence of the number of POs, WOs, and SOs per day

For the simulation model, the number of POs, WOs, and SOs picked on a day should be independent. If a low number of production orders indicates a high number of warehouse orders or sales orders (and vice versa), this should be considered. To check this independence, formal Chi-square independence tests are performed. This is outlined in Appendix A.7.

All tests performed conclude that there is not enough evidence to suggest an association between the number of production orders, warehouse orders, and sales orders per day (sign. level 5%). To underline these formal tests, two more arguments can be given for independence:

- Physical argument: the trigger of sales and warehouse orders does not consider how busy the warehouse is. Customer or other warehouse demands are fulfilled, and the warehouse is asked to pick these orders (regardless of how busy they are).

- Population correlation coefficient: using the bivariate Pearson correlation to construct a population correlation coefficient, no significant correlations (two-tailed test) are found (see Appendix A.7). Note, independence implies correlation zero, but not the other way around.

Fitting a distribution to the number of POs, WOs, and SOs per day

Next, it is tested if the number of orders per day for each type of order can be approached with a theoretical distribution (also see Section 3.2.2). This is done such that it is easier to implement in the simulation model. Also, Law (2015) advises using theoretical distributions over historical data. To check if the number of orders can be approached with a theoretical distribution, the following three steps are followed (Law, 2015):

1. Hypothesize the families of distributions.
2. Estimate parameters.
3. Check fit between probability distribution function and data.

Unfortunately, in step 1 (also using Minitab and the R-package *fitdistrplus),* no probability distributions are found that properly describe the number of WOs or SOs per day. However, for POs, the Gamma distribution seems to describe the number of POs per day quite well. This is underlined by the summary statistics, QQ-plot, PP-plot, and the histogram of the data and the Gamma distribution, which can be found in Appendix A.8. The Gamma distribution is a continuous function, whereas our data is discrete. However, since '*n*' (the number of days) is large (249), not much is lost by approaching our discrete data with a continuous one. Also, the Gamma distribution can give problems when modeling discrete data if a significant portion of low values (close to zero) is present in the data. However, this is not the case in the dataset, where only 1.2% (3 of the 249 observations) of the values is lower than *xx* per day. Hence, it is decided to continue with the Gamma distribution. To properly use it in the simulation model, decimal values are rounded to the nearest integer value. Using the method of moments, the scale (θ) and the shape (*k)* can be estimated from the data, where $\theta = \frac{Var(X)}{E(X)} \approx xx$ and $k = \frac{E(X)^2}{Var(X)} \approx xx$. Finally, a goodness-of-fit test is performed with the Chi-square test (again, see Section 3.2.2). In this test, the expected frequencies (using the Gamma distribution) are compared to the observed frequencies in an interval (see Appendix A.8). The results from the test cannot prove that there is a significant difference (significance level 5%) between the expected and observed frequencies. Thus, based on the goodness-of-fit test, together with the QQ-plot, PP-plot, and histogram, the Gamma distribution seems to be a good fit for the number of production orders per day.

2.5. Resources: tugger train, ERP, working hours, and the public warehouse

This section covers some general resources like the tugger train, the warehouse management system, working hours, and the 'public warehouse'. What these are, is explained here.

2.5.1. Tugger train

VMI uses tugger trains to deliver POs to the different production halls. The tugger train determines which items are picked and when these are picked. Hence, the tugger train is also investigated. The train is only used for the items that come from the SP, EP, and RB zone. ZD items are delivered using the normal pallet trucks. Currently, not all production halls are delivered with the tugger train. However, in the future, the intention is to deliver each hall with the tugger train. In that case, also sales and warehouse orders, which need to be delivered to the expedition department, are delivered with the tugger train. A picture of the tugger train is displayed in Figure 2.12.

Figure 2.12: One of the two tugger trains currently in use at VMI.

The route of the train is controlled by an Excel macro. The macro considers the number of trains, carts, the capacity of carts, and routing. The routing is based on production halls that are closer together. The routes are indicated with color codes. On the carts, steel pallets and racks can be placed, which in itself can contain multiple SP, EP, and RB items. Eventually, the macro creates all picklists on a day, which determines per train which items have to be picked from the SP, EP, and RB zone. Hence, the train leads the picking process. This can be a point of discussion since the macro is currently based on optimizing the train capacity and routes. However, perhaps more gains can be acquired by focusing more on creating efficient picklists, for example, by creating picklists based on where orders are located. An example of a (censored) picklist of one train is displayed in Figure 2.13.

Project	Workplace	Activity	Day	PO no.	Barcode	T.TR.TP	SP	EP	GB	Place	Print duplicates?	Comment	Locations	Time	Route
E...	E..C..	EM...	13-04-2021	EPR...		A.01.1	1			SP	Yes	Eenmalig verdichten	CD.05.12		BLACK
E...	E..A..	EM...	13-04-2021	EPR...		A.01.2	1			SP	Yes	Verdichten	CD.34.02		BLACK
E...	E..C..	EM...	13-04-2021	EPR...		A.01.4	2			SP	No		CD.34.06CD.01.11		BLACK
E...	E..A..	EM...	13-04-2021	EPR...		A.01.1		1		SP	Yes	Eenmalig verdichten	AG.79.04		BLACK
E...	E..C..	EM...	13-04-2021	EPR...		A.01.1		1		SP	No	Eenmalig verdichten	AE.55.03		BLACK
E...	E..A..	EM...	13-04-2021	EPR...		A.01.1		1		SP	Yes	Eenmalig verdichten	AE.24.02		BLACK
E...	E..C..	EM...	13-04-2021	EPR...		A.01.2		2		SP	No	Verdichten	AH.12.02AG.53.02		BLACK
E...	E..A..	EM...	13-04-2021	EPR...		A.01.3		1		SP	Yes	Eenmalig verdichten	AG.13.03		BLACK
E...	E..B..	EM...	13-04-2021	EPR...		A.01.4		1		SP	No		AH.47.03		BLACK
E...	E..A..	EM...	13-04-2021	EPR...		A.01.4		2		SP	No		AE.07.04AH.26.03		BLACK
E...	E..C..	EM...	13-04-2021	EPR...		A.01.1			1	SP	No	Eenmalig verdichten	BK.04.07		BLACK
E...	E..A..	EM...	13-04-2021	EPR...		A.01.1			1	SP	No	Eenmalig verdichten	BJ.18.06		BLACK
E...	E..B..	EM...	13-04-2021	EPR...		A.01.1			1	SP	No	Eenmalig verdichten	BP.01.05		BLACK
E...	E..A..	EM...	13-04-2021	EPR...		A.01.2			1	SP	No	Verdichten	BF.32.07		BLACK

Figure 2.13: Example of a part of a picklist (censored). The picklist shows which item has to be picked and where it is located. Moreover, it shows for which train and order these items are. A barcode can be used to scan the list.

Going into the details of the train macro and its capacity of individual items is beyond the scope of this research. Hence, only the number of orders on a train is analyzed, which is also relevant for the simulation model (see Section 5.5). However, the train macro sometimes splits up the orders per zone. For example, the steel pallets of one order can be on train number two of that day, whereas the RB items are on train number four of that day. To still acquire the number of orders per train, it is assumed that the first time an order was present on the train, the full order was present on that train. Subsequently, the order is removed from all other trains on which it was also present, such that orders are not counted double. Due to these simplifications, it can be that, at times, an unrealistic number of items has been counted on the train. The obtained empirical distribution of the number of POs per train is displayed in Figure 2.14.

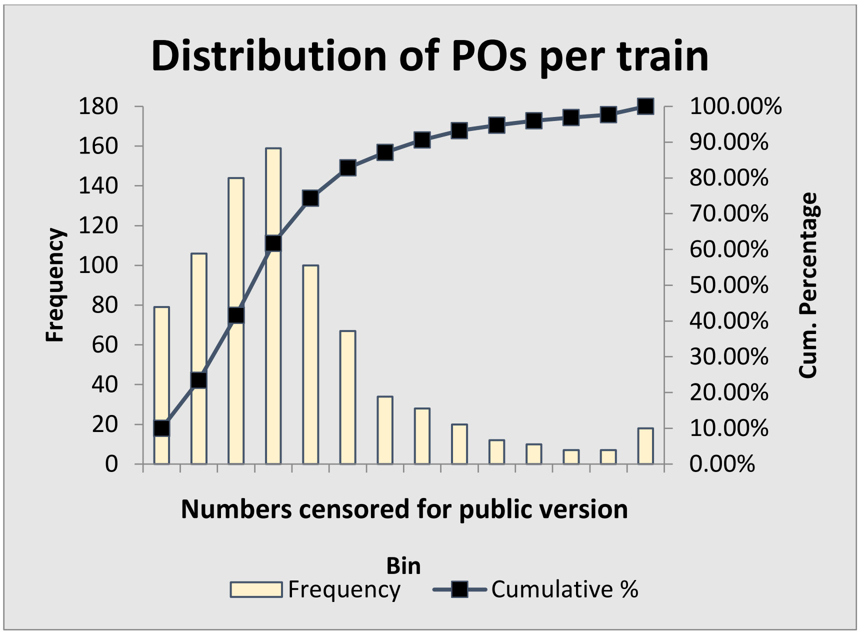


Figure 2.14: Distribution of the number of POs per train.

The distribution is based on picklists of 88 random days in 2020. The average number of orders per train is 8.65, with a standard deviation of 6.48. More statistics can be found in Appendix A.9, together with a distribution of the number of trains per day.

2.5.2. Enterprise resource planning

The ERP influences the current way of working in the warehouse. The current ERP system in use is ERP LN 6.1 of Infor. Infor is a software provider for enterprises, with approximately 67.000 customers around the world (Infor, 2020). The current system was released in 2009 as a follow-up of Baan IVc. Infor supports all logistics processes within VMI, from, for example, purchasing until production. Attached to this ERP system is a custom-made scan application developed by VMI and other external companies. The scan application communicates with the ERP system. This scan application was mainly built to be used on the warehouse floor such that employee activities and item movements can be tracked via scanning devices. The statuses and locations generated by this application can be found per warehouse process in Appendix A.2.

2.5.3. Working hours and working days

In a normal week, the warehouse department works five days per week, from Monday to Friday. The warehouse starts at 7:30 and ends at 16:15. There are two breaks: one morning break and one lunch break. The morning break is from 9:30 to 9:45 and the lunch break is from 12:30 to 13:00. During breaks, no items are processed. In total, 2020 had 249 working days.

2.5.4. The public warehouse

Sometimes VMI makes use of the “public warehouse” (the name is not mentioned due to confidentiality). This public warehouse provides logistic services, like transport, storage, and warehousing. VMI uses this warehouse for items that:

- Cannot be stored anymore due to capacity limits.
- Are large frames that take a lot of space in the warehouse and come in too early.
- Are part of projects that were rescheduled and occupy a lot of space.

The public warehouse receives these items from the top corner of the warehouse (see floor map in Section 1.1) and brings them to this same spot when the items are needed for a production order soon.

2.6. Throughput times

This section describes distributions for the inbound processes and the sojourn time, which can be used as input for the simulation model. These throughput and sojourn times determine how long an item is in the warehouse, and how much space items occupy. This is important to know, to check the performance of alternative storage policies.

2.6.1. Inbound time

The inbound throughput times are based on the logging inbound data from the scan application. In the throughput times, only the steps from unloading, until the item is behind the track are considered. So, put away time is not part of this throughput time. Note that throughput times also contain buffer times, for example, when an item is waiting to be inspected. Outliers have been deleted from the data using the 1.5 * IKA rule. This was done to prevent extreme values or even negative values from the scan application. Also, the minimum has been set to ten minutes to prevent unrealistic throughput times. Throughput times of less than ten minutes are observed, for example, when items have been booked and inspected, but not scanned. In that case, the operator scans all operations after each other and the scan application only observes throughput times of seconds. Lastly, the throughput times for the inbound of SP and ZD items and RB, EP, and LL items have been separated since the SP and ZD items take longer to inspect. The acquired empirical distributions are displayed in Figure 2.15 and Figure 2.16.

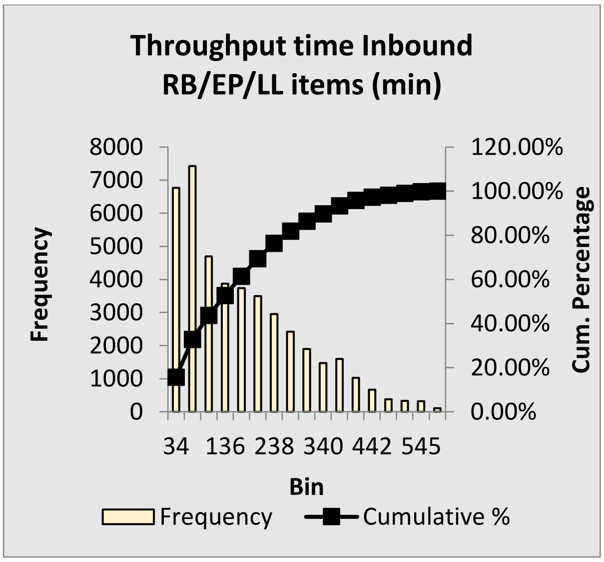


Figure 2.15: Distribution of throughput time inbound for items in the RB, ST-GB, EP, ST-EP, or ST-LL zones.

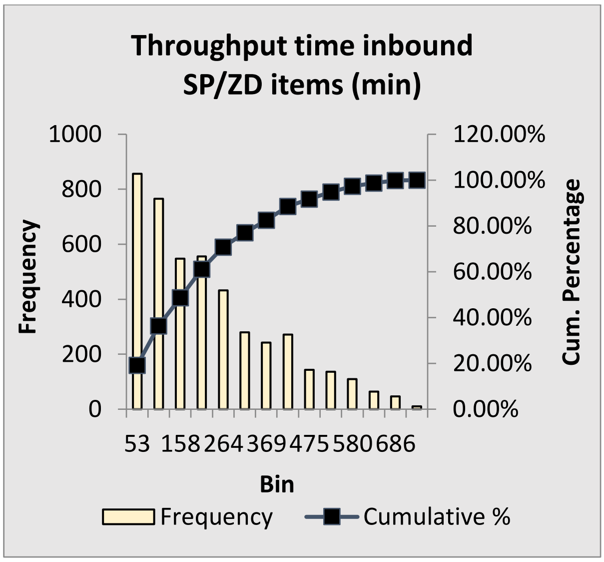


Figure 2.16: Distribution of throughput time inbound for items in the SP or ZD zones.

The mean time to inspect RB/EP/LL items was 155.2 minutes, whereas the averages time to inspect SP/ZD items was 201.8 minutes. More summary statistics are displayed in Appendix A.10. To verify these distributions, the averages were shown to the inbound foreman. Unfortunately, no probability distributions are found that properly describe the inbound throughput times (also not using Minitab and the R-package *fitdistrplus).*

2.6.2. Sojourn time

The sojourn time of an article is based on the location transaction history of 2020. It is calculated by calculating the moment on which an item was picked from a location minus when it was put away on that location. This is only done for project items since incoming anonymous item lines are broken down into multiple outgoing item lines. From this subtraction, weekends and holidays are deleted, leaving the sojourn time in working days, which is more relevant for the simulation model. The distribution of the sojourn time is displayed in Figure 2.17.

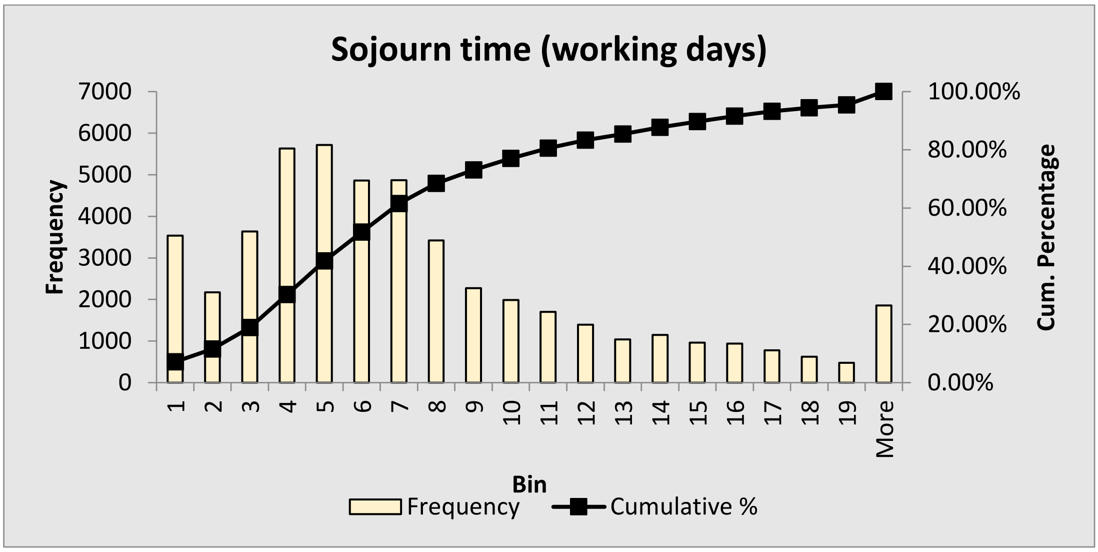


Figure 2.17: Empirical distribution of the sojourn times of items in working days. Note the peak at 5 days.

The average sojourn time was 7.71 working days. More summary statistics are displayed in Appendix A.10, together with the distribution of the sojourn time in days. The peak is around 5 working days which you would expect since many suppliers have fixed delivery days. Longer sojourn time can be due to the rescheduling of projects. The sojourn time before this peak can be from suppliers without fixed delivery days or late deliveries. Unfortunately, no probability distributions are found that properly describe the sojourn time.

2.6.3. Put away and picking time

Unfortunately, no (reliable) data is present about putting items away and picking items from the different storage zones. For this, an assumption has to be made, see Section 5.5.

2.7. Summary: key points from Chapter 2

At the end of each chapter, the key points of that chapter are summarized.

- A VMI machine consists of multiple production orders (POs). A PO contains multiple items.
- Items come into the VMI warehouse either project-related (when an item is already attached to a certain order) or anonymous (when an item is not yet allocated to an order).
- VMI has five storage zones: the red box (RB) zone consisting of grey plastic boxes on shelves, the euro pallet (EP) zone, consisting of pallet compartments in a pallet rack, the steel pallet (SP) zone, consisting of stacked steel pallets and some euro pallet compartments, the self-carrying (ZD) zone, consisting of various storage options for larger items, and the lean lift (LL). The RB zone can be subdivided into the RB (for project-related items) and the ST-GB (for anonymous items) zones. “ST” stands for standard and “GB” for grey bin. The EP zone can be subdivided into the EP (for project-related items) and the ST-EP zone (for anonymous items). Pictures of these storage zones are displayed in Appendix A.3.
- VMI has two storage policies: project storage and anonymous storage. In the project storage, items are stored per order. This is used in the RB, EP, SP, and ZD zones. In the anonymous storage, items are stored per SKU. This is used in the ST-GB zone, ST-EP zone, and the lean lift (called the ST-LL zone).
- Most items are put away and picked from the RB and EP zone.
- In 2020, [*information censored for public version*]
- VMI needs to consolidate multiple order types. Productions orders (POs) are delivered to production. Sales orders (SOs) are requests for parts by customers. Warehouse orders (WOs) are orders for parts that need to go to other VMI warehouses. The number of POs, WOs, and SOs per day is independent. Moreover, the number of production orders per day can be approached with a Gamma distribution.
- VMI delivers their items to the production halls using a tugger train system, which consequently leads the order-picking process.
- At times, VMI makes use of the “public warehouse”. This public warehouse is used for the storage of items that could not be stored due to capacity limits, large frames that occupy a lot of space, and parts of large projects that have been rescheduled.
- Using historical data, sojourn times and inbound times can be approached with an empirical distribution. Throughput times about order picking and putting away items, could not be acquired from the ERP system.

3. Theoretical framework

The theoretical framework consists of two main parts: warehousing (Section 3.1) and simulation (Section 3.2).

3.1. Warehousing

The warehousing part covers three topics: the warehouse function, together with its main processes and resources, the storage location assignment problem, and the performance measurement of a warehouse. The warehousing function is covered in Section 3.1.1, the storage location assignment problem is explained in Section 3.1.2, whereas the performance measurement of a warehouse is covered in Section 3.1.3.

3.1.1. Warehouse function, processes, resources, and management system

To introduce a warehouse, the warehouse function, main processes, resources, and warehouse management systems are discussed like in ten Hompel & Schmidt (2007) and Bartholdi and Hackman (2019).

The warehouse function

A warehouse is "a large building for storing goods and products prior to distribution" (Davies & Jokiniemi, 2008, p. 410). These goods and products are usually referred to as stock keeping units (SKUs). These stock keeping units are an item type with a unique code and are "completely specified as to function, style, size, color, and, often, location" (Silver et al., 2017, p. 28). In the past, warehouses were constantly referred to as a cost item, with little value-adding activities. However, with developments like production abroad, e-commerce, and increasing customer demands, warehouses are seen as a vital part of the supply chain (Richards, 2011).

A warehouse has the following functions (Tompkins & Smith, 1998):

- Bridge the interval of time between the moment that goods and products are received and the moment they are needed (storing).
- Change the composition of the goods (order picking).
- Guide goods to their destinations (receiving and shipping).

There are different types of warehouses. Rouwenhorst et al. (2000) distinguish two types: a distribution warehouse and a production warehouse, their function and design criteria are displayed in Table 3-1.

Table 3-1: Function and design criteria for distribution and production warehouse types (Rouwenhorst et al., 2000).

Type of warehouse:	**Function**	**Design criteria**
Distribution	Store products and fulfill external customer orders typically composed of a large number of order lines.	Maximum throughput to be reached at minimum investment and operational costs.
Production	Store raw materials, WIP, and finished products.	Storage capacity to be reached at minimum investment and operational costs. Response time could be a constraint to prevent production delays.

Warehouse activities and decisions

Different types of warehouses also perform different activities. However, the general warehousing activities are receiving, storing, order picking, and shipping (Gu et al., 2007). These activities are briefly outlined here, together with the typical problems faced in these activities. Decisions to be made during these activities on a strategic, tactical, and operational level can be found in Table 3-2.

1. Receiving and shipping

Receiving is the first step for products and goods before they enter the warehouse. Items are unloaded from the carrier by which they arrive. After unloading, items are probably scanned and inspected. Sometimes, larger packages need to be broken down into smaller packages (Bartholdi & Hackman, 2019). In the shipping phase, the picked items are checked, packed, and loaded. Dependent on the customer, this can be done on trucks, trains, etc. (Rouwenhorst et al., 2000).

To manage the decisions to be taken in this stage, few formal models have been developed. Most literature is about shipping and receiving operations and the truck-to-dock assignment in cross-docking warehouses (Gu et al., 2007).

Table 3-2: Decisions to be made on a strategic, tactical, and operational level, regarding the organization and resources in a warehouse per activity (Rouwenhorst et al., 2000; Gu et al., 2007).

Process	**Decision level**		
	Strategic	**Tactical**	**Operational**
Receiving & shipping		- Number of docks	- Dock assignment - Schedule of service
Storing	- Type(s) of storage system(s) - Layout - Storage capacity - Reserve area or not - Pick zones or not - Storage policy	- Dimensioning picking and ABC zones - Way of replenishing forward area - Allocating SKUs to departments and zones - Slotting of goods - Storing equipment	- Assigning replenishment tasks - Allocation of incoming goods to locations
Order picking	- Batch picking or not - Order sorting	- Batch size - Method of sequencing - Priority rules (single order picking)	- Batch formation - Picking task assignment - Routing and sequencing - Dwell point - Sorting task assignment - Sorter chute assignment
All		Layout Workforce and peripheral equipment	Workforce and material assignment

2. Storage / put-away

During the storage phase, items are delivered to the storage area or directly to the shipping/consumption area. In the case of the latter, this is also called split storage or cross-docking. It should already be identified to which storage unit the item has to be assigned in the receiving phase, but it could also be that this is done in the storage phase (ten Hompel & Schmidt, 2007).

In several warehouses, there is a reserve and a forward area. The reserve area, also called the bulk area, is the area where products are stored most efficiently. In the forward area, products are stored for easy retrieval by an order picker. Transfer of items from reserve to the forward area is called a replenishment (Rouwenhorst et al., 2000).

The storage phase is shaped by three decisions: how much inventory should be kept, replenishment frequencies, and locations of products and items. The first two are mainly problems corresponding to inventory management. The latter has to do with storage assignment. Storage assignment is dependent on two main criteria: storage efficiency (e.g. space needed to store SKUs) and access efficiency (e.g. efficient put away and order picking processes).

Storage assignment consequently consists of three decisions: assigning SKUs to departments, assigning SKUs across zones, and storage location assignment. Assigning SKUs across departments has to do with allocating SKUs to the forward area, the reserve area, or designated areas per customer. Assigning SKUs across zones (zoning) has to do with specifying SKUs to different zones in a department. If different zones have the same storage systems, this allocation is a soft constraint. However, if storage systems differ per zone, this allocation is a hard constraint. Zoning (with similar storage systems) can be useful for the order picking activities since pickers only have to walk in a smaller space to pick an order, pickers can get familiar with the products in the zone, and when orders in zones are picked in parallel, the order picking time can be decreased (Gu et al., 2007). The last decision, storage location assignment, is covered in the next section since it is the main concern of this research.

3. Order picking

Order picking has to do with retrieving the items from the storage area. It is often seen as the most labor- and capital-intensive warehouse operation (Frazelle, 2002). It is initiated by a receipt of the customer of the warehouse. This receipt has to be converted into several pick lines: instructions telling what to pick where in the warehouse. Multiple pick lines form the pick lists. Most of the order picker's time is allocated to traveling. A typical distribution can be found in Figure 3.1. Order picking methods consist of three basic steps: batching, routing and sequencing, and sorting (Gu et al., 2007).

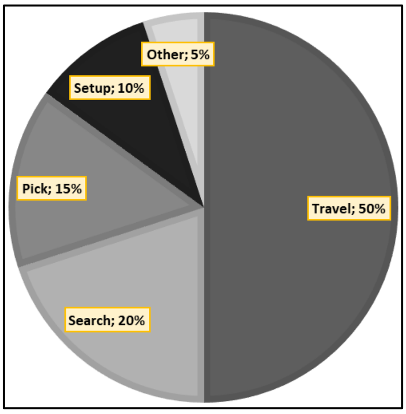


Figure 3.1: Typical distribution of an order picker's time (Tompkins et al., 2003).

Order batching

Order picking can be done efficiently if the pick density is high. The pick density is the number of picks per unit of area or volume. Pick density can be increased by storing more popular SKUs together or by order batching. Order batching is retrieving more than one customer request per trip (Bartholdi & Hackman, 2019). The order batching problem can be outlined as follows: given a set of orders that need to be picked, determine which orders will be picked and composed during a specific time window. This partitioning can be done in different time windows or per picker. The first is a special case of the bin packing problem, whereas the latter is a special case of the vehicle routing problem (Gu et al., 2007).

Routing and sequencing

Routing and sequencing determine the picking route and the sequence in which orders are picked from the warehouse. The goal is to visit a set of locations as quickly as possible. It is the most researched warehousing problem and a variation of the famous traveling salesman problem (Bartholdi & Hackman, 2019).

Sorting

Sorting is only done when multiple orders are picked together. This can be done during picking (sort-while-pick) or after the picking process (sort-after-pick).

Warehouse resources

In a warehouse, multiple resources can be identified (Rouwenhorst et al., 2000):

- **Storage unit**: wherein or whereon products are stored (e.g. pallets, boxes).
- **Storage system**: wherein or whereon storage units are stored (e.g. racks, lean lifts).
- **Pick equipment**: systems to retrieve items (e.g. reach trucks, pallet jacks).
- **Order pick auxiliaries**: support equipment for order picking (e.g. scanners, headsets).
- **Computer system:** for a warehouse management system that controls the warehouse processes. More about this in the next section.
- **Material handling equipment:** to prepare for shipping (e.g. sorter systems, palletizers).
- **Personnel:** the people working in the warehouse.

The warehouse management system

A warehouse management system is “a complex software package that helps manage inventory, storage locations, and the workforce, to ensure that customer orders are picked quickly, packed, and shipped” (Bartholdi & Hackman, 2019, p. 33). The warehouse management system should support the main activities of the warehouse. The first warehouse management systems appeared in the early 1970s. Currently, these systems are not only capable of overviewing the warehouse, but also capable of controlling and optimizing them (Kappauf et al., 2012). Warehouse management systems are typically provided in the ERP packages of, for example, Oracle, SAP, or Infor.

3.1.2. The storage location assignment problem

This section formulates the storage location assignment problem together with formulating storage policies to solve the problem.

Problem formulation

A storage policy or storage (location) assignment strategy tries to give a solution to the storage location assignment problem (SLAP), which is the NP-hard problem “to assign incoming products to storage locations in storage departments/zones in order to reduce material handling cost and improve space utilization” (Gu et al., 2007, p. 7). In literature, many alternative storage policies are proposed (Frazelle & Sharp, 1989). To formally define the SLAP (Gu et al., 2007):

Given:

- Storage area information including the layout and physical configuration.
- Storage location information including the availability, physical dimensions, and location in the warehouse.
- Information about the set of items to be stored: including the demand, physical dimensions, quantity, arrival, and departure times.

Determine:

- The physical location where arriving items are stored.

Subject to the constraints:

- Storage capacity and efficiency.
- Picker capacity and efficiency based on the picker cycle time.
- Response time.
- Storage and product compatibility.
- Compatibility between products.
- Item retrieval policy e.g. FIFO, LIFO, etc.

Storage assignment strategies

Literature on the SLAP is quite extensive (Petersen et al., 2005; Gu et al., 2007). Hence, this part is not a complete overview of all storage strategies. These storage strategies can roughly be divided into three groups: dedicated, shared, and class-based storage strategies. For each group, some examples are given, to give an idea of the various strategies.

Shared storage strategies

Shared storage strategies do not reserve slots for SKUs. This is more convenient when stock levels change over time (Kovács, 2011). Shared storage assignment results in a high space utilization (low space requirement) at the expense of higher travel times (Il-Choe & Sharp, 1991). Moreover, it is easy to implement, it is immune to fluctuations in demand and product mix (Barhami et al., 2019), and it prevents traffic congestion in aisles (Kofler et al., 2011). Though, since SKUs do not have predetermined locations, a tracking system is required, and a systematic view is missing since the consecutive process and product information is not used. Some examples:

Random, closest-open, farthest-open, or longest-open location storage assignment

Random assignment allocates SKUs randomly over the available storage locations. In this case, there is no logic in storing the products. It is, therefore, often used to benchmark other policies. SKUs do not have a fixed location. Closely related to random storage, the closest-open-location (COL) assignment allocates SKUs to the closest empty location. Closeness is defined by the distance between the input point or output point (which is the same if there is one I/O point). In the long run, this policy converges to random storage assignment (Schwarz et al., 1978). Instead of the COL assignment, the farthest-open-location (FOL) assignment could be chosen. The longest-open-location (LOL) assignment allocates SKUs to the location that has been empty for the longest time. It is not known which of these policies performs best (Gu et al., 2007).

Scattered storage

Scattered storage, mainly used in B2C environments, purposefully breaks down incoming item batches into smaller groups of the same SKU and spreads them all over the shelves. The idea behind this is that an SKU should always be close by. However, if large quantities need to be picked, the walking time increases. Also, the put-away step is longer since multiple locations need to be visited, together with a more complex picking process (Boysen & Weidinger, 2018).

Dedicated storage

Allocates SKUs to a fixed location. In dedicated storage, space utilization is low (high space requirement) since locations remain reserved even if products are out of stock. So, it is not that suitable if the product assortment changes over time. Also, enough space has to be allocated to each SKU to cope with the maximum inventory level. Proper functioning of dedicated storage via, for example, COI-based storage (see later), requires SKU locations to be constantly reviewed. So, it does not work if the nature of demand changes per day. Lastly, traffic congestion in aisles can be quite high. The advantages are that order pickers can become familiar with product locations, products are logically grouped if product-to-location assignment matches the layout of the stores, and it can be helpful if products have different weights (de Koster et al., 2006). Though, the biggest advantage is the reduced travel distance regarding shared storage when SKUs have been allocated to fixed locations efficiently. The question arises, how to allocate the SKUs to a dedicated location efficiently? For this, multiple criteria exist:

Part number

Assigns SKUs to locations on increasing part number. This is relevant if no information system is present. However, with current IT solutions this idea is quite old-fashioned (Bahrami et al., 2019).

Popularity, turnover, pick density, and maximum inventory

Popularity is the number of times a picker travels to an SKU (Napolitano, 1998). It is the most used storage policy in practice (Frazelle, 2002). Turnover refers to the total quantity of an SKU shipped during a given period (demand). Pick density of an SKU refers to the ratio of popularity to the volume of the SKU. Pick density identifies the SKUs that have the highest pick activity per volume, where volume is defined as the demand times the volume of the SKU (Petersen et al., 2005). Maximum inventory can be defined as the maximum warehouse space allocated to a product class (Gu et al., 2007). The higher these measures for an SKU, the more favorable location it will get, except for the last one (maximum inventory) where usually the SKUs that need the least space are allocated to the most favorable locations.

Cube-per-order index

The cube-per-order index (COI) ranks SKUs on the ratio of the number of needed storage locations to the number of trips per period. The SKUs with the lowest COI are assigned to the most favorable locations. When order picking is single command (i.e. an order retrieval cycle is from I/O-point to a single storage location and back to I/O point), COI leads to optimal assignment for dedicated storage. However, when multi command order picking (i.e. when multiple storage locations are visited) is applied, there is no performance guarantee for COI. The worst-case behavior of the COI slotting strategy is even infinitely bad (Schuur, 2015).

Family grouping or correlated storage

Tries to make use of the relationship between products. In this approach, the correlation between SKUs should be known, which is the frequency at which they appear together in an order. Two types are mentioned:

1. Complimentary-based: cluster SKUs based on their correlation (1) and locate SKUs in one cluster close to each other (2).
2. Contact-based: uses contact frequencies to make the clusters, which is the number of times SKU A is picked after SKU B or the other way around. Of course, this depends on the routing strategy used. Again, SKUs in a cluster are located close to each other (de Koster et al., 2006).

Order-oriented slotting

Given an empty warehouse, set of orders, and routing policy, order-oriented slotting (OOS) tries to store SKUs in a warehouse such that the total travel time needed to pick all orders is minimized. To do so, Mantel et al. (2007) define an integer linear program for small problem instances, but for larger instances, they also propose the interaction frequency-based quadratic assignment heuristic which tries to store SKUs that are often ordered together close to each other, while at the same time ensuring that fast-movers are placed close to the I/O point (Mantel et al., 2007).

Class-based storage

Combines dedicated and random storage, where SKUs are grouped into classes. Each class is assigned to a dedicated storage area, however, within these storage areas, a shared storage policy is applied. Space requirements and traffic congestion for class-based storage are higher than for shared storage but lower than for dedicated storage. Space requirements increase with the number of classes. Regarding travel distance, class-based storage performs worse than dedicated storage but better than shared storage. A shared storage policy can be seen as a class-based storage policy with one class whereas a dedicated storage policy can be seen as a class-based storage policy with as many classes as SKUs. The challenge of class-based storage is assigning products to classes and classes to a storage region in the warehouse.

The class-based storage policy is quite popular due to its compromising capabilities between dedicated and shared storage together with its simple implementation, manageable maintenance, and ability to cope with demand and product mix variations (Bahrami et al., 2019; Le-Duc, 2005). Examples are:

ABC classification or Pareto's Law

Group SKUs into a class, such that the fastest moving SKU class contains a small percentage of the SKUs, but that this class contributes to a large part of the turnover. There is no fixed rule about how many SKUs to assign to which class and there is also no fixed rule for the number of classes. However, often, three classes are used: A, B, and C, which contain approximately 20, 30, and 50 percent of the SKUs. The SKUs in these classes correspond to approximately 80, 15, and 5 percent of the picks respectively (Le-Duc, 2005). The A-class will be assigned to the most favorable locations and the C class to the worst locations.

Duration of Stay policy[2]

The duration of stay policy (DoS) sorts SKUs on ascending duration of stay. Then, SKUs are assigned to classes based on their duration of say. The classes with the shortest duration of stay are assigned to the best locations (Goetschalckx & Ratliff, 1990).

Above, the 'best' or 'most favorable' locations have been mentioned. What these locations are, depends on the system and the travel pattern used in the warehouse. However, these are often the locations with minimum material handling cost of order picking and replenishment. Sometimes also referred to the locations in the golden zone (the area between a picker's waist and shoulders), close to the floor, or close to the door (Petersen et al., 2005).

The different types of storage policies, together with their (dis)advantages and some examples are displayed in Table 3-3.

Table 3-3: Summary of shared, dedicated, and class-based storage, together with the (dis)advantages of each strategy and some examples.

	Idea	**Advantages**	**Disadvantages**	**Examples**
Shared storage	No slots dedicated to SKUs	+ High space utilization + Low congestion in aisles + Robust to stock level changes + Easy to implement	- Higher travel times - No affinity with locations for order pickers - Not utilizing any information about demand/products	- Random - Scattered - COL, FOL, etc.
Dedicated storage	Allocate SKUs to a fixed location	+ Reduced travel times + Familiar product locations + Logical storage	- Low space utilization - Needs constant reviewing (otherwise not robust) - Congestion in aisles	- OOS - COI - Based on popularity, turnover, etc. - Family grouping
Class-based storage	Allocate SKUs to classes	Compromise between shared and dedicated storage		- DoS - ABC

A final note on SLAP literature

While searching for literature about the SLAP and solutions to the problem, no articles were found that covered the way of storing items for which it is already known when and by which customer order they are included. This is the case for most items at the VMI warehouse. This may be a special case, but this is true for many engineer- and make-to-order companies who order parts based on customer orders. How and when should these parts be combined? After storage? Before storage? During storage (which VMI currently does)? What should be the level of combining, e.g. based on delivery date? Based on

[2] There is some discussion about whether DoS should be classified as a dedicated or class-based storage policy (Bahrami et al., 2019). However, it was initially introduced as a class-based storage policy (Goetschalckx & Ratliff, 1990).

the full customer order? Based on smaller modules? What are (dis)advantages of immediately storing per customer order? How does it compare to the classical strategies? Unfortunately, no answers were found during this literature search. Hence, this research tries to fill this gap a little bit by testing different strategies for this particular case.

3.1.3. Warehouse performance measurement

This section starts with general literature about performance measurement, followed by supply chain performance metrics, warehouse performance metrics, and subsequently SLAP metrics.

Performance management and key performance indicators

Before diving into performance measurement, it is good to question: why should this even be measured in the warehouse? The reason is fourfold (Richards, 2011):

1. To ensure customer satisfaction.
2. To ensure continuous improvement cycles.
3. Discover issues before they become major problems.
4. Train staff in the right areas.

Process performance measures are “measures of different process characteristics that tell us how the process is performing” (Reid & Sanders, 2013, p. 74). In this research, we want to know how we can measure the efficiency and effectiveness of the warehousing process. **Efficiency** is a measure of the inputs required for each unit of output. It is often referred to as “doing things right”. If something is more efficient, the same output is reached with fewer resources, or more output is generated with the same resources. To name a few examples for the warehouse, think about order picking time, inventory costs, etc. **Effectiveness** is a measure of how well an activity contributes to achieving organizational goals. It is often referred to as “doing the right things” (Boddy & Paton, 2011). To name a few examples for the warehouse, think about the accuracy of the picking process, consistency of deliveries to production, etc.

In literature, multiple frameworks that define how the operation’s performance should be measured are defined. To mention a few:

- **Stakeholder perspective**: performance measurement should reflect the interest of the stakeholder groups (Mendelow, 1991).
- **Corporate social responsibility (CSR):** performance measurement should incorporate the organization’s impact on society and the environment, beyond its legal obligations via ethical and transparent behavior (Government of the United Kingdom, 2013).
- **The balanced scorecard:** measures the performance by posing four questions: 1. How do customers see us? 2. What must we excel at? 3. Can we continue to improve and create value? 4. How do we look to shareholders (Kaplan & Norton, 1992)?
- **Based on quality, flexibility, speed, dependability, and cost** (Slack et al., 2013).

These frameworks use performance indicators to measure the performance of different aspects. Key performance indicators (KPIs) are the most important performance measures. These should be measured and compared to a standard of performance, which is the defined level of performance to be achieved or the norm. Sometimes, it is difficult to exactly match this standard. In this case, acceptable ranges of variations should be set, which are the acceptable limits in which the performance should be (Boddy & Paton, 2011).

The KPIs should be S.M.A.R.T. defined which means that a KPI should be (Doran, 1981; Richards, 2011):

- **Specific:** target a specific part of the operation for improvement.
- **Measurable:** choose a quantifiable indicator to measure it.
- **Attainable (previous assignable):** it should be within the ability of people and resources to attain the goal.
- **Realistic:** the set standard should be achievable and realistic.
- **Timely:** realized in realistic time scales and frequently measured.

Supply chain performance indicators

Before diving into warehouse-specific metrics, it is good to zoom out and look at the broader function of the warehouse within the supply chain. Warehouses are a fundamental part of a supply chain. Therefore, Chopra and Meindl (2015) mention multiple facility-related metrics. These are displayed in Appendix B.1. More abstract, Caplice and Sheffi (1994) mention multiple “logistic metrics” or metrics for a “transformational process”. A distinction between productivity, effectiveness, and utilization is made:

Table 3-4: Performance measures of a transformational process, the form in which this metric usually occurs, and an example of such a metric (Caplice & Sheffi, 1994).

Dimension	Form of the metric	Example of a metric
Utilization	$\frac{Actual\ input}{Norm\ input}$	$\frac{Area\ of\ warehouse\ occupied}{Total\ area}$
Productivity	$\frac{Actual\ output}{Actual\ input}$	$\frac{Orders\ processed}{Hours\ of\ labor}$
Effectiveness	$\frac{Actual\ output}{Norm\ output}$	$\frac{Number\ of\ shipments\ on\ time}{Number\ of\ shipments\ sent}$

For each of these dimensions, multiple subcategories and metrics are mentioned which partially overlap with the metrics mentioned in Chopra and Meindl (2015).

Warehouse-specific performance indicators

Zooming into the warehouse process specifically, Richards (2011) also mentions the operational aspects of Slack, Brandon-Jones, and Johnston to measure warehouse performance. In addition, Ackerman (2003) mentions reliability, flexibility, costs, and asset utilization as the four areas to measure warehouse performance. These areas can include different KPIs which in itself can be assessed in different manners. Also, multiple articles only focus on one part of the warehouse process, like order picking problems or storage optimization, using only KPIs involved in these processes. Luckily, Staudt et al. (2015) made a literature review about warehouse performance measurement to address all these issues. This article is used as a basis for this thesis to identify KPIs to measure efficiency and effectiveness in a warehouse.

Staudt et al. (2015) make a distinction between direct or hard and indirect or soft measures. Direct measures are quantitative measures that are more easily computable with some simple mathematical expressions. Direct measures can be divided into four groups: time, quality, cost, and productivity. Eventually, they counted the number of publications using individual indicators used in papers by regrouping similar indicators and including specific metrics into generic ones. These were subsequently assigned to the groups. The resulting KPIs are displayed in Appendix B.2. Indirect measures are not easily computable but require more structured mathematical tools. The resulting KPIs are displayed in Appendix B.3.

These KPIs fit nicely to the supply chain performance metrics of Caplice and Sheffi. By dividing individual warehouse metrics over time, quality, cost, and productivity, which are subsequently subdivided over the warehouse processes and resource-related indicators, the KPIs of Staudt et al. can be divided over the three areas of Caplice and Sheffi. Quality-related measures are mainly attached to effectiveness, whereas time, productivity, and cost are mainly attached to productivity. However, not all productivity measures fit the definition of Caplice and Sheffi, some have to be allocated to the utilization measure. This is summarized in Table 3-5.

The influence of storage assignment

When talking about the SLAP problem, performance is mainly measured on two variables: the space reserved for material allocation and the time required for handling materials (Bahrami et al., 2019). However, both of these variables influence multiple metrics. Also, some other metrics might be indirectly influenced like scrap rate (if more articles are stored together), picking accuracy (if products are always on different locations), etc. All metrics that are influenced by the storage policy have been indicated with a star (*) in Table 3-5.

*Table 3-5: Supply chain and warehouse performance metrics, summarized in one table (Caplice & Sheffi, 1994; Staudt et al., 2015). The metrics influenced by the storage policy are indicated with a *.*

<table>
<tr><th colspan="3">Supply chain metrics</th></tr>
<tr><th>Effectiveness</th><th>Utilization</th><th>Productivity</th></tr>
<tr><td>Actual output / norm output (Quality)</td><td>Actual input / norm input (Productivity: utilization measures)</td><td>Actual output / actual input (Time, cost, productivity)</td></tr>
</table>

<table>
<tr><th colspan="9">Warehouse-specific metrics</th></tr>
<tr><td rowspan="2"></td><th colspan="6">Activity-specific indicator</th><th colspan="2">Resource related indicators</th></tr>
<tr><th>Receiving</th><th>Storage</th><th>Inventory</th><th>Picking</th><th>Shipping</th><th>Delivery</th><th>Labor</th><th>Equipment and building</th></tr>
<tr><th rowspan="3">Time</th><td>Receiving time</td><td>Put away time*</td><td></td><td>Order picking time*</td><td>Shipping time</td><td>Delivery lead time</td><td rowspan="3"></td><td rowspan="3">Equipment downtime</td></tr>
<tr><td colspan="2">Dock to stock time*</td><td></td><td colspan="3">Order lead time*</td></tr>
<tr><td colspan="5">Queuing time*</td><td></td></tr>
<tr><th rowspan="3">Quality</th><td></td><td>Storage accuracy *</td><td>Physical inventory accuracy, stock-out rate</td><td>Picking accuracy *</td><td>Shipping accuracy, orders shipped on time</td><td>Delivery accuracy, on-time delivery, cargo damage rate</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td colspan="3"></td><td colspan="3">Order fill rate, perfect orders*</td></tr>
<tr><td colspan="6">Customer satisfaction*, scrap rate*</td></tr>
<tr><th rowspan="3">Cost</th><td></td><td></td><td>Inv. Cost</td><td></td><td></td><td>Distribution cost</td><td rowspan="3">Labor cost*</td><td rowspan="3">Maintenance cost*</td></tr>
<tr><td colspan="3"></td><td colspan="2">Order processing cost*</td><td></td></tr>
<tr><td colspan="5">Cost as % of sales*</td><td></td></tr>
<tr><th rowspan="3">Productivity</th><td>Receiving productivity</td><td></td><td>Inv. Space utilization*, turnover</td><td>Picking productivity *</td><td>Shipping productivity</td><td>Transport utilization</td><td rowspan="3">Labor productivity *</td><td rowspan="3">Warehouse utilization*</td></tr>
<tr><td colspan="3"></td><td colspan="2">Outbound space utilization*</td><td></td></tr>
<tr><td colspan="6">Throughput*</td></tr>
</table>

**Metrics directly or indirectly influenced by the storage policy chosen.*

3.2. Simulation study

In this section, the key concepts of a simulation study are outlined. This section mainly focuses on the use for this research and hence it is not a complete overview. For a more complete overview, the books of Robinson (2014) or Law (2015) can be consulted.

3.2.1. Simulation and types of simulation

Simulation can be defined as: "the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behavior of the system and/or evaluating various strategies for the operation of the system" (Shannon, 1998, p. 7). A simulation model imitates the real-world system, via a set of assumptions about the system it tries to describe, expressed as mathematical and logical relations between objects within the system (Winston, 2004).

Next to simulation, there are multiple other ways to study a system, as described in Section 1.3.2. Simulation has multiple advantages and disadvantages. These are briefly repeated and summarized here:

Table 3-6: (Dis)advantages of simulation, also see Section 1.3.2. (Law, 2015; Winston, 2004).

Advantages	**Disadvantages**
- Can be used repeatedly to test various interventions/scenarios. - Suitable if analytical evaluation is not possible. - Capable of estimating the performance of a system. - Good control over experimental factors in contrast to testing with the real-world system.	- It can be time-consuming to make a simulation model. - It only produces point estimates. - There is a tendency to put too much confidence in the study's results. - Even though it is possible, simulation is in general, not an optimization technique (but more for what-if questions).

Multiple simulation model types can be defined, to name a few examples:

Table 3-7: Types of simulation models, their definition, and some examples (Law, 2015; Robinson, 2014).

Simulation type	**Definition**	**Examples**
Discrete-event	Models the system as it evolves over time, where the state of the system changes at countable points in time (events).	All kinds of business processes, like warehouses, hospitals, production, etc.
Continuous	Models the system as it continuously evolves over time.	Airplane in the sky or water levels.
Monte Carlo	Sampling from probability distributions without time dimension (static models).	Modeling future of investment portfolios or multi-dimensional integrals.
System dynamics	Type of continuous simulation, where systems are modeled as stocks and flows.	Governing of water quality or road congestion.
Agent-based	A discrete event simulation, where entities interact with other entities and their environment.	Spread of epidemics or animal group behavior.

This list is by no means complete, there are multiple other types of simulation. The focus of this research is on discrete event simulation (DES).

A simulation model can be made in multiple software types (Robinson, 2014): spreadsheets (Excel), programming languages (C#, Java, Excel VBA), and specialist software (Simio, Plantsimulation, AnyLogic).

The steps followed in a simulation study are displayed in Section 1.4, Figure 1.7. The problem formulation and data collection are already part of this research. Therefore, in this section, data analysis, conceptual modeling, construction of the model (with a focus on verification, validation, and credibility), experimental design, and analysis of output are considered.

3.2.2. Data analysis

The first question is how to use the collected data in the simulation model. There are three main approaches:

Table 3-8: Possible use of collected data in a simulation model, the definition, and the advantages (Robinson, 2014).

Approach	**Definition**	**Advantages**
Direct data use	Use obtained data directly in the simulation	Useful for model validation Includes intrinsic data issues
Empirical distribution	Use data to define an empirical distribution	Unlimited data generation Facilitates custom data patterns
Theoretical distribution	Use data to fit a theoretical probability distribution to the data	Smoothens irregularities Facilitates data outside of the range of historical data Can facilitate physical reasons to justify a certain theoretical probability distribution Compact representation Easier modifications

It is preferred to use a theoretical distribution over an empirical distribution, whereas it is preferred to use an empirical distribution over direct data use (Law, 2015). To fit data to a theoretical distribution, the following three steps should be followed.

1. Hypothesize the families of distributions: select a distribution that represents the data using summary statistics, box plots, quantile summaries, and histograms.
2. Estimate parameters: estimate parameters of the selected distribution using the method of moments or maximum likelihood estimation.
3. Check fit between probability distribution function and data: use histograms of the distribution and the data, QQ-plots, PP-plots, and formal goodness-of-fit tests.

The latter can be done with a Chi-square test or Kolmogorov-Smirnov test. In the Chi-square test, the range of the distribution is divided into k adjacent intervals. Then, the number of observations in the jth interval is counted (N_j) and compared to the expected number of observations (np_j) in that interval. The null hypothesis states (H_0): there is no significant difference between the expected and observed frequencies, whereas the alternative hypothesis (H_1): states that there is a significant difference that cannot be due to chance alone. To test this, the test statistic $\chi^2 = \sum_{j=1}^{k} \frac{(N_j - np_j)^2}{np_j}$ is used, where j is the interval number, k the number of intervals, N_j the observed number of observations in the interval, and np_j the expected number of observations in the interval. If H_0 is true, and $n \rightarrow \infty$, then the test statistic converges to a distribution function between the Chi-square distribution with k-1 degrees of freedom and the Chi-square distribution with k-m-1 degrees of freedom, where m is the number of estimated parameters. Robinson (2014) subtracts the number of estimated parameters m. However, Law (2015) advises using k-1 degrees of freedom, which is more conservative: the probability of a Type

I error is at least as small as the chosen significance level α. The H_0 is rejected if the calculated test statistic is higher than the $\chi^2_{1-\alpha,k-1}$ value from the Chi-square distribution (Law, 2015; Robinson, 2014). Note, not rejecting the H_0 does not mean accepting it.

The number of intervals can be determined using the square root rule ($\sqrt{n}$) or Sturges' rule ($1 + \log_2 n$), where n denotes the number of data points. The interval width should be as such, such that each interval has the same probability using the inverse of the theoretical CDF (the equiprobable approach). For this, the theoretical number of observations should be larger than or equal to five.

For statistical analysis, often independence of data is assumed. If this condition is violated, wrong conclusions may be drawn. To assess independence, correlation coefficients, scatter plots, and correlation plots can be used. However, independence implies correlation zero, but not the other way around. To formally check independence, Chi-square independence tests can be used with contingency tables. However, if this is not needed, correlation coefficients and plots can point in the direction of independence (Law, 2015; Larsen & Marx, 2012).

3.2.3. Conceptual modeling

Conceptual modeling involves a description of the computer simulation model, not based on the software that is used to make the model (Robinson, 2014). The conceptual model should contain the following things (Law, 2015):

- Objectives of the research: goals, inputs, performance measures (outputs), restrictions, timing visualization, and run times.
- Process-flow diagrams.
- Description of each sub-system and the interaction between them.
- Assumptions and simplifications made, and the reason why these are made.
    - Assumptions: fill in gaps in our knowledge about the real world.
    - Simplifications: are made for more rapid model development.

  Here, also the level of detail of the model should be outlined.
- Limitations of the model.
- Summaries of data.
- Sources of controversial information.

This model should be communicated with each important stakeholder to make sure that everyone agrees on each part of the model, before continuing with the actual computer modeling.

3.2.4. Making the model while ensuring verification, validation, and credibility

When each stakeholder agrees on the conceptual mode, it is time to code the simulation model. The coded model should be judged on three aspects (Davis, 1992; Carson, 1986):

- **Verification:** has the assumptions document been correctly translated into a computer program?
- **Validation:** is the model an accurate representation of the actual system being studied?
- **Credibility:** do the key stakeholders accept the simulation model and its results?

These aspects should be judged into the various stages of simulation modeling, as displayed in Figure 3.2.

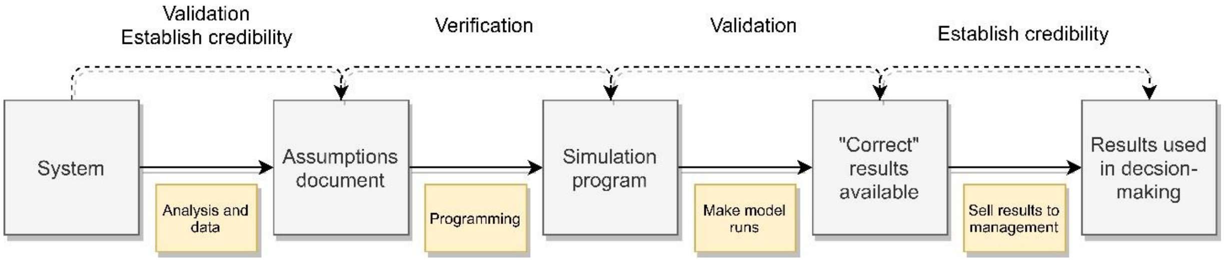


Figure 3.2: Timing and relationships of validation, verification, and establishing credibility (Law, 2015, p. 248).

However, Robinson (2014) points out that verification and validation is a continuous process that is performed throughout the life-cycle of a simulation study. It is used to prevent three types of errors (Balci, 1990):

- Type I error: rejecting the model when it is sufficiently accurate.
- Type II error: accepting the model when it isn't sufficiently accurate.
- Type III error: the error of solving the wrong problem.

Verification can be done using eight techniques (Law, 2015):

- Write the program in modules and subprograms and debug.
- Let more than one person review the program.
- Run the model on a variety of settings.
- Use a trace: compare hand calculations to a state change in the program.
- Run the model under simplifying assumptions.
- Observe animations.
- Compute sample means and variances and compare them to the desired mean and variance of each input probability distribution.
- Use a commercial simulation package to reduce programming effort.

For validation, the following forms exist (Robinson, 2014):

- **Conceptual model validation:** does the conceptual model contain all aspects that are relevant for the goals and objectives set?
- **Data validation:** is the data that is used accurate enough?
- **White-box validation:** does each part of the model represent its real-world counterpart accurately enough?
- **Black-box validation:** does the overall model represent the real world accurately enough?
- **Experimentation validation:** are the experimental procedures that are used for providing results sufficiently accurate?
- **Solution validation:** are the results obtained from the model sufficiently accurate?

3.2.5. Experimental set-up

When the model is built, validated, and verified, experiments can be run with the model. However, results cannot directly be interpreted. This section briefly outlines why, and what has to be done to run proper experiments.

Simulation output

Most simulation studies try to approximate some system parameters. Since inputs of a simulation model are generally stochastic, so are the outputs. Hence, statistics from one simulation run are only point estimates of the real system performance. Simulation output can be deterministic, but this is not covered here since stochasticity was one of the main reasons to choose simulation. The simulation model does not provide independent identically distributed (i.i.d.) observations. Hence, the “classical” statistical techniques cannot be used (Alexopoulus & Seila, 1998).

A simulation can be terminating or non-terminating. In a terminating simulation, the simulation runs for a certain time T_E and stops due to a specified event E. A non-terminating simulation does not have such an event (Winston, 2004). The simulation output can be transient or steady-state. Transient output means that the output is constantly changing, whereas, with steady-state behavior, the output is varying according to some fixed distribution: the steady-state distribution. Next to these two main types of output, two additional outputs are defined: steady-state cycles and shifting steady-state. With steady-state cycles, the simulation shifts between multiple steady-states according to a predictable or regular pattern, whereas, with shifting steady-state the simulation shifts between multiple steady-states in an unpredictable manner. Usually, terminating simulations have transient output whereas non-terminating simulations have steady-state output. However, this should be investigated by inspecting both the input data and the output data (Robinson, 2014).

There are two main issues in obtaining accurate estimates for system parameters.

1. Removing the initialization bias

The initialization bias is the period before the system reaches a steady-state. For example, when starting a simulation for the throughput time of a beer-bottle production line, it is quite unlikely that a system was completely empty. Hence, the throughput time estimates for the first number of bottles are not proper estimates of the true system performance. To overcome this, mainly two things can be done:

1.1 Discard the initial part of the simulation/warm-up period

By using a warm-up period, the period before the system reaches a steady-state should be removed. To determine the length of this period, multiple methods exist, which can be classified into five categories (Hoad et al., 2010):

1. **Graphical methods:** visually inspect time-series data.
2. **Heuristic approaches:** use simple rules to delete the warm-up period.
3. **Statistical methods:** determine warm-up period using statistical principles.
4. **Initialization bias tests:** are tests to determine if an initialization bias is present. They work together with the other approaches to check if the use of a warm-up period is effective.
5. **Hybrid methods:** use a combination of (1) or (2) together with (4).

1.2 Set initial conditions

Setting initial conditions can be done in two ways (Winston, 2004):

- Run a warm-up period for the model, record the model status, and take the average. Use this as the initial condition.
- Look at the real system and apply those averages.

These initial conditions should be set for work-in-progress, activities that take place, and equipment stoppages (Robinson, 2014).

Next to setting either initial conditions or deleting the warm-up period to overcome the initialization bias, a combination of both can be used or the model can be run very long (such that the bias effect is negligible).

In this research, a graphical method is used, namely Welch's procedure. The procedure is as follows (Law, 2015; Welch, 1983):

1. Make *n* ≥ 5 replications, with the same length m. Let X_{ji} be the *i*th observation of the *j*th replication, where *j* = 1, 2, … *n* and *i* = 1,2, … *m*.
2. Calculate the mean of each *i*th observation over the *j* replications: $\overline{X_i} = \frac{1}{n}\sum_{j=1}^{n} X_{ji}$.
3. Calculate the moving average over window w $\overline{X_i}(w) = \frac{1}{2w+1}\sum_{s=-w}^{w} X_{i+s}$. Choose the window as such, such that $w \leq \left\lfloor \frac{1}{4} m \right\rfloor$ Also, if $i \leq w$, then use w=i-1.
4. Plot the moving averages $\overline{X_i}(w)'s$ and choose observation *h* beyond which the output seems to have converged.

A few remarks:

- Choose *m* much larger than the anticipated warm-up period.
- Plot for several values of *w* and choose the smallest *w* for which the plot is reasonably smooth.
- If the plot is still not smooth for $w \leq \left\lfloor \frac{1}{4} m \right\rfloor$, add more replications.
- If the plot is smooth, but the output is not stable yet, increase *m*.

2. Obtaining sufficient data
To obtain sufficient data, two things can be done.

1. Run multiple replications

A replication is a simulation run with a specific random number. When running multiple replications, multiple simulation runs, each with different random numbers, are executed. In this way, multiple samples of the output are obtained. The initialization bias is removed for each replication. The question arises, how many replications should be run? There are three main methods found in literature:

- **Rule of thumb:** use three to five replications (Law & McComas, 1990).
- **Graphical method:** plot the cumulative mean of a chosen output against the number of replications and choose the point on the graph where the cumulative mean line becomes flat (Robinson, 2014).
- **Confidence interval:** the user needs to select a certain precision of their model. Based on this, replications are run, and confidence intervals constructed around the cumulative means are constructed. If the chosen precision is obtained by a certain number of replications, that number is chosen (Banks et al., 2010).

The rule of thumb does not use the output of the simulation model, in contrast to the graphical method and confidence interval method. The confidence interval method provides a measure of accuracy in contrast to the graphical method. Hence, Robinson (2014) recommends using the confidence interval method, even though it requires more complex calculations.

2. Batch means method

In the batch means method, one long run is performed. From this long run, multiple batches of observations are taken to obtain multiple samples of the output. The advantage is that the warm-up period only has to be removed once and the mean is usually estimated better. The batch size influences the correlation between the samples. If it is large, the batches are approximately uncorrelated and normally distributed, however, if it is too small, batches are correlated and confidence intervals are too optimistic on model accuracy (Law, 2015).

In this research, multiple replications are used to obtain sufficient data. To determine the number of replications, the sequential procedure is used. However, before the sequential procedure is applied, an estimation is made.

The basic idea is to perform sufficient replications such that the confidence interval half-width, relative to the average is smaller than γ', where $\gamma' = \frac{\gamma}{1+\gamma}$, and γ denotes the relative error. For more details about the relative error, see Law (2015). An estimation for the number of runs is made to check if γ is not chosen too small and an unrealistic number of replications would be needed regarding run length. To estimate the number of replications, make *n* replications (*n* not too large), and calculate the sample mean $\bar{X}_n$ and sample variance S_n^2. Then, an estimate for the number of replications can be made with (1).

$$n^* = \left\lceil S_n^2 * \left(\frac{1.96}{\gamma' * \bar{X}_n}\right)^2 \right\rceil \qquad (1)$$

Where the 1.96 originates from the student's t-distribution with α = 0.05 and $n \rightarrow \infty$. If the estimate results in a realistic number of replications regarding the run length for the chosen relative error, the number of replications can be determined using the sequential procedure:

1. Start: make $n_0 \geq 2$ replications and set $n = n_0$.
2. Calculate the mean $\bar{X}_n$ and sample variance S_n^2, together with the confidence interval half-width: $\delta(n, \alpha) = t_{i-1,1-\alpha/2}\sqrt{S_n^2/n}$.
3. Then, if $\frac{\delta(n,\alpha)}{|\bar{X}_n|} = \frac{t_{i-1,1-\alpha/2}\sqrt{S_n^2/i}}{|\bar{X}_n|} \leq \frac{\gamma}{1+\gamma}$, stop. Else, make another replication, *n* = *n*+1, and go to step 2.

3.2.6.Comparing scenarios

When the right methods are used to obtain accurate simulation output, the system can be analyzed. For a single system, the 'general' statistical procedures can be used to analyze the average, standard deviation, or confidence interval of a certain KPI. However, also think about the median, mode, and quantiles.

It is also interesting to compare different simulation models to each other, for example, to check how much improvement a different policy would bring. For the comparison of two systems, multiple procedures exist based on a few conditions that determine if this approach can be used (Table 3-9). These conditions depend on the number of observations from each system, correlation, and variances.

Table 3-9: Statistical procedures to compare the output of two simulation models, together with the conditions about when to use them (Law, 2015).

Procedure	**Condition to use this approach**
Paired-*t* approach	An equal number of observations, both systems might be correlated.
Two-sample-*t* approach	Both systems are independent, have more than one observation, and have equal variances. An unequal number of observations is allowed.
Welch approach	Same as the two-sample-*t* approach, except that there is no restriction on the variances.

Usually, the paired-*t* approach is used due to common random numbers and the ability to control the number of replications used. A problem for these approaches is that they assume that the observations are (approximately) normally distributed. When only a few replications are used, this can be questionable. Based on these confidence intervals, a statistical conclusion can be drawn. If the confidence interval includes zero, with a certain significance level, it can be concluded that the true mean of the KPI of system one is not different from the true mean of the KPI of system two. If the confidence interval does not contain zero, the true mean of the KPI of one of the systems is (with a certain significance level) higher than that of the other, dependent on the order in which the confidence interval was constructed. The approaches can also be used to compare multiple systems, by making a cross-comparison (Law, 2015; Robinson, 2014).

3.3. Summary: key points from Chapter 3

At the end of each chapter, the key points of that chapter are summarized.

Warehousing literature

- A warehouse has the following functions (Tompkins & Smith, 1998): 1. Bridge the interval of time between the moment that goods and products are received and the moment they are needed (storing). 2. Change the composition of the goods (order picking). 3. Guide goods to their destinations (receiving and shipping).
- The storage location assignment problem (SLAP) is "to assign incoming products to storage locations in storage departments/zones in order to reduce material handling cost and improve space utilization" (Gu et al., 2007).
- Many storage strategies exist, which can be divided into three main groups: dedicated, random, and shared storage strategies. These groups include multiple storage strategies.
- Performance of the SLAP is mainly measured on the space reserved for material allocation and the time required for handling materials.

Simulation literature

- A simulation model imitates the real-world system, via a set of assumptions about the system it tries to describe, expressed as mathematical and logical relations between objects within the system (Winston, 2004).
- The data used in a simulation model can be based upon direct data use, empirical distributions, or theoretical distributions.
- A simulation model should first be outlined on paper (the conceptual model). This paper model should be properly communicated with important stakeholders.
- The simulation model should be verified and validated continuously during model development.
- To acquire proper simulation output, the number of replications and run length should be determined using several formal procedures. Moreover, the initialization bias should be removed.
- Statistical procedures should be used to analyze simulation output.

Usage in this research

- The alternative storage policies are used as input for the solution generation process in the next chapter.
- The KPIs considered are also used as input for the next chapter. Eventually, KPIs to measure the efficiency and effectiveness of a storage policy are selected.
- As input for the model, empirical and theoretical distributions are used.
- The conceptual model is outlined in Chapter 5.
- To verify the model, the steps of Law (2015) are followed.
- To validate the model, the arrival of items, utilization levels, and working hours per day are compared to reality.
- To acquire proper output, the simulation model uses a warm-up period of 100 days, a run length of 600 days, and five replications.

4. Solution generation

Chapter 4 displays the solution generation and selection phase of this research. First, this chapter outlines important stakeholders for this research within VMI. Secondly, it is analyzed which KPIs VMI uses in its warehouse, and this is compared to the literature of Chapter 3. Third, the solution generation process is explained. Lastly, the decision-making process is illustrated.

4.1. Stakeholder analysis

A stakeholder analysis is performed to determine who should be involved in the decision-making process. A stakeholder is: "any group or individual who can affect or is affected by the achievement of the organization's objectives" (Freeman, 1984, p. 46). The stakeholders considered here are the departments/people who are directly or indirectly involved by the results of this assignment. These are mapped in the power-interest grid of Mendelow (1991) in Figure 4.1.

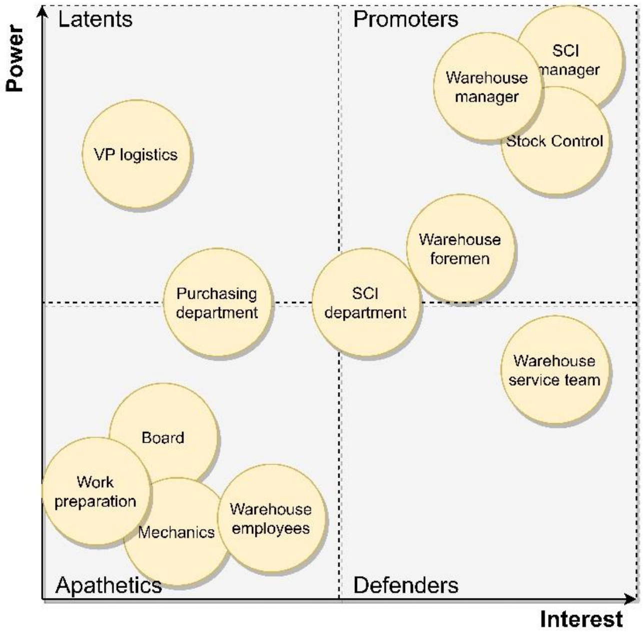


Figure 4.1: The power-interest grid of Mendelow (1991) applied to identify the most important stakeholders for this assignment.

By using the grid, the stakeholders are divided into four groups:

Promoters

The stakeholders in this group are engaged in the project and managed closely. They are involved in the decision-making process within this project.

- *Supply Chain Innovation manager*
  The SCI manager initiated the assignment. The assignment involves a strategic decision in the warehouse. The warehouse is an essential part of the supply chain of VMI. Furthermore, the SCI manager is the external supervisor of this master thesis project. So, both his power and interest are high.
- *Warehouse manager*
  The warehouse manager has a lot of power over the warehouse since he makes the final decisions in it. Also, he initiated this project. Moreover, the assignment involves strategic decisions in the warehouse. So, both his power and his interest are high.

- *Stock control manager*
  The stock control manager initiated the assignment. He has a lot of experience and knowledge about data at VMI, warehousing, simulation, and graduation assignments in general. Also, he is quite involved in this project from the start on. So, the stock control manager has high power and interest.
- *Warehouse foremen*
  The warehouse foremen (incl. their assistants) of the inbound and outbound departments of the warehouse are responsible for the management of each inbound and outbound process, respectively. The storage assignment influences both the put-away and the picking process of the warehouse. They were not that closely involved in initiating the project, but the result is still important to them. To conclude, their power and interest are not that high as that of the managers, but still relatively high.

Defenders

The stakeholders in this group are adequately informed and provide feedback for this assignment. Though, they are not involved in the decision-making process.

- *Warehouse service team*
  The warehouse service team consists of two FTEs who are quite interested in both the progress and results of this research. Moreover, they also provide data. Hence, their interest is high, but their power is moderate since they are not involved in the decision-making.
- *SCI department*
  The SCI department consists of four FTEs, of which two are already mentioned (stock control/SCI manager). Though, not all SCI department employees are closely involved in this assignment. Two of them are less involved. However, they know about the assignment and are interested in its outcomes. They also already provided feedback and input for this assignment. Hence, their power and interest are moderate.

Latents

The latents are the group with high power, but low interest. For them, the final results are interesting. Hence, these stakeholders are involved in a late stage of the project when the results can be presented. They are not involved in the decision-making process or progress of this assignment.

- *Purchasing department*
  The purchasing department has a lot of power over the arrival process at the warehouse. However, going into purchasing decisions is beyond the scope of this research. Nevertheless, in some scenarios in the simulation model, the arrival of items can be changed to analyze their effects. If these effects turn out favorable, the purchasing department could revisit the decisions that impact these arrivals.
- *Vice-president logistics*
  The vice-president (VP) logistics is responsible for the processes within the warehouse, supply, sourcing, expedition, and SCI departments. The VP is again under the supervision of the Chief Operating Officer (COO). So, he is the person that can defend the results of this research to the board. He is less interested in the steps conducted in this research, but he is interested in the final results. Hence, his power is relatively high, but his interest is low.

Apathetics

The stakeholders in this group are influenced by the results of this project but have low interest and low power. They are monitored and, at times, questioned about how things work. They are not involved in the decision-making process. They mainly formulate the restrictions for this research.

- *Warehouse employees*
  The warehouse inbound, outbound, and support employees are moderately interested in this assignment, however, they are interested in the outcomes.
- *Mechanics*
  The mechanics do not have a particular interest in this assignment. They want the POs on time and complete at their workstation.
- *Work preparation*
  Similarly, work preparation poses a restriction of this research by determining PO sizes, production planning, etc.
- *Board of VMI*
  The board of VMI has the most power of all stakeholders involved. However, their power and interest over this individual assignment are quite low. They are slightly interested in eventual outcomes.

4.2. KPIs in use at the VMI warehouse

This section outlines the KPIs currently in use at the VMI warehouse. This is compared to the metrics mentioned in Section 3.1.3. The KPIs are identified to determine which performance measures are considered by VMI. The VMI warehouse has two main management sheets on which the performance of the current warehouse is tracked. One is for the board of VMI called "TQC Dashboard" and one is for the warehouse foremen called "Warehouse control 4.0".

TQC Dashboard

The time-quality-costs (TQC) dashboard displays eight KPIs, defined in three segments. The KPIs on this dashboard are mainly distributed to the warehouse manager and the board of VMI. The data on the dashboard is based upon the material management sheet, in which the warehouse foremen, service team, support, administration, and expedition foremen fill in different metrics weekly.

With this dashboard, the board and management can quickly judge the current performance of the warehouse. It is distributed to the VMI board monthly. Norms are based upon experiences in the past of the warehouse manager and the warehouse service team. To stimulate improvements, norms are sharpened over time if norms are easily achieved for a longer period.

Table 4-1: KPIs on the TQC dashboard, together with their used description at VMI, in literature, and the norms that VMI sets (March 2021).

KPI name at VMI	Description VMI	Norm	Description in literature*
Time segment			
Value-added time	Put away time – arrival time (in working hours)	*15% of throughput time*	*Dock to stock time*
Sojourn time	Pick moment – put away moment (hours)	*85% of throughput time*	*Queuing time (however, only between put away and picking)*
Throughput time	Value added time + sojourn time	*100% of throughput time*	*Dock to stock time + queuing time*
Quality segment			
Completeness PO level	Number of POs delivered on time/number of delivered POs	*90%*	*Order fill rate*
Completeness PO line level	Number of PO lines delivered on time/number of delivered PO lines	*99%*	*Order line fill rate*
Cost segment			
Ratio direct/indirect FTE	The ratio of people who are directly adding value to the warehouse process to people who are supporting the process	*Direct FTE: xx Indirect FTE: xx*	*Not mentioned*
Labor cost	Total labor cost (direct and indirect FTEs)	*€xxx,xxx*	*Labor cost*
Return on labor	Number of total lines processed / (Direct FTEs + indirect FTEs)	*300*	*Labor productivity*

**Based on Staudt et al. (2015).*

Most metrics are also mentioned in literature, albeit with different names. The labor productivity metric is not exactly defined in the same way. VMI defines labor productivity for the warehouse as *(lines actually received inbound + processed lines expedition + picked lines actual out + picked lines actual out (DPS) + anonymous picked lines in lean lift * 0.25 + picked lines outside of the lean lift) / (direct FTE in expedition and warehouse)*. DPS stands for directly pick and scan. VMI defines direct FTEs as people who are directly involved in the core process of putting away items, picking, consolidating the items, etc. Indirect FTEs are people who support the process like managers, foremen, support team, etc. Interestingly, the anonymous picked lines are multiplied by ¼. Also, multiple lines are combined, whereas, for example, processing an expedition line is more work than processing an inbound line. The metric can, therefore, be a point of discussion. The measure is computed weekly.

Warehouse control 4.0

The warehouse control tool is more or less a monitoring and control sheet for the warehouse foremen. When things are not going as they should, this sheet should immediately provide insight into what goes wrong. To name two examples, the number of order lines not picked the last day (that should have been picked) or the number of products in front of inspection more than one day. These metrics are composed weekly. This sheet is mainly operational and hence is not considered in this research. This method is also called “management by exception”.

Comparison to literature

Comparing the used metrics to the literature in Section 3.1.3, many metrics are missing. One reason for this is missing data in the ERP system of VMI. It is debatable if the used metrics give a good overview of the overall current warehouse performance. This point is also underlined by the warehouse manager. Therefore, it might be interesting for VMI to consider this when implementing the new ERP system such that a better view of the warehouse performance can be obtained. Missing data is not a problem in the simulation model, so, already more KPIs can be included. Hence, in this research, the relevant stakeholders are involved to decide the most interesting KPIs.

4.3. Solution generation

The key question of this research is: *what is an efficient and effective storage and picking policy for the VMI warehouse that can cope with the long-term changing environment?* This section outlines the process in which alternatives and scenarios are generated for this question. Alternatives are alternative storage policies or improvements for the current storage policy. Scenarios are the scenarios to which these alternatives are tested. The solution generation step is displayed in Figure 4.2 below.

To generate solutions, four things are done. First, literature is consulted as explained in Section 3.1.2. Second, a brainstorming meeting is planned with the decision-makers. Third, informal interviews are held with several stakeholders. Fourth, a questionnaire is distributed among the relevant stakeholders.

This questionnaire is created using Google Forms such that it could be filled in digitally. A questionnaire is a quick and effective way of gathering multiple opinions of multiple people, especially during the current pandemic which makes interviewing more difficult. By using a questionnaire, relevant stakeholders can give their opinion on already generated ideas. Moreover, they could add their ideas in open fields about which interventions, improvements, and/or scenarios to test. The printed version of the questionnaire is shown in Appendix C.1. The questionnaire is in Dutch.

The four sources resulted in a long list of alternatives and scenarios. Each alternative is posed and explained in Appendix C.2, together with the advantages and disadvantages of each alternative.

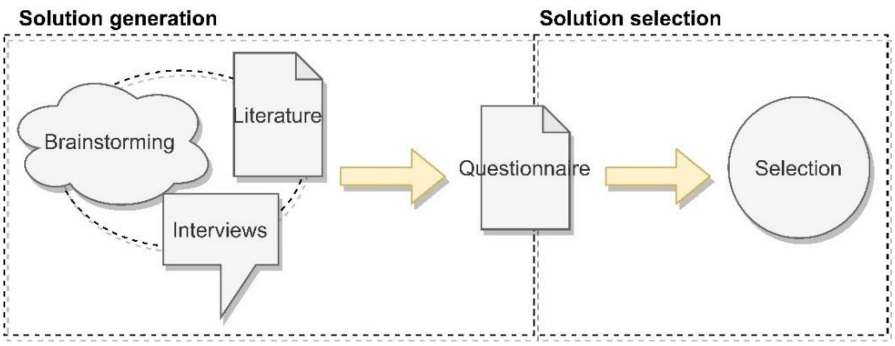


Figure 4.2: The process of solution selection and generation in this research. For solution generation, the questionnaire, brainstorming, literature, and interviews are used. The questionnaire is also used for solution selection, together with planning a meeting with important stakeholders.

4.4. Solution selection

From the long list of alternatives and scenarios, a selection is made since not everything can be tested in the simulation model due to the time frame of this research. How this is done, is explained here.

4.4.1. Response to the questionnaire

First, the results of the questionnaire are analyzed. The questionnaire was filled in by twelve relevant respondents, who are:

- All promoters in Figure 4.1, the reason for this is explained in Section 4.1.
- One employee of the SCI department. He was involved in constructing the current warehouse around 2009 (also see Section 1.2.3) and he is an important stakeholder.
- The warehouse service team, as an important stakeholder (Section 4.1).

- The lean coordinator of VMI. He was also involved in constructing the current warehouse around 2009. Moreover, he is not involved in this research but has detailed knowledge about the processes at VMI. Therefore, this 'external opinion' could result in interesting new ideas.
- Dr. P.C. Schuur, associate professor at the University of Twente and first supervisor of this research. He is an expert in warehousing. Moreover, he is a bit further away from all VMI processes, which can result in refreshing and new ideas.

The respondents all gave their opinion on a scale of 1 (waste of time) to 5 (very interesting) for each alternative and scenario, next to adding their own (also see Appendix C.1). These scores and new alternatives are discussed with the three decision-makers of this research: the SCI-manager, the warehouse manager, and the stock control manager. This was done by physically meeting at VMI, to properly discuss the results of the questionnaire.

4.4.2. Choosing alternatives

For the alternatives, the average scores and standard deviation of these scores are displayed in Table 4-2. On the left, the scores of all respondents are considered, and on the right, only the decision-makers' scores are displayed. Also, the new ideas from the questionnaire are displayed in Table 4-3. Recall, what these alternatives include, is outlined in Appendix C.2.

Table 4-2: Average and standard deviation of the scores per alternative from all the respondents (left) and the decision-makers (right).

Rank	All respondents			Decision-makers		
	Intervention	**Avg. Score**	**St. dev.**	**Intervention**	**Avg. Score**	**St. dev.**
1	Anonymous picks simultaneously	4.42	1.16	Anonymous picks simultaneously	5.00	0.00
2	Lean lifts next to the train	4.08	0.79	Storing per SKU	4.67	0.58
3	More anonymous procuring	4.08	0.67	More anonymous procuring	4.67	0.58
4	Storing per SKU	3.83	0.83	Lean lifts next to the train	4.33	1.15
5	No restrictions	3.67	1.37	Multiple flows to production	4.33	0.58
6	Outsourcing	3.42	1.31	Store like TKH warehouse	4.00	1.00
7	Multiple flows to production	3.25	1.22	No restrictions	4.00	1.73
8	Store per date of delivery to production	3.17	1.19	Store per train	3.67	1.53
9	Store per train	3.17	1.40	Outsourcing	3.33	1.53
10	Store like TKH warehouse	3.08	1.24	Store per date of delivery to production	3.00	0.00
11	More project procuring	2.50	0.90	More project procuring	2.33	1.53

Table 4-3: New alternatives posed by respondents of the questionnaire.

New ideas from the questionnaire	
Duration of Stay (superSKU)	Racks on wheels/horizontal carrousel
Cube-per-order-index (superSKU)	Hybrid form
Order-oriented slotting (superSKU)	Storing per transport carrier

Interestingly, the top four of the decision-makers are equal to that of all respondents (albeit in a different order). The alternatives below the black lines indicate a score that tends towards three (neutral) whereas the double black line indicates a score tending to two (not interesting).

> *"I find the options [no restrictions] and [storing per transport carrier] still very interesting, but I understand we cannot test it all."*– Stock Control Manager

Looking at the standard deviations, which is an indication for the consensus between the stakeholders, the most consensus is reached for the top four best- and the worst-ranked alternatives. A similar pattern is observed for the decision-makers since most consensus is reached for the top three best-, together with the fifth- and second-last ranked alternative. So, especially in the middle-ranked alternatives, some discussion is present. Then, a few alternatives were excluded in the decision-making (Table 4-4). This exclusion was due to several reasons.

Table 4-4: Alternatives that are excluded from the decision-making process, together with the reason why.

Alternative	Reason for exclusion
No restrictions	The danger of making scope too broad. It is almost a new research question.
Outsourcing	Does not fit the research question.
TKH warehouse	Interesting for VMI, however, difficult to do in a manual warehouse. Also, it overlaps with storing per SKU.
Project procuring	Not the intended direction of VMI. Also, scores bad on the questionnaire.
Racks on wheels or horizontal carousel	Involves making (large) investments, which was beyond the scope of this research.
Hybrid form	Makes the current storage policy more complex. The complexity was one of the reasons this assignment was initiated.
Storing per transport carrier	Is a bit like the situation VMI came from in 2009. Back then, this resulted in multiple problems, so this alternative is not seen as an interesting alternative. Also, this includes multiple (large) investments which are beyond the scope of this research.

Before going into the meeting with the decision-makers, decision criteria with the corresponding weights were determined such that during the meeting, this could be discussed, and weights could be altered. Eventually, this discussion resulted in the following decision criteria and weights (Table 4-5).

Table 4-5: Decision criteria, their weights, and definition. In total four criteria are outlined.

Code	Decision criterion	Weight	Definition
A	Extra simulation effort	0.1	How much extra effort and time does it take to simulate this alternative next to the current situation?
B	Relevance for the research question	0.4	How closely related is this intervention to the research question?
C	Potential gains	0.3	How many gains can be acquired with this alternative?
D	Support	0.2	How much support was there for this alternative in the questionnaire?

Of course, the potential gain is not known exactly while choosing the alternative, since that is tested in the simulation model. However, this was based on current beliefs. Gains are both efficiency gains and interesting insights for VMI. The alternatives were scored before the meeting. During the meeting, after altering the weights, the scores were also discussed with the decision-makers. This eventually resulted in the following weighted scores. The scores are on a scale of 1 to 10.

Table 4-6: Scores for each alternative on each criterion, resulting in a weighted score.

Improvements current situation					
Criterion	**Weight**	**Anonymous simultaneously**	**Lean lifts next to train**	**More anonymous procuring**	**More flows to production**
A	0.1	9	8	6	5
B	0.4	7	7	7	7
C	0.3	8	7	7	6
D	0.2	10	8	9	7
Weighted Score		**8.1**	**7.3**	**7.3**	**6.5**
Alternative storage policies					
Criterion	**Weight**	**Per SKU**	**Per delivery date**	**Per train**	**OOS/COI/LoS**
A	0.1	5	7	6	8
B	0.4	9	8	8	9
C	0.3	6	7	8	4
D	0.2	9	5	6	7
Weighted Score		**7.7**	**7**	**7.4**	**7**

> *"Storing per SKU may not acquire efficiency gains regarding travel time and space, but the insights it gives, together with the ease of implementation in an ERP system, and the fact that it is widely used, makes it really interesting."* – SCI Manager

Not each score is explained here, however, a few which could be debatable are. First, all improvements of the current situation have been given a score of 7 for the criterion 'relevance for the research question'. These are improvements to the current situation, but no actual new alternatives. Second, the score of 6 for potential gains is perhaps a bit high for storing per SKU. The belief is that the efficiency gains are not that much. However, when thinking about less quantifiable measures like simplicity or implementation in the ERP system, this alternative becomes more interesting. Third, the OOS/COI/LoS policies with a superSKU were not questioned to the respondents in the questionnaire. However, since this alternative is only relocating the current project storage, not much resistance is expected. Hence, a score of 7 was given.

So, based on the weighted scores, four alternatives are chosen to test in the simulation model, which can be divided into two segments, with two alternatives per segment: **alternative storage policies** and **improvements to the current storage policy.** Their meaning and (dis)advantages are briefly repeated here. The current storage policy is also simulated, which is explained in Section 2.2.2. This is the benchmark to test all other alternatives against. The reason why only four options were chosen, is because not everything can be simulated due to time restrictions. It was decided to choose two alternatives per segment, which also correspond to the top four weighted scores.

> *"Can't we test all alternatives?"* – Warehouse Manager

Alternative storage policy

Alternative storage policies are alternative storage policies, that change how VMI stores its items.

- **Per SKU**

In this alternative, all items are stored per SKU, like in most warehouses and the current anonymous storage at VMI. Each SKU is allocated to a unique location. As explained in Section 3.1.2, three main storage options are possible: random, dedicated, and class-based. To check if dedicated storage is even possible for VMI, the number of SKUs coming into the warehouse, based on the simulation dataset (see next chapter), are counted and compared to the number of locations in each zone (Table 4-7).

Table 4-7: The number of SKUs compared to the number of locations per zone (simulation dataset).

Storage Zone	SKUs	Locations	SKU to location ratio
EP	A	3830	A
RB	B	6440	B
SP	C	615	C
ZD	D	128	D

This is only a dataset of half a year. A larger dataset of one or two years probably also contains more SKUs. The table shows that dedicated storage is not possible for the VMI warehouse unless a lot of maintenance is performed or co-storage is implemented (where different SKUs are stored in one location). This is not what VMI wants. So, to test this alternative, random storage or class-based storage should be used. In the simulation model, only the EP zone gets an ABC classification, whereas the other zones get a random storage policy. It is believed that the EP zone needs an ABC classification to prevent that popular items are stored in unfavorable locations (higher). The other zones are all nearly symmetric for putting away and picking items. Hence, in those zones, no ABC classification is used.

Advantages:

- Easy to implement in ERP system since this is standard.
- Ideas from literature are applicable.
- Most used way of storing in other warehouses.
- The simplicity of one storage policy in the entire warehouse.
- Possible to decrease sojourn times of anonymous items since they are needed later.
- Fewer storage zones are needed since the project and anonymous storage can be added together.

Disadvantage:

- Walking distance increases when orders are picked since items from the same order are not stored together anymore and, thus, multiple locations need to be visited instead.
- It is more difficult to physically oversee when a project is not complete since these items are now stored apart.
- It is easier to 'steal' items from other orders. When using an item that was actually for a different order, currently, operators need to do a lot of handling since items need to be overbooked, relocated, etc. This 'stealing' becomes easier when storing per SKU.

The influence on the number of storage locations is a bit unclear. On the one hand, you need more space because you do not store multiple different items together, however, at the same time you store the same items together.

In a way, not many efficiency gains are expected with this policy. However, especially its simplicity and ease of implementation in an ERP system are quite important reasons why VMI wants to test this. If it turns out that no efficiency gains can be made, or perhaps even minor losses are made, this alternative might still be interesting. Currently, VMI has a custom-made scan application to incorporate their current way of storing items. When identifying new ERP systems, it turns out only a few can support this way of storing, limiting the scope of systems for VMI. Also, the current way of storing needs two types of storage policies, increasing complexity and introducing an extra flow from anonymous storage to project storage.

- **Per train**

Production orders are transported to production using a tugger train system for items picked from the SP, EP, and RB zones. This is explained in Section 2.5. In this alternative, storage is not per order but per train on which items are delivered to production.

Advantages:

- While picking the train, only one or a few locations next to each other have to be visited, decreasing picking time.
- Less space is needed since more items are stored together.

Disadvantages:

- You need to sort the orders after picking.
- Rescheduling gives more problems than in the current situation.
- The train needs to be generated when items arrive which decreases flexibility.
- The complexity of the current situation with two storage policies keeps existing.

Storing per train can acquire efficiency gains while picking the orders since all items are stored together. This was the key reason for choosing this alternative. This alternative was based upon the idea of correlated storage and order-oriented slotting principles mentioned in literature. A big disadvantage is the loss of flexibility with the current train macro, which has to be altered to incorporate this.

To clarify the choice for alternative storage policies, Figure 4.3 was drawn. A production order consists of multiple items. A train consequently consists of multiple production orders. Hence, storing per train widens the storage scope whereas storing per SKU shrinks this scope compared to the current situation.

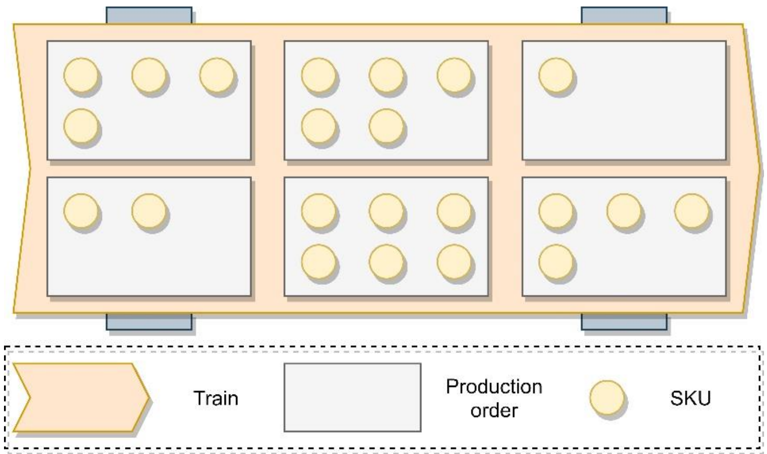


Figure 4.3: The difference between storing per train, production order, and SKU. A train contains one or multiple (partial) orders. An order consequently contains one or multiple items.

These two alternatives are also the first two alternatives when widening or shrinking the scope of storage. In this way, the 'direction' of improvement can be investigated. For example, if one direction seems interesting, further research can test extra alternatives in that direction. Figure 4.4 tries to clarify this point.

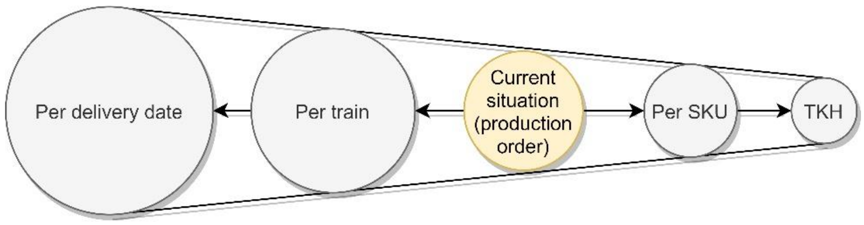


Figure 4.4: Storage policies when widening or narrowing the scope of storage. When the scope is widened, a larger unit is stored on a location, like a full train or a production date. When the scope is narrowed, a smaller unit is stored in a location, like an SKU or a fraction of an SKU (TKH).

Improvements to the current storage policy

Improvements to the current storage policy are about how warehousing processes in the current storage policies can be changed, such that the current way of storing becomes more efficient.

- **Pick anonymous items simultaneously with the project items**

In the current situation, anonymous items are picked three to six working days before production needs the order, dependent on the storage zone (LL or EP/RB). After picking anonymous items, the articles are being put away behind the tracks in the inbound department, who subsequently put away the articles in the project location. Therefore, these items are picked and put away twice. In this alternative, it is investigated what is needed to perform this anonymous pick simultaneously with project items one day before production needs the order, such that this extra put-away and pick can be saved.

Advantage:

- Saving of one put-away and pick step, decreasing total pick and put away times.
- Possible to decrease sojourn times of anonymous items since they are needed later.

Disadvantages:

- More pressure on the date of delivery.
- You are too late if anonymous stock is not sufficient.
- Time to pick a train increases.

- **More anonymous procuring**

Buying more SKUs anonymously means that SKUs are not procured for a specific production order. By buying more SKUs anonymously, SKUs can be procured together and come in together, instead of coming in separately for each project.

Advantages:

- Only one booking, inspection, and put away for all SKUs that come in together.
- Ordering cost reductions for the procurement department.
- When storing per SKU, this also means walking to a location once when putting away the items.

Disadvantages:

- Extra pick and put-away step with the current storage policy.
- It is not possible for all articles, especially not the larger articles in the ZD and SP zone.
- It is less interesting for accounting reasons.

Instead of more anonymous procuring, lean lifts next to the train is also an interesting option since the weighted score is as high as that of anonymous procuring. The effect of this alternative is also slightly considered in the alternative in which the anonymous pick step is done simultaneously. Because of this, and to keep the number of alternatives and scenarios small, more anonymous procuring is chosen over lean lifts next to the train.

4.4.3. Choosing scenarios

With the alternatives chosen, it is time to choose scenarios to test them against. This was done in the same way as in Section 4.4.2. The results are displayed below (Table 4-8). Recall, their explanation can be found in Appendix C.2.

Table 4-8: Average scores per scenario from all the respondents (left) and the decision-makers (right).

Rank	All respondents			Decision-makers		
	Scenario	**Avg. Score**	**St. Dev.**	**Scenario**	**Avg. Score**	**St. Dev.**
1	Volume	4.08	1.08	Volume	4.33	1.15
2	Arrival large/small parts	3.75	1.14	Arrival large/small parts	4.33	0.58
3	Rescheduling	3.75	1.06	Rescheduling	4.00	1.00
4	Arrival more/fewer SKUs	3.08	0.67	Yantai	3.33	1.15
5	Yantai	3.00	0.95	Arrival of more/fewer SKUS	2.67	0.58

Now, the top three are equal for both the decision-makers and respondents. Subsequently, the scenarios were scored again in Table 4-9. Note that at this stage, it was known which alternatives were chosen.

Table 4-9: Scores for each scenario on each criterion, resulting in a weighted score.

Criterion	**Weight**	**Volume**	**Arrival large/small parts**	**Rescheduling**	**Arrivals similar/different parts**	**Yantai**
Extra simulation effort	0.1	9	7	6	7	5
Relevance for RQ	0.4	9	7	6	8	4
Potential gains	0.3	8	5	7	8	6
Support	0.2	9	8	7	4	4
Weighted Score		**8.7**	**6.6**	**6.5**	**7.1**	**4.7**

> *"Why did we give such a low score?"* – SCI Manager

It is interesting to see that arrival of more/fewer SKUs had a low score in the questionnaire, whereas it has a high eventual weighted score. In the meeting in which the final decisions are taken, it was also a bit unclear why this score was so low. Especially since at that point, the alternatives were already decided, this scenario became more interesting. It heavily influences the storage per SKU alternative, it is quite important for testing the robustness of the system, and it is quite likely to happen in reality. For example, if mainly the same machines were sold or mainly different machines were sold. Especially the latter is quite likely to happen for the warehouse in Epe since strategic decisions probably appoint the most standard machines to mainly the production locations in Poland and China in the future. Therefore, this scenario is chosen over the variation between the arrival of large and small parts. It is expected that the latter mainly shows a shift of utilization levels between zones. Rescheduling is mainly interesting for storing per train, but not that much for the other alternatives. Lastly, Yantai scores quite poorly. It is quite interesting for VMI itself, but it is beyond the scope of this research since only the warehouse of Epe is considered. Moreover, it is unclear if by only changing a few parameters, the simulation model could give interesting results for the warehouse of Yantai. This could potentially be something for further research.

To conclude, two scenarios are chosen to test the alternatives against, based on the weighted scores. These scenarios are briefly repeated here.

- **Shift in volume:** what if the number of arriving items increases? This scenario should acquire insight into where bottlenecks occur when volume increases. What are the critical areas of the warehouse? Also, when volumes are increased, one scenario can be better than the other, for example, because one alternative needs more space. Or perhaps the outbound department cannot deal with all order requests since one alternative increases picking times. Hence, altering the volume is seen as an interesting scenario to test the alternatives against.
- **Arrival of more/fewer SKUs:** what if more SKUs arrive, while the volume remains the same? And what if fewer SKUs arrive? For example, when storing per SKU, more locations are needed if more SKUs arrive, whereas this is not the case for storing per production order or per train. However, this is still needed in the anonymous storage, and perhaps problems occur there. So, this scenario influences all alternatives and hence it is also considered.

4.4.4. KPIs

Lastly, next to alternatives and scenarios, KPIs were presented to the respondents of the questionnaire. These were mainly the KPIs mentioned by Staudt et al. (2015). First respondents were asked which dimension they found most interesting. For these, the following scores were obtained:

Table 4-10: Average scores per KPI dimension from all the respondents (left) and the decision-makers (right).

All respondents			Decision-makers		
Dimension	**Avg. Score**	**St. dev.**	**Dimension**	**Avg. Score**	**St. dev.**
Time	4.67	0.65	Time	3.25	1.15
Quality	4.50	0.90	Quality	3.25	0.58
Productivity	4.08	0.90	Costs	3.25	0.58
Costs	3.75	1.14	Productivity	2.50	1.15

Varying from very interesting to interesting for all respondents and neutral for the decision-makers. Not a clear favorite can be appointed, but from this ranking, at least time and quality seem to be the most important dimensions. In the questionnaire, respondents could check the checkbox of the corresponding KPI they thought is important per dimension, together with adding their own KPIs. For each dimension, a top-three was made on how often the checkbox was checked (Table 4-11).

Table 4-11: Ranking of KPIs per dimension.

Time		Quality		Costs		Productivity	
R*	**KPI**	**R**	**KPI**	**R**	**KPI**	**R**	**KPI**
1	Dock-to-stock (9)**	**1**	Storage accuracy, picking accuracy, shipping accuracy, order line fill rate, and on-time delivery (8)	**1**	Order processing cost (8)	**1**	Labor productivity and picking productivity (10)
2	Order picking time (7)			**2**	Labor costs and stock costs (5)		
3	Delivery lead time (6)					**3**	Utilization (6)

**Rank*
*** The number between brackets displays how often the checkbox of this KPI was checked.*

It is decided that in the simulation model, all work that needs to be done on a day, is completed. Subsequently, it is calculated what is needed to attain this regarding time and space. These time and space issues can subsequently be translated to costs. In addition, mistakes from purchasing or suppliers are not present in the model and order pickers do not make mistakes. Hence, in the model, the quality standards are always attained. Then, together with the decision-makers, it has been decided to consider the following KPIs in the simulation model, divided into two dimensions: time and productivity.

Time

- *Put away time:* total time between the start of a put-away route and the end of it.
- *Picking time:* total time between the start of a pick route and the end of it.

Hence, the total put-away and picking time can be calculated by summing over all routes made. This can be subdivided into averages and totals per zone, item (line), day (or other time intervals), route, order, and train. Via the time per day, the FTEs needed can be calculated. Note that this put-away and picking time includes set up time, handling time, searching time, and traveling time.

- *Dock-to-stock time:* lead time from the arrival of a product until it is stored in its designated zone.

Which can also be subdivided per item (line) and zone. Two dock-to-stock time definitions are considered in the simulation model. 1. Lead time from supply arrival until the product is available for order picking (including waiting time). 2. Inbound time (time for inspection, booking, etc.) + put-away time (excluding waiting time).

Productivity

- *Utilization level per zone:* $\frac{locations\ occupied_z}{total\ number\ of\ locations_z}$ *for z ϵ {ST-GB, ST-EP, RB, EP, SP, ZD}.*
- *$OverFlow_z$/Number of items that could not be stored in zone z, z ϵ {ST-GB, ST-EP, RB, EP, SP, ZD}.* This happens when all locations in a particular zone are full, and a new item arrives. In that case, the item cannot be stored and is stored at the public warehouse. This "public warehouse" is explained in 2.5.4.

The lean lift is not included since it is assumed that this zone has an infinite capacity in the simulation model (see Section 5.6). Also, note that labor/picking productivity is not considered. This is done since this calculates output relative to its input. It should be investigated what input is needed for the given output.

The savings in productivity and time are later calculated back to costs in euros. Hence, each dimension is considered since quality is always attained, two time-related measures, two productivity measures, and the costs are considered.

4.5. Summary: key points from Chapter 4

At the end of each chapter, the key points of that chapter are summarized.

- The most important stakeholders for this research are the warehouse manager, SCI manager, and stock control manager.
- Current KPIs in use at VMI do not seem to give a complete overview of the overall warehouse performance.
- To generate alternative storage policies, interviews have been held, a brainstorm session was planned, literature has been consulted, and a questionnaire has been sent to multiple stakeholders. The questionnaire was also used to gather the opinions of people involved in this research about the proposed alternatives.
- The current storage policy stores items per production order in the project storage and per SKU in the anonymous storage. As alternative storage policies, storage per SKU and storage per train are proposed. When storing per SKU, items are stored according to their unique item code in the entire warehouse (so, the anonymous storage plus project storage). When storing per train, items are stored per train on which they are delivered to production in the project storage. On a train, usually, multiple orders are present. The anonymous storage remains as it is.
- As an improvement for the current storage policy, simultaneously picking the anonymous storage with the project storage and buying more SKUs anonymously are proposed. For the first, anonymous items, that are currently picked three or six days before production needs them, are picked simultaneously with project items that are picked one day before production needs them. This can save one put-away and pick step. With the latter, SKUs that are currently procured per order are procured anonymously. Anonymous SKUs come in together and are inspected together, such that put-away and pick times can be saved.
- As scenarios to test the alternatives against, the volume and the number of SKUs are varied. With the first, the volume is increased with a factor of 1.5 or 2. With the latter, the number of SKUs is increased or decreased, while the volume of the number of items remains the same.
- As KPIs to test the alternatives against, put-away, picking, and dock-to-stock times are considered, as well as productivity measures like utilization levels and overflow per zone.

5. The simulation model

With the scenarios and interventions chosen, the simulation literature of Chapter 3 can now be applied to make a simulation model. This chapter outlines the motivation for simulation, the objectives, inputs, outputs, model contents, assumptions, simplifications, and experimental setup.

5.1. Method selection: why simulation?

To test the various scenarios and interventions of the previous chapter, a simulation model is used. The reason why simulation is chosen instead of other ways to study a system is explained in Section 1.3.2. Here, the (dis)advantages of simulation regarding this thesis are outlined.

5.2. Objectives of the simulation study

The objective of the simulation model is to acquire insight into the performance of different storage assignment policies, changes to the current warehouse processes, and different scenarios for the VMI warehouse. To acquire insight, time- and productivity-related KPIs are used to measure the performance of the different interventions. These KPIs can subsequently be used to compare the differences in performance per intervention or scenario. The simulation model also helps in understanding the effects of the interventions and scenarios on the warehouse processes, as well as understanding the current warehouse processes. The outcomes of the model eventually support decisions about whether or not different storage policies or improvements should be implemented.

5.3. Inputs for the model

With the key stakeholders, it is decided to test the following interventions in the simulation model. Chapter 4 explains what these include:

- **The current situation,** to use as a benchmark for the other interventions.
- **Different storage options:** storage per SKU and storage per train.
- **Improvements to the current situation**
    - Doing the anonymous picks simultaneously with the project picks
    - Procuring more SKUs anonymous (not project related)

These interventions are tested against the following scenarios.

- **Increasing volume**
- **Increase/decrease of the number of SKUs arriving**

A detailed explanation of these interventions and scenarios is outlined in Section 4.4.2. How these inputs are modeled in the simulation model is explained in Section 5.9.

5.4. Outputs from the model

To measure the performance of the various interventions, the following KPIs are used:

Time

- Put-away and pick time, which can be divided per train, zone, day, and order. This can subsequently be translated to the number of FTE needed per day.
- Dock-to-stock time per project item, anonymous item, or anonymous line (see later).

Productivity

- Utilization level per zone
- The number of items that could not be stored in its zone because it was full when the item arrived.

What these KPIs are, and how they are calculated, is explained in Section 4.4.4.

5.5. Model contents

This part briefly explains the model contents. This section only explains the basic outline of the model. A significantly more detailed description is outlined in Appendix D.1. The simulation model mainly describes the current VMI warehouse. Hence, it is recommended to first read Chapter 2.

Generating orders and item arrival in the simulation model

To test the various interventions and scenarios, items should enter the VMI warehouse in the model with the same characteristics as in reality. To model this, the following is done.

First of all, a dataset is used that is based on *xx,xxx* production orders (POs), *x,xxx* warehouse orders (WOs), and *xxx* sales orders (SOs), from the second half of 2020. These orders, together with their contents and sizes are explained in Section 2.4. Recall that one order consists of one or multiple items. Each day, the number of POs is drawn from the Gamma distribution with $\theta = xx$ and $k = xx$. The obtained number is rounded to the nearest integer as explained in Section 2.4.5. The number of WOs and SOs are drawn from the empirical distributions displayed in Appendix A.6. For example, on a random day t, 108 POs, 40 WOs, and 1 SO are drawn from the distributions. Then, 108 times a random PO is chosen from the complete list of *xx,xxx* POs, 40 times, a random WO is chosen from the *x,xxx* WOs, and one time an SO is chosen from the *xxx* SOs. Each of these orders has an order date of $t + 46$ days. The order date determines the date on which this order with the corresponding items is picked. It is decided to schedule orders 46 days in advance and to truncate the sojourn time distribution at $t = 20$ *days*, to make sure that item arrivals are only one or two months ahead of the current day t.

Then, for each item in the PO, WO, or SO, a sojourn time is drawn from the empirical distribution displayed in Section 2.6.2. This sojourn time is subtracted from the order date, resulting in the arrival day for this particular item. On this arrival day, the item physically arrives in the warehouse. Figure 5.1 illustrates this process. The next day, this process is repeated.

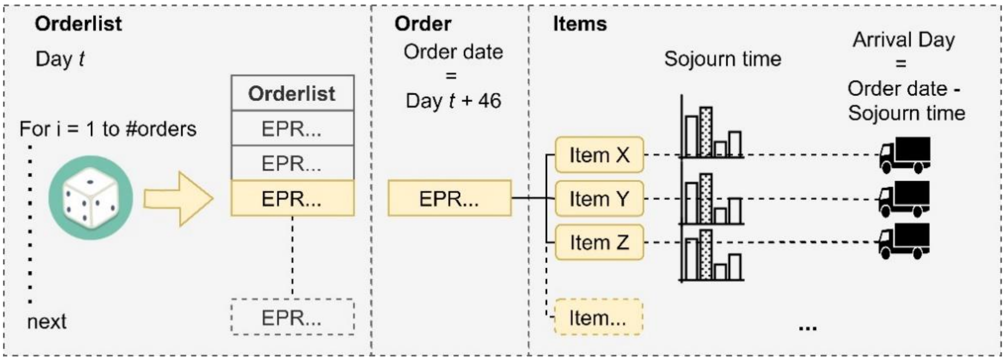


Figure 5.1: Illustration of item arrival in the simulation model. Each day, a number of orders are drawn from the chosen distributions. Then, per order, one 'historical' order is randomly chosen. This order contains individual items, where each individual item gets a certain arrival day, which determines when this individual item arrives in the warehouse.

Anonymous items in the simulation model

Anonymous items arrive a little bit different. In reality, anonymous items come in together, with a fixed quantity (EOQ) as one anonymous item line. So, this anonymous line contains multiple anonymous items of the same SKU. This anonymous line is inspected once, and put away on location once, in contrast to project items that are inspected and put away one by one. To save modeling time, the EOQs for each SKU are not programmed. However, to still create the effect of one inspection and put-away for anonymous item lines, all anonymous items of one SKU, that should arrive in a certain month, are combined into one anonymous line. This anonymous line gets the earliest arrival date of all items contained in that anonymous line.

Using a trace vs. the current approach

The question arises, why not use a trace: a historical dataset that determines the sequence of events in the model? This is useful, especially for validation purposes. However, an important part of this research is to test the robustness of the mentioned interventions. This is tested against an increase in volume and an increase/decrease of the number of SKUs in the dataset. It is believed that this can easier be modeled using the current approach in contrast to using a trace. Moreover, the used trace should be accurate. It is difficult to attain such data from the current scanner application at VMI. Lastly, the current approach is still an accurate representation of the items arriving in reality, as shown in the validation of the model in Appendix D.3.

The tugger train in the simulation model

In reality, based on the train, orders are picked and delivered to production. To save modeling time, the entire, complex train macro is not recreated. It is investigated how many orders are present on the train. This empirical distribution is displayed in Section 2.5.1. When orders are generated, the number of orders on the train is drawn from the empirical distribution in Section 2.5.1. Then, orders with corresponding items are allocated to the train until the number of orders on the train drawn is reached. In that case, the train is full, and a new train is created. A new number of orders per train is drawn, and the train is filled again. This continues until all orders on that day are processed and placed on a train.

Items and their attributes

Items within the orders have the following attributes:

Table 5-1: All twelve attributes of an item in the simulation model, their description, and an example.

Attribute	Data type	Description	Example
ItemID	Integer	Unique item ID within the simulation	3257
Item_string	String	Item number at VMI	“K.259.0534”
Description	String	Brief description of the item	“Cover”
Inboundtime	Time	Processing time at the inbound department	2:08:33 (DD:HH:MM:SS)
Arrivaltime	Time	Time of arrival of the item	31:10:52:44
Order_date	Time	Pick date of the order to which it belongs	48:00:00:00
Order_string	String	Original order number of VMI to which the item belonged	“EPR497357”
OrderNum	Integer	Unique order ID within the simulation	533
Storage_zone	String	Zone in which the item needs to be stored	“ZD”
Storage_destination	String	Destination within the zone (only for SP/ZD)	“ZD-ZDFloor”
TrainNum	Integer	Unique train ID within the simulation	73
Size	Real	Fraction of a location the item occupies in its storage zone	0.4

The size of an item had to be assumed. How this is done, is explained in Appendix D.2.

Storage zones and locations

The storage zones considered in the model are the ZD, SP, EP, RB, ST-GB, ST-EP, and ST-LL zone. Their definitions, capacities, etc. are the same as displayed in Section 2.2. It is assumed that the lean lift has infinite capacity since the mentioned interventions do not influence storage in the lean lift. Moreover, in the SP zone, a distinction is made between rack and floor locations. In the ZD zone, a distinction is made between floor, rack, XL, cantilever, and “public warehouse” locations. It is assumed that the latter three have an infinite capacity since only a small percentage of items go to these zones.

The inbound process

The entire inbound process (unloading, booking, inspection) is modeled as one process to simplify the model. The inbound time of an item is based on the empirical distributions displayed in Section 2.6.1. The working times for the inbound process are the same as explained in Section 2.5.3.

Storage location assignment policy

The storage policies in use at the VMI warehouse (explained in Section 2.2.2) are implemented in the model. However, the current anonymous storage (where dedicated storage is in use) is modeled as a random storage policy. The question arises: why is this done? Well, the main reason for this is that the current dedicated storage policy is close to a random storage policy: if an SKU is not present in the anonymous storage, the empty location is opened again. Hence, you can even debate if this is a dedicated storage policy. This maintenance is done periodically using reports. However, this manual maintenance cannot be done in the simulation model. Hence to prevent overflowing in the model, the random storage policy is implemented that automatically opens up locations when they are empty. In the ST-EP zone, an ABC storage policy is used to prevent that popular items are stored in unfavorable locations (high up the shelf). This is also underlying the current dedicated storage. This is not done in the ST-GB zone since this effect is not that big there. The lean lift has an infinite capacity in the model, hence no storage policy is implemented there.

Put away and picking items

Item put-away is done as explained in Sections 2.2.2 and 2.3.1. Picking of items is done as explained in Sections 2.2.2 and 2.4.3.

Item flow in the warehouse

Items that arrive follow the process displayed in Figure 5.2.

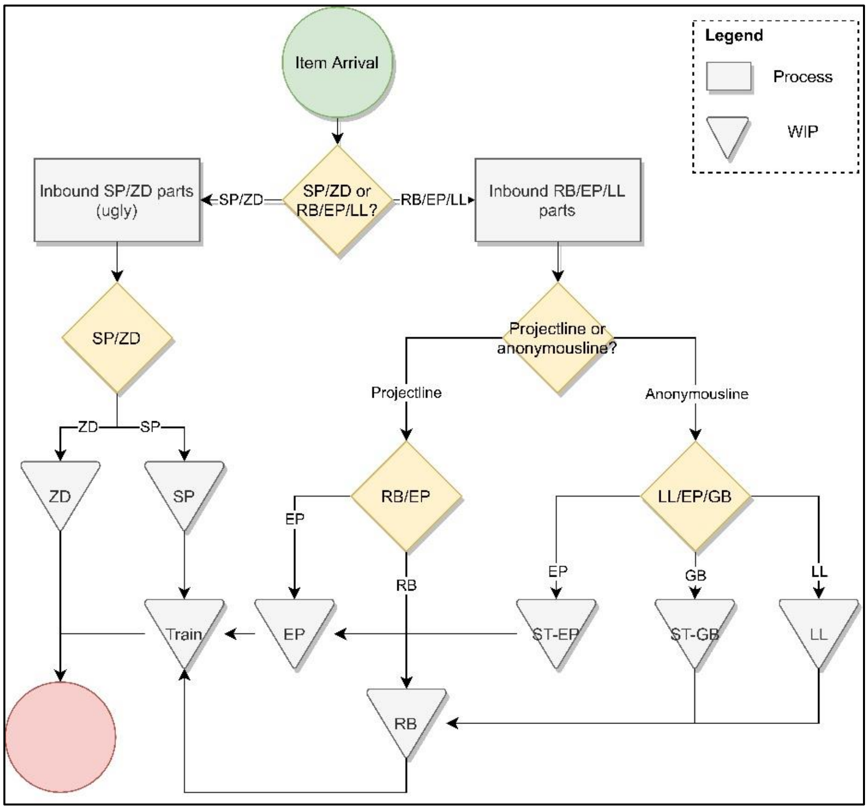


Figure 5.2: The flow of individual items in the simulation model. The route of an item mainly depends on its storage zone and if it is anonymous or project-related.

Pick actions are triggered by all trains that should be picked on a day. Anonymous items from the ST-EP zone and ST-GB zone are picked six working days before production needs the orders and ST-LL items are picked three working days before production needs the order. After these anonymous items are picked from the anonymous storage, they are placed in the project storage.

Put-away and pick capacity

Since routes are made, picker capacities have to be determined. The put-away capacity is per zone:

- ST-GB, ST-EP: per 8 anonymous item lines.
- RB, EP, and ST-EP (2): per 8 items. Where (2) indicates the put-away of anonymous items in the project storage after they have been picked from the anonymous storage.
- ST-GB (2): per 8 GB. Recall from Section 2.3.1 that one GB is one grey bin, that contains one or multiple items from an order that was picked from the ST-GB zone.
- SP and ZD: per item due to their size.

Pick capacity:

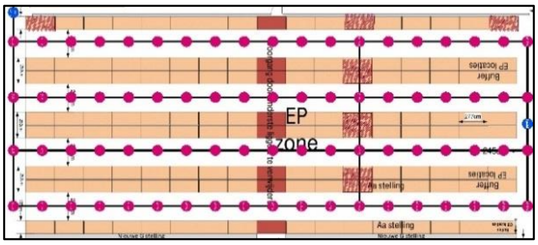
- ST-GB, RB: per 8 GB.
- EP, ST-EP: per 8 items.
- SP and ZD: per location visited. Since these items are stored on a pallet, and one pallet takes one location, the entire pallet is picked.

These capacities are based upon the current put-away and pick processes and scan application in place at the VMI warehouse, as explained in Chapter 2.

Put-away and picking time

Unfortunately, no time to put away and pick items was present at VMI (also see Section 2.6.3). Hence times needed to be assumed. Time to put away and pick items consists of four components: travel time, search time, handling time, and set-up time. These are briefly covered here.

- **Travel time:** for this, distance grids are drawn over the warehouse map for each zone, where coordinates are allocated over the warehouse map. These are displayed in Appendix D.5. By doing so, the Manhattan distance between each coordinate can be calculated, and by subsequently assigning each location to a coordinate, the Manhattan distance (in m) between each location can be calculated. This results in a symmetric distance matrix per zone between each location.



$$D = \begin{pmatrix} 0 & d_{01} & d_{02} & \cdots \\ d_{10} & 0 & d_{12} & \\ d_{20} & d_{21} & \ddots & \\ \vdots & & & 0 \end{pmatrix}$$

Figure 5.3: An illustration of how the distance grids have been used to create distance grids.

By assuming a speed of 2.4 km/h, based on the average speed used in the three articles of Ruben and Jacobs (1999), Schrotenboer et al. (2017), and Roodbergen (2012), a travel time could be computed. The vertical travel time used in seconds t is based on the report of an employee of VMI, Veldhuis (2016), which is:

$t = \begin{cases} 50 + (h-3) * 14 \; for \; h \geq 4 \\ 0 \quad\quad\quad\quad\quad\quad otherwise \end{cases}$ Where h is the height of the location, $h \in \{1,2,3,4,5,6,7\}$.

The first three floors are on picking height. So, for those heights, the vertical travel time is equal to zero.

- **Handling time:** based on the same journal articles, the time for scanning items and putting items in the location, is set to 20 seconds per item in the RB, EP, and SP rack zones. For the SP floor and ZD items, this handling time is set to 36.7 seconds since these are larger items.
- **Search time:** the time to search for a location is set to 26.67 seconds per location visited.
- **Set up time:** the time to set up a route is set to 13.33 seconds per location visited.

The chosen search and set up times are based upon the distribution of an order picker's time of Tompkins et al. (2003). The put-away and pick capacity, together with the chosen times is summarized in Table 5-2.

Table 5-2: Summary of the put-away and pick capacity, handling, searching, and set-up time, subdivided per zone.

Put-away										
Time	**RB**	**EP**	**ST-GB**	**ST-EP**	**SP rack**	**SP floor**	**ZD rack**	**ZD floor**	**ST-EP (2)*****	**ST-GB (2)**
Handling	Item (20)**		Location (20)		Item (20)	Item (36.7)			Item (20)	GB (20)
Travel capacity	Route per 8 items		Route per 8 lines		Per item				Route per 8 items	Route per 8 GB
Pick										
Time	**RB**	**EP**	**ST-GB**	**ST-EP**	**SP rack**	**SP floor**	**ZD rack**	**ZD floor**	**ST-EP (2)**	**ST-GB (2)**
Handling	GB (20)	Per item (20)				Loc* (36.7)		Item (36.7)	n.a.	
Travel capacity	Route per 8 GB	Route per 8 items	Route per 8 GB	Route per 8 items	Route per location visited				n.a.	
General										
Set-up	Per route (13.33)									
Search	Per location visited (26.67)									

**Loc: per location visited.*
*** Time in seconds.*
**** Put away in the project storage after the items are picked from the anonymous storage.*

Routing

Since putting away is done for multiple items in the RB, ST-GB, EP, and ST-EP zone, a route has to be created. This routing is based on the current routing in the scan application of VMI. This scan application uses a location prioritization on which the put-aways in the current warehouse are based. This prioritization determines the route an order picker has to walk (see Section 2.2.2 for a detailed explanation). Hence, it is recreated in the model. Recall that each location is assigned to a coordinate with an x, y, and z coordinate. These coordinates are used to recreate the location prioritization of Section 2.2.2. A put-away route starts from the I-point and ends at the I-point (see Appendix D.5). Note that put-away routes in other zones are one by one, so the route only consists of I point – location – I point.

Picking is also done for multiple items in the RB, ST-GB, EP, and ST-EP zone, so, also a route has to be created. This routing is based on the current routing in the scan application of VMI. For this, also the coordinates of locations are used, such that the routing from section 2.4.2 could be recreated. A picking route for anonymous items starts at the I-point and ends at the I-point. Picking for project items starts at the O-point and ends at the O-point. Note that picking in the other zones is per location, so this only consists of one location visit. This item routing for both put-away and picking can perhaps be improved regarding distance minimization, but it is the current way VMI works. Improving the routing is not part of this research. Again, a more detailed description of the routing can be found in Appendix D.1.

Implementation

The aforementioned is implemented in a computer program. For this, a commercial software package is used: Tecnomatix Plant Simulation 13 from Siemens. Screenshots of the model are displayed in Appendix D.6. Running one replication (699 simulation days incl. warmup, see later) takes approximately seven minutes.

5.6. Assumptions and simplifications in the simulation model

To model the VMI warehouse, multiple assumptions and simplifications have to be made. This section touches upon these assumptions and simplifications. A detailed explanation of each assumption and simplification is outlined in Appendix D.2.

Assumptions

1. **Item sizes:** there is no data about the size of items. Hence, the fraction of a location that an item takes has been calculated by looking at the average number of items with which this SKU was stored.
2. **Public warehouse:** an item that cannot be stored in its zone is stored at the "public warehouse" location, which can be seen as a penalty for that particular scenario. Note, what this "public warehouse" includes, is outlined in Sections 2.5 and 4.4.4.
3. **Deterministic search time, set-up time, handling time, and speed.**
4. **Stacking height:** the stacking height of SP floor pallets is 3, whereas the stacking height of ZD floor pallets is 3.5.
5. **Fewer locations ST-GB and ST-EP zones:** locations in which items did not move for more than half a year have been removed from the model.
6. **Order picker's utilization:** the order picker's utilization has been set to 70%.

Simplifications

1. **Working days:** only working days are simulated. Overtime is not considered.
2. **Backorders:** since only a small percentage of the total items are backordered, these have not been considered.
3. **Infinite capacity:** the lean lift, ZD-XL, cantilever, and public warehouse all have an infinite capacity in the simulation model.
4. **Sojourn time:** the sojourn time is truncated at 20 working days. Moreover, the minimum sojourn time for lean lift items has been set to 6 working days.
5. **Anonymous item arrivals:** in a month are combined to create the effect of one booking and inspection, in contrast to modeling individual reorder points and order quantities.
6. **Fixed schedule:** it is assumed that inbound time never takes longer than eight hours. Moreover, one day is added to the sojourn time to take this inspection into account. Also, items behind tracks at the end of the day are being put away. This is done such that the schedule that items should follow is not distorted, for example, if items that should be picked are still at the inspection phase.
7. **Seasonality:** seasonality that is present at the inbound and outbound sides of the warehouse has not been modeled (see Sections 2.3 and 2.4).

8. **ABC classification/random storage:** in the ST-GB zone, a random storage policy is used. In the ST-EP zone, an ABC classification is used to prevent that popular items are stored in unfavorable locations. Why this is done, is explained above.
9. **All orders on the train:** in the model, all orders are stored on the train. In reality, WOs and SOs are not stored on the train. However, in the future, it is planned to also do this. Since these orders are smaller, a WO takes only 0.12th fraction of an order, and an SO takes 0.26th fraction of an order.
10. **No mistakes:** order pickers do not make mistakes in the model.

5.7. Verification and validation of the simulation model

The model has been verified and validated quite extensively. This procedure can be found in Appendix D.3. Here, a summary is given.

The model has been verified using the eight techniques of Law (2015), also see Section 3.2.4. It is believed that the paper model has been correctly translated into the computer program.

To validate the model, three things were done:

1. Comparing the orders generated and the arrival of items in the simulation model with the number of items and orders picked in the second half of 2020. This is compared per storage zone.
2. The obtained utilization levels from the simulation model have been compared to the lower and upper bound. The lower bound has been obtained by simply adding the item sizes. The upper bound has been obtained by assuming one location per item. In addition, a prediction has been made for the utilization levels based on the orders in the dataset, sojourn time, and the number of orders per day. The lower bound, upper bound, and predication are compared to the results of the simulation model.
3. The obtained pick time, put-away time, FTE needed, and pick time per train has been compared to the real situation and the used rule of thumb in the warehouse. Moreover, the warehouse foremen, manager, and SCI manager have been questioned about the obtained results.

All in all, it is believed that the model is a sufficiently accurate representation of the current VMI warehouse, for the objectives of this research.

5.8. Experimental setup: replications, warm-up period, and run length

In this section, the warm-up period, run length, and the number of replications are determined for the base simulation model. These should be analyzed for every experiment performed. However, to save time, this is only done for the base model. By doing so, multiple KPIs are considered and the maximum warm-up, run length, and number of replications are chosen for these KPIs. Moreover, this is overestimated a little bit to give a margin of safety, as advised by Robinson (2014).

5.8.1. The warm-up period

To determine the warm-up period, Welch's procedure is used as described in 3.2.5. For the KPIs two utilization measures and two time measures are used: the utilization in the EP zone, the utilization on the ZD floor, the time to pick per day, and the time to pick a train. For Welch's procedure, ten replications, each with a run length of m = 700 days are used. For the moving average, a window of w = 25 days is used, after which the plot was reasonably smooth.

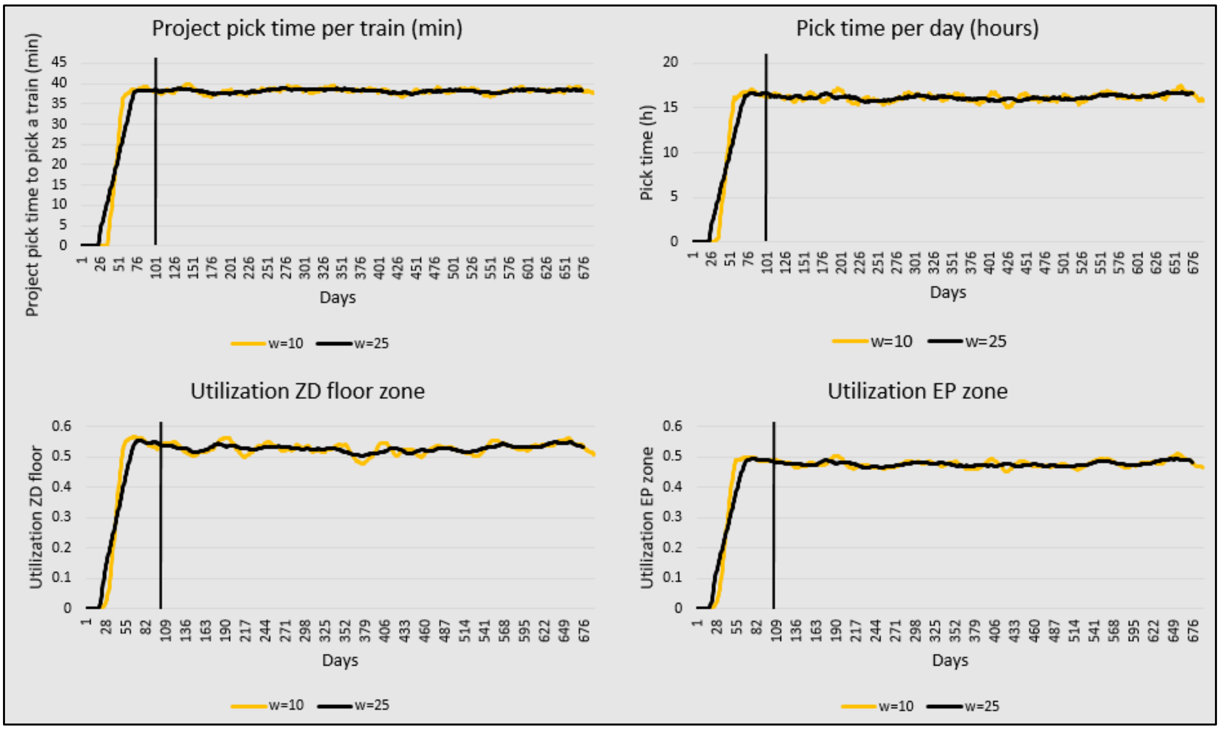


Figure 5.4: Determining the warm-up period for four KPIs, using Welch's approach. After approximately 100 days, each KPI seems to remain in a steady-state.

It is decided to use a warm-up length of 100 days. Perhaps, a shorter warm-up period was already sufficient. However, for the reasons mentioned before, this is overestimated to 100 days.

5.8.2. Number of replications and run length

To obtain sufficient data from the model, the model should be run longer than the warm-up period (Law, 2015). It is decided to let the model run for 600 days, next to the 100-day warm-up period, resulting in a total run length of 700 days. So, the run length is six times larger than the warm-up period. 600 days correspond to approximately 2.4 years since only working days are simulated.

Next, the number of replications is decided by estimation and using the sequential procedure, as described in Section 3.2.5. The relative error chosen is 0.05. The chosen significance level has been set to $\alpha = 0.05$. Then, by making $n = 10$ runs, an estimation is made for the number of replications needed, to see if γ' is not chosen too small. For the estimation of the number of replications, again two utilization and two time measures are chosen: the utilization in the RB zone, the utilization in the ST-EP zone, total put-away time per day, and dock-to-stock time. The estimated results did not result in an unrealistic number of replications (see Appendix D.4). Hence, it is decided to continue with the sequential procedure. The total sequential procedure for each KPI is also displayed in Appendix D.4.

The maximum number of replications needed is three, for the utilization in the RB and the put-away time per day (hour). However, since the sequential procedure has not been applied to each KPI and experimental setting, it is decided to use $n = 5$ replications. As Robinson (2014) advises, it is, in that case, good to overestimate the number of replications a little bit. Moreover, Law and McComas (1990) also advise using at least 3 to 5 replications.

5.9. Experimental design

The following experiments are run with the simulation model. Why it is decided to choose these experiments, is explained in Chapter 4.

Table 5-3: A description of the interventions and scenarios that are run in the simulation model. Due to the time frame of this research, not every intervention can be tested against each scenario.

Intervention / Scenario	Current situation	Storing per SKU	Storing per train
Volume	x	x	x
More/fewer SKUs	x	x	
Procuring more SKUs anonymously	x	x	
Doing anonymous picks simultaneously with project picks	x	n.a.	

These experiments are implemented as follows:

- **Volume:** multiplying the number of orders per day with a factor 1, 1.5, and 2. In this way, the total number of generated orders per day is increased. This is done since it is believed that item arrival in 2020 (on which the current orders per day are based) was low. Currently (June 2021), the warehouse handles a factor of 1.5 to 1.7 more items than in 2020. Furthermore, in the coming quarters, it is believed that the warehouse will be twice as busy as the previous year. Hence the chosen factors.
- **More SKUs:** adding an extra "0" to the item code when it is created (see model contents). This is done such that a new 'unique' item code is created. The item keeps all its original attributes. Only the item code changes. This is done for 3%, 5%, and 10% of items. These percentages are based upon the current belief of the possible increase in SKUs, for example, due to the introduction of new machines.
- **Fewer SKUs:** duplicate an item code when it is created (see model contents). This duplication is done by making a certain item code the same as a previous item code in that zone. The item keeps all its original attributes, only the item code changes. The item code duplication is also done for 3%, 5%, and 10% of items. These percentages are based upon current belief at VMI of what reduction in SKUs can be attained, for example, via standardization. Note, for both the fewer and more SKU scenarios, the volume of items is not increased or decreased.
- **Procuring more SKUs anonymously:** by making all current RB items anonymous, and subsequently all EP items anonymous. An exception is made for painted parts that can never be procured anonymously. This means that 91.7% of the RB items in the dataset can be converted to anonymous items. For EP items, 68.9% of the items in the dataset can be converted to anonymous items.
- **Doing anonymous pick simultaneously with project picks:** see Chapter 4. First, it is investigated what happens if only ST-GB and ST-EP zones are picked simultaneously. Second, it is investigated if also the lean lift is picked simultaneously, next to the ST-GB and ST-EP picks.
- **Storing per SKU:** see Chapter 4.
- **Storing per train:** see Chapter 4.

A summary of the scenarios to which the interventions are tested is displayed in Table 5-4.

Table 5-4: The number of levels and their corresponding values used in each scenario.

Scenario/intervention	Number of levels	Values
Volume	3	Nr. of orders per day times 1, 1.5 and 2.
More/fewer SKUs	7	+-10%, +-5%, +-3%, and +- 0%
Procuring more SKUs anonymously	3	Base case, all possible RB items, and all possible RB and EP items
Doing anonymous picks simultaneously with project picks	3	Base case, picking ST-GB and ST-EP simultaneously, and picking ST-GB, ST-EP, and ST-LL simultaneously.

5.10. Summary: key points from Chapter 5

At the end of each chapter, the key points of that chapter are summarized.

- The inputs for the simulation model are the current situation and two different storage options: storage per SKU and per train. Moreover, doing anonymous picks simultaneously with project picks and buying more SKUs anonymously are also tested. These are tested against a scenario in which more items arrive and when the number of SKUs increases or decreases.
- Outputs of the model are time and utilization related. Regarding time, the put-away time, pick time, and dock-to-stock time are considered. Regarding utilization, the utilization levels per zone and the number of items that could not be stored because the warehouse was full, are considered.
- All key warehouse processes of Chapter 2 are implemented in the model.
- To construct the simulation model, several assumptions and simplifications are made.
- The model has been verified using several techniques of Law (2015).
- The model has been validated by looking at the arrival of parts, utilization levels, and time measures.
- It is decided to use a warm-up period of 100 days, a run length of 700 days, and five replications for each experiment.
- The inputs are tested against a scenario in which the volume increases. Moreover, storage per SKU and the current situation are also tested against a scenario in which more SKUs arrive.

6. Results

In this chapter, the results from the simulation model in which the various scenarios and interventions of Chapters 4 and 5 have been implemented, are outlined and analyzed. Using the results, a comparison is made. In the end, the results are compared regarding the costs made (in euros). In this chapter, mainly the quantitative results are analyzed. In Section 6.6, all qualitative results from Chapter 4 and quantitative results from this chapter are combined and summarized for each intervention. Next, a road map for implementation is made for two interventions, together with making a small sidestep by looking at how automatization can impact the results mentioned.

6.1. Intervention 1: Picking anonymous items simultaneously with project items

In this intervention, the current situation (in the Figures indicated with "Base") is compared to when:

- **ST-GB and ST-EP items** are picked simultaneously with project items. In the Figures, this is indicated with "STGBSTEP".
- **ST-GB, ST-EP, and ST-LL items** are picked simultaneously with project items. In the Figures, this is indicated with "STGBSTEPSTLL".

Recall that ST-GB items are anonymous items stored in the anonymous part of the RB zone. Similarly, ST-EP items are anonymous items stored in the anonymous part of the EP zone. ST-LL items are anonymous items stored in the lean lift (see Section 2.2). These were picked days in advance. In this scenario, these items are picked simultaneously with project items, one day before production needs the order. For a more detailed description of this scenario, see Section 4.4.

6.1.1. Utilization levels

First, the utilization levels are compared.

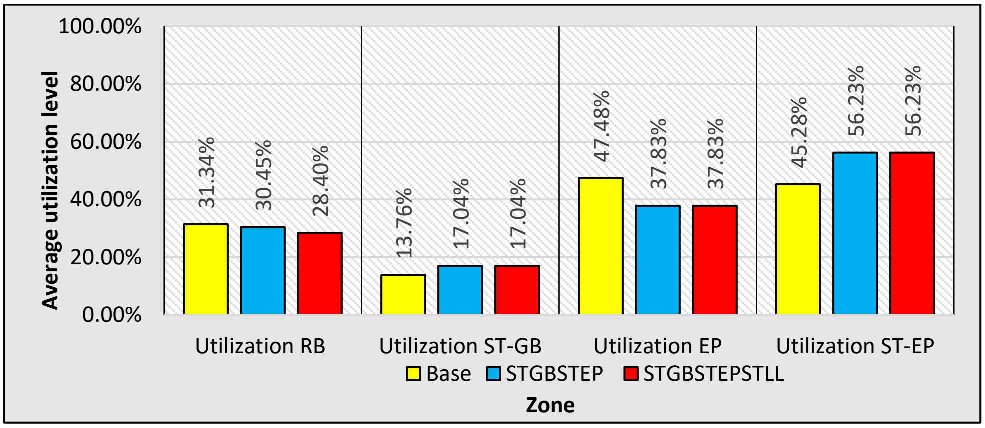


Figure 6.1: Average utilization levels for the current situation and when anonymous items are picked simultaneously. The figure shows a decrease of utilization levels in project storage zones (RB/EP) when more anonymous items are picked simultaneously with project items, while utilization levels increase in the anonymous storage zones (ST-GB/ST-EP).

Table 6-1: Average and standard deviation of the utilization levels for the current situation and when anonymous items are picked simultaneously.

Zone	**Utilization RB**		**Utilization ST-GB**		**Utilization EP**		**Utilization ST-EP**	
	Avg	**Stdev.**	**Avg**	**Stdev.**	**Avg**	**Stdev.**	**Avg**	**Stdev.**
Base	31.34%	0.64%	13.76%	0.26%	47.48%	0.69%	45.28%	0.64%
STGBSTEP	30.45%	0.63%	17.04%	0.31%	37.83%	0.60%	56.23%	0.72%
STGBSTEPSTLL	28.40%	0.57%	17.04%	0.31%	37.83%	0.60%	56.23%	0.72%

Table 6-1 shows a decrease in utilization levels in the project storage, whereas the utilization levels increase in the anonymous storage. This is since items stay longer in the anonymous storage zones whereas they do not enter the project storage zones anymore. Moreover, when items from the lean lift are also picked simultaneously, the utilization in the RB zone decreases further since these items also do not go to the project storage anymore.

When calculating these utilization levels back to physical locations, this means that the EP zone needs 25.68 locations less whereas the RB zone needs 13.4 more locations when ST-GB and ST-EP items are picked simultaneously. However, when also the ST-LL items are picked simultaneously, the RB zone needs 68.31 fewer locations since these items are not entering the project storage anymore. There are no items that could not be stored, for each zone.

6.1.2. Pick and put away time

Secondly, the time to pick and put away items can be compared.

Table 6-2: Comparison of the average and standard deviation of the put-away and pick time between the current situation and when anonymous items are picked simultaneously. The table shows a decrease in the total time needed per day, resulting in less FTE. Though, the time to pick a train increases.

	Total put-away time per day (h)		**Total pick time per day (h)**		**FTE (0.7)**		**Time to pick one train (min)**	
	Avg.	**Stdev.**	**Avg.**	**Stdev.**	**Avg.**	**Stdev.**	**Avg.**	**Stdev.**
Base (A)	16.16	0.35	14.00	0.28	5.38	0.11	35.89	0.27
STGBSTEP (B)	14.46	0.32	15.07	0.32	5.27	0.11	46.82	0.37
STGBSTEP STLL (C)	13.28	0.29	13.02	0.27	4.70	0.10	40.42	0.30
A-B	1.70		-1.07		0.11		-10.93	
A-C	2.87		0.98		0.69		-4.53	

Table 6-2 shows a decrease in the put-away time since the anonymous items do not have to be put away twice, but once. This is also the case for picking. However, when picking the order, the picking time increases since next to the project storage locations, also multiple other SKU locations have to be visited. When only simultaneously picking the ST-GB and ST-EP items, this even leads to an increase in total picking time. However, when the ST-LL items are also simultaneously picked, the total pick time decreases regarding the current scenario since these items do not have to be picked from the project storage anymore. Another interesting point is the time to pick one train. The time to pick one train increases again since next to the project storage locations, also multiple other SKU locations have to be visited when picking the train.

6.1.3. Sensitivity analysis: more volume

This intervention is tested against an increase of volume (1.5x more orders and 2x more orders), also see Chapter 4. The results for the utilization levels, items not stored, put-away, and pick times are displayed in Appendix E.1.

This analysis shows that the gains mentioned before become even bigger when the volume is increased. When the volume is doubled, two FTE less are needed per day, while at the same time approximately 112 locations less in the RB zone are needed and 74 locations less in the EP zone are needed when anonymous items are picked simultaneously. However, the number of items that could not be stored in the EP zone increased when picking anonymous items simultaneously. When the volume is 1.5x more, approximately 1.10 items per day could not be stored in the EP zone. In the current situation, this was only 0.04 items per day. When the volume is 2x more, approximately 24.50 items per day could not be stored in the EP zone. In the current situation, this is 18.07 items per day. The average time to pick a train remains approximately four to five minutes longer compared to the current situation, regardless of the volume. This is since the train sizes do not increase.

6.1.4. Final notes

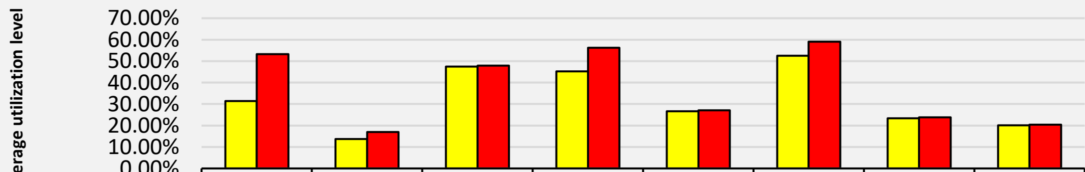
To conclude, when picking anonymous items simultaneously with project items, space in the warehouse can be saved in the RB and EP zones. This is mainly since these items do not enter these project storage zones anymore. However, in the ST-EP zone, more items cannot be stored. The total time needed per day to pick and put away items decreases since anonymous items do not have to be put away or picked twice. The time to pick one train increases since now also the anonymous items need to be picked when picking a train, decreasing responsiveness. It was expected that time could be saved by picking these items simultaneously. However, it was not expected that the savings (especially when volume increases) could be this big. In addition, the saving in locations is a nice additional catch.

6.2. Intervention 2: Storage per SKU

In this intervention, the current situation is compared to when items are stored per SKU (see Chapter 4) instead of per production order. Note, that when storing per SKU, anonymous items are also picked simultaneously with project items, like in the previous intervention. So, the gains and losses incurred in the previous scenario are also present here. Can storage per SKU, therefore, be more interesting than the current situation? Here, all storage zones are considered. Recall, these storage zones (with their abbreviations) are outlined in Section 2.2.

6.2.1. Utilization levels

First, the utilization levels are compared.



	RB	ST-GB	EP	ST-EP	SP floor	ZD floor	SP rack	ZD rack
Base (avg.)	31.34%	13.76%	47.48%	45.28%	26.61%	52.50%	23.37%	20.07%
Per SKU (avg.)	53.34%	17.04%	47.93%	56.23%	27.03%	59.00%	23.84%	20.41%
Base (st. dev.)	0.64%	0.26%	0.69%	0.64%	0.85%	1.03%	0.74%	1.32%
Per SKU (st. dev.)	1.02%	0.31%	0.79%	0.72%	0.86%	1.19%	0.80%	1.23%

Zone

Figure 6.2: Average and standard deviations of utilization levels for the current situation and when storing per SKU. An increase of utilization level in each zone is observed when storing per SKU. Especially in the RB zone, a large increase can be observed.

On average one item could not be stored, which was when storing per SKU in the ZD floor zone. How much space is needed depends on the size of items, SKUs (when storing per SKU), production order sizes (when storing per order), the number of locations per zone, etc. So, it is a bit unclear which factor (or a combination thereof) exactly influences the increase in utilization levels when storing per SKU (also see Appendix E.2). The increase in the ST-GB and ST-EP is because these items stay longer in the anonymous zone, just like in Section 6.1. There is a large increase in the RB zone regarding the current situation. Note that also in the EP zone all gains acquired in the previous section are gone. Lastly, in the ZD zone, an increase in utilization levels can be observed. The items in these zones have got a relatively large number of SKUs together with a small item size relative to their zone. This possibly causes that items that were together are now being stored apart, causing an increase in utilization levels. For example, the items in the SP zone are approximately 0.7 SP large. So, probably these items were already not stored together, hence no large increase was observed.

Calculating these utilization levels back to locations, per zone, the following increases of needed locations can be observed.

Table 6-3: Average number of locations more needed when storing per SKU in contrast to the current scenario, divided per zone.

RB	ST-GB	EP	ST-EP	SP floor	ZD floor	SP rack	ZD rack
879.90	49.24	8.33	154.20	1.73	10.91	2.26	0.25

6.2.2. Pick and put away time

Secondly, the time to pick and put away items can be compared.

Table 6-4: Comparison of the average and standard deviation of the put-away and pick time between the current situation and when storing per SKU. The table shows a decrease in put-away time and a substantial increase in pick time. Eventually, this results in the fact that slightly more FTEs are needed. In addition, the time to pick a train increases.

	Total put-away time per day (h)		Total pick time per day (h)		FTE (0.7)		Time to pick one train (min)	
	Avg.	Stdev.	Avg.	Stdev.	Avg.	Stdev.	Avg.	Stdev.
Base (A)	16.16	0.35	14.00	0.28	5.38	0.11	35.89	0.27
Per SKU (B)	14.53	0.32	17.16	0.37	5.66	0.12	53.36	0.45
A-B	1.63		-3.17		-0.28		-17.47	

When storing per SKU, the gains regarding the previous intervention are also acquired since you do not need to put away anonymous items twice. Hence, the decrease in put-away time. However, a large increase of approximately three hours per day in the pick time is observed. In addition, the time to pick one train is significantly increased, decreasing responsiveness. To look where these losses are incurred, Figure 6.3 is made:

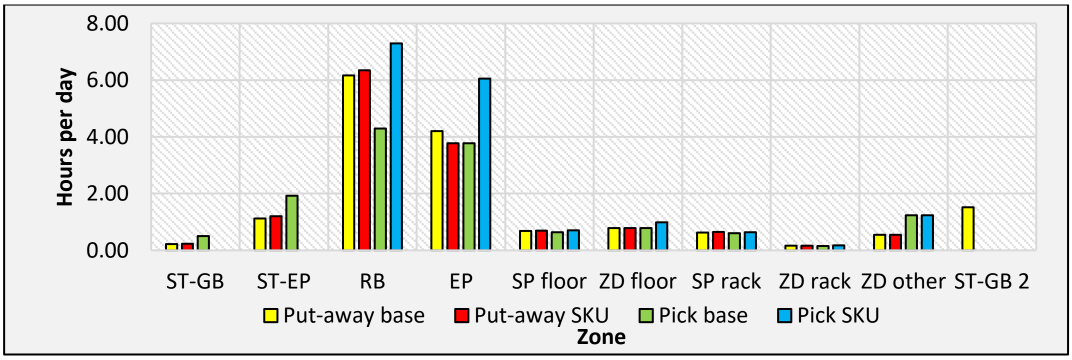


Figure 6.3: Average hours to put away and pick items per zone per day in the current scenario and when storing per SKU. The figure shows a large increase in pick times in the RB and EP zones.

Recall that ST-GB (2) includes the put-away in the project storage after ST-GB items have been picked from the anonymous storage. The main losses when storing per SKU are incurred at picking from the EP and RB zone. This is since you now need to visit multiple item locations instead of one or a few (at least less) order locations. The main quantitative gains when storing per SKU are from the fact that anonymous items do not have to be picked and put away twice.

6.2.3.Sensitivity analysis: more volume

When the volume is increased to 1.5 or 2 times more orders, it turns out that storing per SKU is less robust since it cannot store more items than in the current scenario (see Appendix E.2). Also, the RB zone becomes a new 'bottleneck' zone, where this is not the case in the current scenario. Also, the difference in locations needed between the current scenario and storing per SKU increases when the volume is increased.

Regarding time to put away and pick items, something interesting occurs (see Appendix E.2). When storing per SKU, the time needed to pick all items increases compared to the current scenario. However, the savings in the put-away time also increase. Eventually, the losses in pick time are canceled out by the gains in put-away time since anonymous items do not have to be put away twice (compared to the current scenario). So, the performance regarding time between both scenarios is almost equal when the volume is twice as high. The difference (item-current scenario) between the time to pick a train remains stable.

6.2.4. Sensitivity analysis: more or fewer different SKUs

To look at the robustness of the current scenario vs. storing per SKU, it is tested how both models react when more or fewer different SKUs come into the VMI warehouse. This is done by looking at +- 10%, +- 5%, and +- 3% of SKU types (see Chapters 4 and 5) with a constant volume of 1.5x more orders as in the base case. The results are displayed in Appendix E.2.

The results show that the current scenario barely reacts to changes in fewer or more different SKUs regarding average utilization levels. The only differences are observed in the anonymous storage zones. This is different when storage per SKU is applied. Here, a steady increase of utilization levels and items not stored can be observed when more different SKUs come in. For the RB zone, this change is the largest with an increase of approximately 4.66% when 10% more SKUs arrive.

Regarding time, a similar conclusion can be drawn. The current scenario barely reacts to an increase of SKU types, except for the anonymous storage where pick and put-away times slowly increase. When storing per SKU, put-away times slowly increase but not that much. However, pick times do increase. This increase is mainly observed in the RB and EP zones. In addition, the time to pick a train also slowly increases when storing per SKU, whereas in the current scenario, this remains stable.

At the start of this research, it was seen as a possible scenario that the number of SKU types determines if storing per SKU could outperform the current scenario regarding time and utilization. Unfortunately, this point was not found with this experiment. A decrease or increase of different SKUs outside the chosen ranges is seen as unrealistic.

6.2.5. Final notes

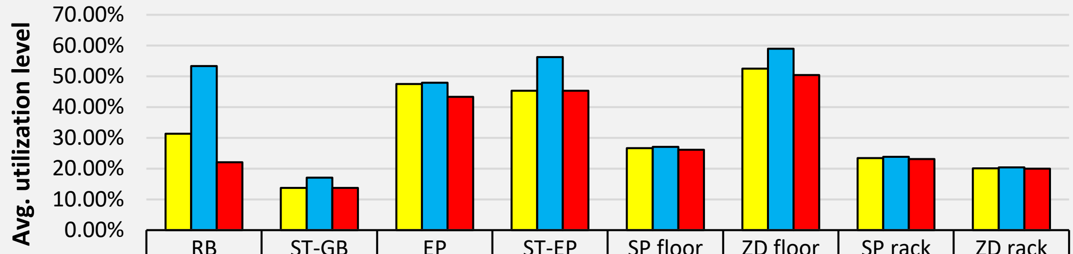
To conclude, when storing per SKU, more locations are needed. Moreover, more pick time is needed to acquire all orders, increasing the time to pick a train, and decreasing responsiveness. This is since items are no longer stored per order. However, since anonymous items do not have to be picked and put away twice, the put-away time per day decreases regarding the current scenario. Lastly, when storing per SKU, the warehouse is less robust when more SKU types arrive, whereas the volume remains the same. It was expected that storage per SKU would not acquire efficiency gains. Unfortunately, the results only underline this. However, multiple qualitative gains can still be acquired when storing per SKU.

6.3. Intervention 3: Storage per train

In this intervention, the current situation is compared to when items are stored per train (see Chapter 4). This is compared to storing per SKU and the current scenario (indicated with “Base” in the figures).

6.3.1. Utilization levels

First, the utilization levels are compared.



	RB	ST-GB	EP	ST-EP	SP floor	ZD floor	SP rack	ZD rack
Base (avg.)	31.34%	13.76%	47.48%	45.28%	26.61%	52.50%	23.37%	20.07%
Per SKU (avg.)	53.34%	17.04%	47.93%	56.23%	27.03%	59.00%	23.84%	20.41%
Per train (avg.)	22.10%	13.76%	43.33%	45.28%	26.08%	50.45%	23.11%	20.01%
Base (st. dev.)	0.64%	0.26%	0.69%	0.64%	0.85%	1.03%	0.74%	1.32%
Per SKU (st. dev.)	1.02%	0.31%	0.79%	0.72%	0.86%	1.19%	0.80%	1.23%
Per train (st. dev.)	0.47%	0.26%	0.65%	0.64%	0.87%	0.99%	0.75%	1.29%

Figure 6.4: Average and standard deviations of utilization levels (storage per train, item, and current situation). Apart from the anonymous storage zones, storage per train needs fewer locations than the other two storage policies.

Note that the results from the base scenario and item scenario are the same as before. Regarding utilization levels, storage per train outperforms both scenarios in each zone. Note that between the current scenario and storage per train, no differences in anonymous zones are observed since these remain the same. This gain is acquired since now more items are stored together in one location: where production orders were first put apart, they are now allowed to be put together. The differences regarding physical locations can be found in Appendix E.3.

6.3.2. Pick and put away time

Next, the time-related measures are analyzed when storing per train.

Table 6-5: Average and standard deviations of time measures (storage per train, item, and current situation). The table indicates a small increase in put-away time. Though, pick time is saved, such that fewer FTEs are needed. Moreover, the time to pick a train decreases.

	Total put-away time per day (h)		Total pick time per day (h)		FTE (0.7)		Time to pick one train (min)	
	Avg.	Stdev.	Avg.	Stdev.	Avg.	Stdev.	Avg.	Stdev.
Base (A)	16.16	0.35	14.00	0.28	5.38	0.11	35.89	0.27
Per SKU (B)	14.53	0.32	17.16	0.37	5.66	0.12	53.36	0.45
Per Train (C)	16.32	0.34	12.62	0.24	5.17	0.10	31.59	0.25
A-C	-0.16		1.38		0.22		4.30	
B-C	-1.79		4.55		0.49		21.77	

It can be observed that the put-away time is slightly larger when storing per train compared to the current scenario. However, the pick time is shorter. This is also reflected in the time to pick one train, increasing responsiveness. The time to pick a train has not been shorter in any scenario. To see where gains and losses are made, Figure 6.5 is created.

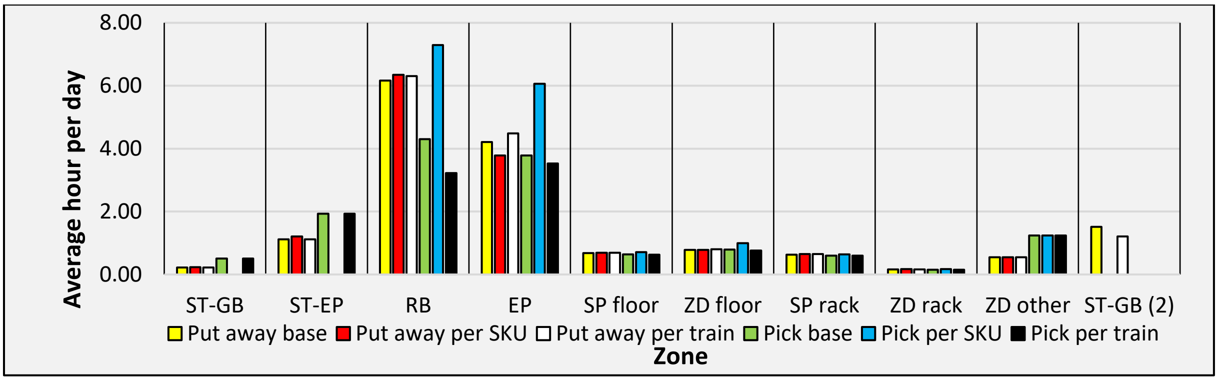


Figure 6.5: Average hours needed for putting away and picking items (storage per train, item, and current situation). The biggest decrease in time can be observed for picking items in the RB zone.

Figure 6.5 shows that the biggest gains are again acquired in the EP and RB zone regarding pick time. These gains are acquired since more items can be stored together. Therefore, an order picker has to walk to fewer locations to pick a train, saving picking time. On the other hand, when putting away items, the employee more often sees a location full, after which he/she has to look for a new one, increasing put-away time. This trade-off is won by the picking side since more time is saved.

6.3.3. Sensitivity analysis: more volume

Again the volume is increased with a factor of 1.5 and 2 to see if the conclusions change. The results are displayed in Appendix E.3. When the volume is increased, the space saved while storing per train becomes even larger in comparison to the current scenario and storing per SKU. Consequently, also fewer items could not be stored in their zones while storing per train. Regarding time, the total time saved while storing per train increases when the volume is increased in comparison to the current scenario and storing per SKU. The savings regarding pick time increase while the losses of putting-away items even decrease compared to the current scenario. This is since the train size does not change if the volume is increased. Compared to storing per SKU, the time loss when putting away items increases when volume increases, just like for the base scenario. This is, again, since anonymous items do not have to be put away and picked twice. The saved time to pick a train also slowly increases when volume increases.

6.3.4. Final notes

Storage per train can save multiple locations in each zone compared to the current situation and storing per SKU. This is since now more items are stored together, that were stored separately in the other scenarios. Moreover, pick time decreases, while time to put away items increases a little. In total, more time can be saved while storing per train. Also, the time to pick a train decreases while storing per train, increasing responsiveness. The time to pick all items decreases since the entire train that you need to pick is stored in one or a few locations, that are close to each other. If the volume increases, the acquired gains when storing per train, increase. The acquired results were not a major surprise: some efficiency gains were expected. The efficiency gains possible make this scenario quite interesting. However, multiple qualitative arguments against this scenario can be given.

6.4. Intervention 4: Procuring more SKUs anonymously

In this intervention, it is investigated what happens in the warehouse when more SKUs are procured anonymously. Therefore, multiple unpainted, project-related SKUs have been converted to anonymous SKUs. This means that 91.7% of the RB items can be converted to anonymous items. For EP items, 68.9% of the items can be converted to anonymous items. Also, see Chapters 4 and 5.

For this, three interventions are used:

- **The current situation:** indicated with "Base".
- **The current situation when anonymous items are picked simultaneously, see 6.1:** indicated with "AnonyIn1".
- **Storage per SKU**: indicated with "per SKU".

Tested against three scenarios: all with the dataset as before, all possible RB items converted to anonymous items (indicated with "RB"), and all possible RB and EP items converted to anonymous items (indicated with "RB-EP"). Hence in total, there are 3x3=9 experiments. Note that these experiments are conducted with a volume of 1.5 times more orders than in the dataset used.

6.4.1. Locations needed

First, it is investigated how many locations are occupied in each zone on average. However, when converting so many SKUs to anonymous, the current anonymous zones are not big enough and a lot of items will not be able to be stored. Therefore, locations of the project storage have been added to the anonymous zone to increase capacity there. This is also how VMI would do it if more SKUs would be procured anonymously. In this way, an indication of the average locations and time needed can be given.

For the number of locations needed per zone, the averages, and standard deviations are displayed in Appendix E.4. In Table 6-6, the average locations needed in the RB, EP, SP, and ZD zones are displayed.

Table 6-6: The average locations needed in the RB, EP, SP, and ZD zones when procuring more SKUs anonymously. In this table, three interventions are compared: the current scenario, when anonymous items are picked simultaneously, and storage per SKU. The table shows an increase in the locations needed when more SKUs are procured anonymously.

Intervention	Scenario	RB (RB+ST-GB)	EP (EP+ST-EP)	SP	ZD
Base		2160.26	2245.60	329.24	151.37
Base	RB	4572.64	2312.57	328.42	150.94
Base	RB-EP	4574.12	3283.38	327.96	150.55
AnonyIn1		2049.65	2177.75	329.24	151.37
AnonyIn1	RB	4652.47	2216.38	328.42	150.94
AnonyIn1	RB-EP	4653.23	3193.17	327.96	150.55
per SKU		3266.98	2417.03	333.11	160.11
per SKU	RB	4647.04	2453.85	331.96	159.72
per SKU	RB-EP	4648.12	3252.61	331.43	159.56

Table 6-6 shows that:

- For each intervention, more locations are needed in the RB and EP zones when more SKUs are procured anonymously. This is as expected since anonymous items come in earlier than project items, hence occupying space for a longer time.
- Little differences occur in the SP and ZD zone per scenario, however, these are due to the way items are converted to anonymous items. Hence, these are negligible. The same can be said for the differences in RB locations between the "RB" and "RB-EP" scenarios.

- When storing per SKU or doing anonymous picks simultaneously, more locations are needed compared to the current scenario in the RB zone. As shown, storing per SKU was disadvantageous for the number of locations needed. Apparently, in the RB zone, the benefits of picking anonymous items simultaneously are outweighed by the extra items that now need to be stored longer 'per SKU'. In the EP zone, this is not the case.

All in all, anonymous procuring currently harms the number of locations needed. This can be diminished by shortening the sojourn times of anonymous items (if possible).

6.4.2. Time needed

The average and standard deviations of the time-related measures are displayed in Appendix E.4. Here, only the averages are displayed in Table 6-7.

Table 6-7: Time-measures when procuring more SKUs anonymously. The table shows a substantial decrease in put-away times for each scenario. Though, this is for some interventions outweighed by an increase in pick times.

Intervention	Scenario	Total put-away time per day (h)	Total pick time per day (h)	FTE (0.7)	Time to pick one train (min)
Base		25.24	21.37	8.32	36.73
Base	**RB**	23.02	30.48	9.55	36.79
Base	**RB-EP**	23.85	34.13	10.35	36.32
AnonyIn1		20.38	19.67	7.15	41.37
AnonyIn1	**RB**	15.68	23.12	6.93	48.65
AnonyIn1	**RB-EP**	15.07	24.29	7.03	51.12
per SKU		22.38	25.95	8.63	54.61
per SKU	**RB**	16.16	25.30	7.40	53.24
per SKU	**RB-EP**	15.66	25.57	7.36	53.81

Table 6-7 shows:

- That when more SKUs are procured anonymously, the time to put away items decreases substantially. This decrease is not that much in the current scenario since anonymous SKUs also need to be put away twice. However, this becomes clear when storing per SKU or when picking anonymous items simultaneously with project items where items are only put away once.
- Pick times increase for the base case since anonymous items are picked twice.
- Pick times increase when storing per order and when anonymous items are picked simultaneously with project items since more items are stored 'per SKU'. As shown, storing per SKU increases pick time.
- Pick times do not increase when storing everything per SKU and more items are procured anonymously.
- The time to pick a train remains constant when more SKUs are procured anonymously and storing per SKU or in the current scenario. When anonymous items are picked simultaneously, the time to pick a train increases.

All in all, it shows that storing per SKU is more robust when more SKUs are procured anonymously. In that case, storage per SKU even outperforms the current scenario. However, picking anonymous items simultaneously with project items still outperforms storage per SKU.

6.4.3. Dock-to-stock time

Another advantage of procuring more SKUs anonymously is a decrease in dock-to-stock time. Since anonymous items come in together as one anonymous line, the entire anonymous line (that contains multiple anonymous items) only needs to be inspected and put away once. Project items need to be put away one by one. The results of the average dock-to-stock time per item are displayed in Table 6-8.

Table 6-8: Average dock-to-stock time when procuring more SKUs anonymously. When more SKUs are procured anonymously, dock-to-stock time decreases.

Intervention	Scenario	Average dock-to-stock time per item (min)
Base/AnonyIn1/Per SKU		≈108
Base/AnonyIn1/Per SKU	RB	≈72
Base/AnonyIn1/Per SKU	RB-EP	≈63.6

The dock-to-stock time per item has been calculated as follows (2):

$$Average\ dock\ to\ stock\ time\ per\ item = \frac{\sum_z DockToStockPerItem_z * NumberofItemsPutAway_z}{TotalItemsPutAway} \qquad (2)$$

Where:

- All units are in minutes.
- $z \in$ {ST-GB, RB, ST-EP, EP, ST-LL, SP, ZD}.
- $DocktostockPeritem_z$: is the average dock to stock time of an item in zone *z*.
- $NumberofItemsPutAway_z$: is the average number of items put away in zone *z.*
- TotalItemsPutAway: is the average number of items put away in the entire warehouse.
- The dock-to-stock time here only included the time to unload, book, inspect, and put away the item. The time the item is waiting, for example, to be put away, is not included.

Table 6-8 shows that:

- The average dock-to-stock time does not differ that much between the interventions. This is since the inspection time (hours) per item is higher than the put-away time (a few minutes).
- The dock-to-stock time decreases substantially when more SKUs are procured anonymously, going from 108 minutes to 63.6 minutes per item on average.
- The average dock-to-stock time in Table 6-8 is shorter than the averages in Section 2.6.1. This is since, in the simulation model, the effect of items coming in together is already considered. This is not the case in Section 2.6.1.

6.4.4. Final notes

When procuring more SKUs anonymously, the number of locations needed increases since the sojourn time of these items is longer. So, this increase should be diminished by shortening sojourn times which is possible when the anonymous items are picked simultaneously with project items. The FTE needed per day can be decreased when procuring more SKUs anonymously if the anonymous items are picked simultaneously with project items. For the current scenario, this gain is not acquired since these items need to be picked and put away twice. The time to pick a train remains constant in the current scenario and storing per SKU. Lastly, dock-to-stock time decreases when more SKUs are procured anonymously since these items come in together. This line that comes in together only needs one inspection and put-away.

6.5. Translating savings to euros

In the previous sections, the savings or costs in FTE and physical locations are posed. In this section, these savings and costs are converted to an estimation in euros. In this way, it can be determined if an additional investment to realize the one or other policy, is worthwhile.

To estimate the savings per euro the following parameters are assumed. The costs per location and items not stored are based upon the € per m^2 per year VMI pays at the public warehouse, which is €*xx.xx*. First, the costs per rack are calculated (3). How big a rack is and how many locations it includes depends on the storage zone. The storage zones *z* considered are $z \in$ {RB, EP, SP floor, SP rack, ZD floor, ZD rack, ST-GB, ST-EP}. Aisles are also included in these surfaces. The average number of locations occupied is determined by the experimental results above. By taking this number per zone and dividing this by the number of locations in a rack per zone, the number of racks needed per zone is acquired (4). This number is rounded up since it is assumed that no partial racks are built when needed. Consequently, the costs for all locations can be calculated by multiplying the costs per rack by the number of racks needed and summing this over the zones (5). The total costs for items not stored are calculated by taking the average number of items not stored (see results above), the size of one location (including aisles), and the average size an item in that location occupies, per zone. By eventually summing over all zones, the total costs per item not stored can be computed (6).

$$Cost\ per\ rack_z = m^2\ per\ rack_z * cost\ per\ m^2 \tag{3}$$

$$Racks\ per\ zone_z = \left\lceil \frac{avg.number\ of\ locations\ occupied_z}{number\ of\ locations\ per\ rack_z} \right\rceil \tag{4}$$

$$Location\ costs = \sum_z Cost\ per\ rack_z * Racks\ per\ zone_z \tag{5}$$

$$\begin{aligned} &Costs\ for\ items\ not\ stored \\ &= \sum_z Avg.number\ of\ items\ not\ stored\ per\ year_z * Location\ size\ in\ m^2{}_z \\ &* Average\ size\ of\ an\ item\ in\ location_z \end{aligned} \tag{6}$$

The values of the parameters used are displayed in Appendix E.5. Note that all these values are per year. One FTE costs €*xx,xxx* per year, based upon the hourly wage of a temporary worker and the number of working days in a year. So, now a comparison can be made.

Here, the current scenario, storage per SKU, the current scenario but when anonymous items are picked simultaneously, and storage per train are compared, against the three different volumes (1x, 1.5x, 2x). The yearly costs for each scenario are displayed in Appendix E.5. Then, the following savings in € are acquired compared to the current scenario and storage per SKU.

Table 6-9: Savings per year (€) compared to the current scenario and storage per SKU.

Volume	Intervention	Yearly savings regarding the current scenario	Yearly savings regarding storing per SKU
1x	Base	Numbers censored for public version	
1x	SKU		
1x	Anonyin1x		
1x	Per train		
1.5x	Base		
1.5x	SKU		
1.5x	Anonyin1x		
1.5x	Per train		
2x	Base		
2x	SKU		
2x	Anonyin1x		
2x	Per train		

When there are large savings (or costs), this is mainly acquired since less (or more) FTEs are needed to do all the work. Table 6-9 shows that storage per SKU is more costly every year. In addition, it also shows that substantial gains can be acquired when doing anonymous pick simultaneously.

Note, these savings are rough estimates of costs made only regarding the time to pick, put away, and store items. For example, when storing per train, items have to be sorted which also costs time. In addition, the number of locations per rack can also differ. For example, when more half pallet locations or full pallet locations are used in the EP zone. Nevertheless, the estimates can still acquire proper insights into invest-or-not decisions.

6.6. Summary of all quantitative and qualitative results

In this section, all results found in Chapters 4 and 6 are summarized in one table, to give one last overview.

Table 6-10: Summary of all quantitative and qualitative (dis)advantages for each intervention tested.

Current scenario	
Advantages	**Disadvantages**
Quantitative - You only have to walk to one (or a few) locations when picking an order, decreasing picking time. **Qualitative** - Robust to an increase of SKUs. - Status quo. - Orders are already sorted when they need to be loaded on the train. - It is easier to oversee when a project is complete or not. - It is difficult to ‘steal’ items from other projects.	**Quantitative** - Extra put-away and pick times due to double put-aways and picks for anonymous items. **Qualitative** - Two storage policies in one warehouse, increasing complexity. - Difficult to implement in a new ERP system. - Not robust when more SKUs are procured anonymously.

Doing anonymous pick simultaneously	
Advantages	**Disadvantages**
Quantitative - Less space is needed. - Decrease in put-away and pick times since anonymous picks do not have to be done twice. - Gains become even larger when the volume is increased. **Qualitative** - Possible decrease in sojourn times of anonymous items. - Relatively small change to the status quo.	**Quantitative** - More items cannot be stored in the ST-EP zone when increasing volume. - More time is needed to pick one train, decreasing responsiveness. **Qualitative** - More pressure on the date of delivery. - You are too late if anonymous stock is not sufficient. - Not robust when more SKUs are procured anonymously.
Storage per SKU	
Advantages	**Disadvantages**
Quantitative - Less time is needed to put away items. - No double put-aways and picks for anonymous items. Hence, losses (compared to the current scenario) become less when the volume is increased. **Qualitative** - One storage policy in the entire warehouse. - Standard in ERP systems. - Ideas from literature are applicable. - Most used in other warehouses. - Robust when more SKUs are procured anonymously. - Possible decrease in sojourn times of anonymous items. - No separate storage zones are needed for project and anonymous items.	**Quantitative** - More space is needed to store the same items. This problem increases when volume increases. - Storage capacity (i.e. items could not be stored in their destined zones) is insufficient relative to the other scenarios. - More time is needed to pick items. - More time is needed to pick a train, decreasing responsiveness. **Qualitative** - Sensitive for an increase in SKUs. - Random/class-based storage policy is needed due to the number of SKUs. - More pressure on the date of delivery. - Items need to be sorted per order when picking. - It is difficult to see if a project is complete or not. - It is easier to 'steal' items from other projects
Storage per train	
Advantages	**Disadvantages**
Quantitative - Less space is needed. - Less time is needed to pick items. - Less time is needed to pick a train. - When volume increases, the gains become larger (compared to the current scenario). **Qualitative** - More gains can be acquired when combined with doing anonymous picks simultaneously.	**Quantitative** - Extra put-away and pick times due to double put-away and picks for anonymous items. - Slight increase in put-away time for items. **Qualitative** - Sorting orders after picking. - Rescheduling of projects gives more problems. - Train needs to be generated when items arrive, instead of on the day of delivery, decreasing flexibility. - Complexity of the current situation with two storage policies keeps existing. - Even harder to implement in a new ERP system.

Buying more SKUs anonymously	
Advantages	**Disadvantages**
Quantitative - Decrease of put-away times. - Decrease of dock-to-stock times. **Qualitative** - Gains for the procuring department possible. - Suitable when storing per SKU.	**Quantitative** - More space is needed due to the longer sojourn times of anonymous items. It can, therefore, be investigated if sojourn times can be shortened. - Double put-aways and picks in the current scenario. **Qualitative** - Not suitable for the current situation. - Moderately suitable for the current situation when anonymous picks are done simultaneously. - Not possible for all articles. - Reconsidering the sizes of project and anonymous zones. - Accounting reasons make it less attractive.

6.7. A road map to implementing a new storage policy

With the qualitative and quantitative results summarized, it is time to make a road map for VMI. This road map can be used for the implementation of the one or the other storage policy. In anticipation of the recommendations (see Section 7.2), these road maps are only made for storing per SKU or remaining in the current situation. Regarding efficiency, the current situation (when storing per order) with picking anonymous items simultaneously and storage per train seem like the most interesting options. However, multiple qualitative arguments like implementation in the ERP system and flexibility make it difficult to implement storage per train. The road map can be defined into six overlapping phases (see Figure 6.6). Each phase covers a certain period. What these phases include is briefly explained here.

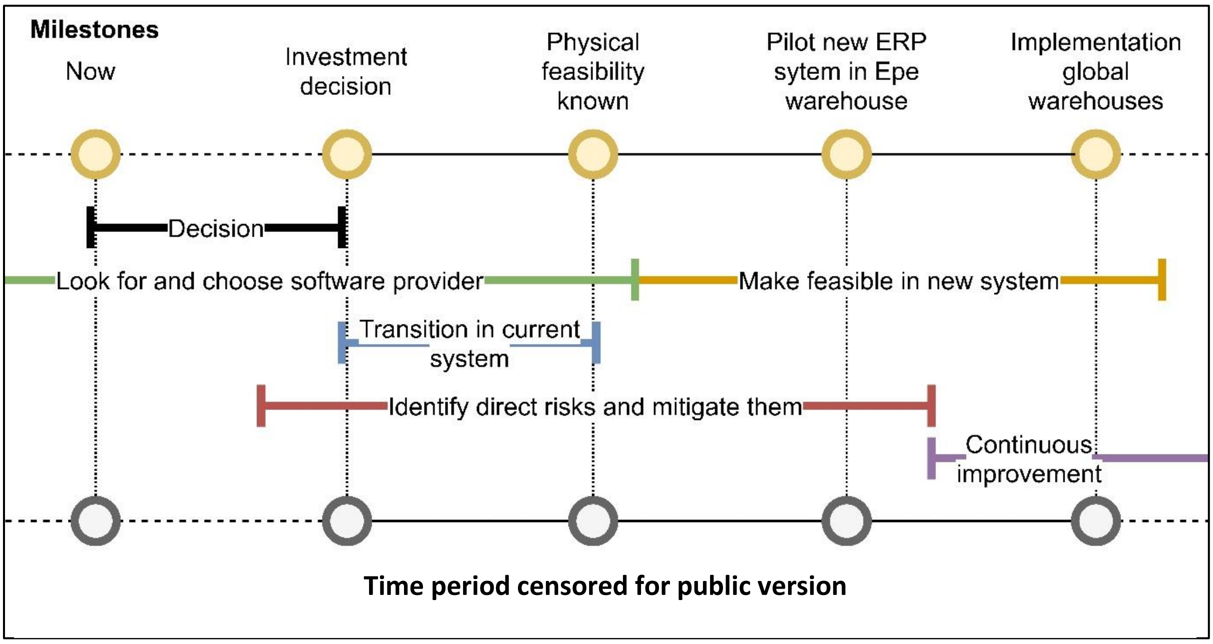


Figure 6.6: A road map to implementing storage per order or SKU. The road map consists of six overlapping phases in time.

Recall, in the future, a new ERP system will be introduced at VMI. Hence, everything (even the current storage policy) will need to be reprogrammed. Programming the current way of storing is more complex and more difficult than storing everything per SKU. Hence, it is also more costly to reprogram this.

6.7.1.The decision and forming a project team

Time frame: between now and the investment decision.

Key question: *are we willing to invest in reprogramming the current storage policy in the new ERP system?*

In this phase, the board of VMI, vice president logistics, and the logistic management team should decide if VMI wants to invest in reprogramming the current storage policy in a new ERP system. Things that should be considered are: looking at the extra costs of storing per SKU, do we think it is worth engaging with a software provider that is willing to program storing per production order? And what will the cost of this be? In this decision, the strategic directions of VMI should be considered.

Tasklist:

- Remain the current system as it is for just now.
- Exploring options for software providers that are capable of programming the storage policies (which is already started).
- Form a project team.

Result:

- An initial decision about which storage policy to implement.
- A project team.

To guide this project, a project team should be formed. This project team should consist of a multi-disciplinary team. An indication of what this team should look like is given in Figure 6.7.

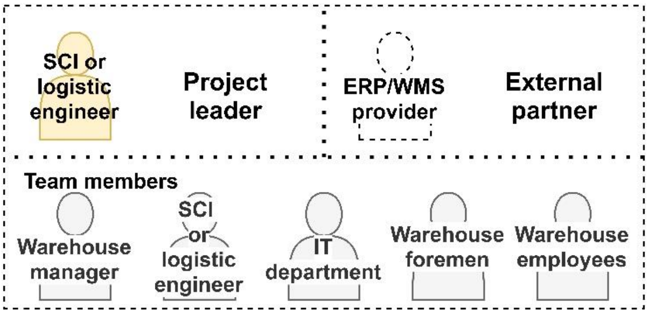


Figure 6.7: A suggestion of what the multi-disciplinary team to implement the storage policy should look like. The team consists of multiple FTEs with in total seven roles.

A brief motivation is given for each member of the team. These members can represent one or multiple employees:

- **SCI or logistic engineer as project leader:** who is involved with the project daily. He/she needs to guide and monitor all project processes of each team member. Moreover, he/she can also help in the execution of the project.
- **ERP/WMS provider:** the software provider for the new ERP or WMS that needs to help to implement the chosen storage policy at VMI. The provider's part is about implementation in the digital environment.

- **Warehouse manager:** needs to be closely involved, especially when decisions have to be taken. He will not be executing the actual project.
- **SCI or logistic engineer:** especially involved in finding direct solutions for potential risks, but also with efficiently and effectively implementing the storage policy in the warehouse itself.
- **IT department:** should work closely together with the external partner to make sure that the storage policy is properly implemented in the digital environment.
- **Warehouse foremen:** should think along about the practical implications of the choices made. Moreover, they can help in the realization of the storage policy in the physical warehouse itself.
- **Warehouse employees:** can help to realize the storage policy in the physical warehouse, together with providing feedback during their daily activities, which is useful for the SCI employee/logistic engineer.

6.7.2. Look for and choose a software provider

Time frame: This phase is currently already started. It should continue until the feasibility of the chosen storage policy is known.

Key question: *which software provider can provide the way of storing per SKU or storing per order?*

In this phase, software providers should be explored. Who are capable of creating the chosen storage policy in the digital environment? What are the costs of this? This should already be started during the decision phase such that a good estimation of the costs of programming can be made. This phase continues until it is known if the chosen storage policy can physically be implemented at VMI. At that time, a final decision for the software provider can be made. For example, one provider might be better in implementing storage per order, whereas the other might be better when storing per SKU. Therefore, the provider should only be decided when VMI knows which storage policy to implement.

Tasklist:

- Explore potential suppliers and create a supplier list
- Select the supplier based on multiple criteria, such as compatibility with the systems in place, costs, quality, etc. Wat the exact decision criteria are, should also be defined here.

Result: a strategic software partner that is capable of implementing the chosen storage policy at VMI in Epe and globally.

6.7.3. Transition in the current system

Timeframe: after the decision for the storage policy has been made until it is known if the chosen storage policy is feasible.

Key question: *is our physical process capable of storing items in the preferred way?*

In this phase, the feasibility of the chosen storage policy should be investigated by implementing this in the current warehouse. Moreover, this is also done such that when the new ERP system is introduced, the change is less big, hopefully providing a smoother transfer. In this case, the warehouse is already used to a potential new way of working. Tasks per storage policy are outlined below.

Storage per SKU

When storing per SKU, it should be investigated if our process is in reality also capable of storing everything by SKU.

Tasklist:

- Train personnel on how to pick and store items per SKU, just like it is currently done in the anonymous storage. This training already exists. The way of working when storing everything per SKU will be almost similar. Hence, after training, the transition for personnel will be less big when the new storage policy is implemented.
- Start gradually rebuilding storage per SKU to check if it is feasible. For this, I would start with the RB zone since it is the smallest regarding the size of items, height, and surface. So, this zone should already give a good indication of the way of working and if it is doable. Moreover, the most volume goes through this zone. Thereafter, I would continue with the EP, SP, and ZD zones respectively. Note, this also includes changing the current scan application, which is probably the most difficult part.

Storage per order

When storing per order, the current situation does not have to be changed. However, as shown, by picking anonymous items simultaneously, significant efficiency gains can be acquired. It should be checked if this is possible in the current situation.

Tasklist:

- Implement and test picking anonymous items simultaneously. In this phase, it should be checked if this is possible: are stock levels reliable enough? Are we responsive enough?

Result:

At the end of this phase, it should be known if the chosen storage policy is feasible in the physical warehouse. Are we capable of storing per SKU? Is it possible to pick anonymous items simultaneously when storing per order?

6.7.4. Identify risks and find quick solutions to mitigate risks

Time frame: during the investment decision until after the ERP system is implemented in Epe.

Key question: w*hat are immediate risks that can harm the flow of goods and how can we solve them?*

This phase is about identifying immediate risks that can occur when storing via the one or the other policy. These risks should be identified in an early stage, and quick solutions should be found. Here it is not necessarily about being more efficient, but more about making sure that the general processes of VMI are not disturbed while VMI is transitioning to a new way of working. This process continues when the storage policy is implemented in the new ERP system. During this period, multiple unexpected risks that only became visible after actually working with the new systems can also occur, which should also be solved. Some risks that are already lurking are outlined below per storage policy.

Storage per SKU

- Storage space in the RB, EP, and ZD zones when volume increases.
    - Solution examples: the public warehouse, shifting more volume to the Haaksbergen warehouse, and allocating RB items to the lean lift.
- Stealing of items from other projects: items destined for other projects are picked for a different project.
    - Solution examples: shelving, labeling.

- Increase of SKUs (while the volume remains the same): which causes that more locations are needed.
    - Solution examples: see “storage space” and creating smaller locations within the zones.
- More personnel needed: when storing per SKU, more personnel is needed to do all the work. Currently, getting personnel is difficult. So, this becomes problematic.
    - Solution examples: involve more employment agencies or acquire rewards for getting more personnel.
- Is it possible to work with this much FTE in the zones or are aisles getting congested?
    - Solution examples: make aisles broader (however, more space will be needed) or parallel picking in aisles.

Storage per order

- Storage space in the EP and ZD zones when volume increases.
    - Solution examples: see above.
- Is it likely that more items are procured anonymously?
    - Solution examples: doing anonymous picks simultaneously and increasing anonymous storage zones.
- Is it possible to work with this much FTE in the zones or are aisles getting congested?
    - Solution examples: see above.
- Are anonymous stock levels reliable? When picking anonymous items simultaneously, are our stock levels reliable enough?
    - Solution example: safety stocks and checking feasibility in an early stage.

Result:

- Identification of immediate risks to the operational processes.
- Solutions to these risks.

6.7.5. Continuous improvement

Time frame: after the pilot of the new ERP system in the Epe warehouse.

Key question: *how can the chosen storage policy become more effective and efficient?*

This phase is about improving the chosen storage policy. Here multiple improvements to the storage policies should be thought of and implemented on a tactical and operational level. Examples from literature are family storage, order batching possibilities, picking strategies, etc. which can be investigated. Also see the article of Rouwenhorst et al. (1999). Moreover, the following improvements can already be investigated regarding the two storage policies:

Table 6-11: Potential improvements when storing per SKU or remaining the current scenario (storage per order).

Storage per SKU	Current scenario (storage per order)
- Shorten sojourn time of anonymous items. - Procure more SKUs anonymously (however, this is a bit of a trade-off due to accounting reasons). - Apply ideas from literature like family grouping or class-based storage. - Try to standardize as much as possible, decreasing the number of SKUs. - Apply order batching.	- Do anonymous picks simultaneously. Then, also shorten the sojourn times of anonymous items and procure more SKUs anonymously. - If possible, increase order sizes. As shown when storing per train, more items can be put away together. - Use order batching in the anonymous storage zones.

Moreover, perhaps, during implementation in both the current and new ERP systems, some quick solutions have been posed to mitigate potential risks. These can be solved more efficiently now.

Phase 6: Make feasible in new ERP system

Time frame: after the feasibility is known and until after everything is implemented in the ERP system (globally).

Key question: *how should the new storage policy be implemented in the new ERP system?*

This phase is about implementing the chosen storage policy in the ERP system. With the chosen software provider, the chosen storage policy should be implemented. This is a process of continuously planning, doing, checking, and acting (PDCA). What should not be forgotten in this phase, is that it should be considered which KPIs VMI wants to include in the ERP system (as mentioned in Chapter 4). By identifying this in an early stage, this can be implemented during programming and not afterward. I would start the implementation at the Epe warehouse. This should continue until everything runs smoothly in Epe. When this is the case, the implementation globally can start, which again poses new problems since these warehouses also have their unique characteristics. After implementation, aftercare will still be needed for a while.

Result: an implemented storage policy in the new ERP system.

6.8. Storage policies and automatization

Taking a bit of a sidestep, this section briefly touches upon automatization options in logistics and warehouses. How can these influence the warehouse processes covered in this chapter?

- **Autonomous put-away and pick robots:** are robots that can put away and pick items without any human intervention. Assuming that a fixed number of robots would be procured, regardless of the storage policy (however, this could be dependent on the expected workload), the time to put away and pick items does not matter that much anymore in terms of cost since no employees are needed anymore. So, ignoring the results regarding time, what would that mean for the storage options considered? In that case, storage per order or per train would still perform better regarding efficiency since the space utilization of storing per order or train is still better. Though, this space is relatively cheaper than FTEs, so, would it then still be worthwhile to invest in reprogramming the current storage policy?
- **Horizontal carousels:** another interesting idea (from dr. P.C. Schuur) is the implementation of horizontal carousels. By allocating these horizontal carousels as such, such that the storage of production orders can be done per date, production orders can move forward as time

progresses, decreasing picking times for the outbound department. It can be questioned if this saving in time is worth the investment in these expensive systems. In addition, usually, these systems are not that high. So it can be questioned if all items can be stored. Nevertheless, the use of such a system with this logic would also require storage per order. Storage per SKU becomes less attractive.

- **Drones:** the use of drones can significantly help to pick smaller items in the EP and RB zones. By using drones, storing items higher does not matter that much anymore because the vertical speed is much faster in comparison to using a pallet truck. Moreover, items in the RB zone can also be stacked much higher, aisles can be narrowed, and congestion is less of a problem. So, by using drones, both the space constraints are less problematic, and the time to put away and pick items decreases. The differences between the scenarios will therefore probably be smaller and it can again be questioned if it is worthwhile to reprogram the current way of storing items, and hence, storing per SKU becomes more interesting.

There are multiple other interesting automatization options like a-frames, AS/RS systems, conveyor belts, etc. but due to the time frame of this research, not all of these are covered.

6.9. Summary: key points from Chapter 6

At the end of each chapter, the key points of that chapter are summarized.

- This chapter covered all results from the interventions tested in the simulation model: doing anonymous picks simultaneously, storing per SKU, storing per train, and procuring more items anonymously. The first three are also tested against an increase of volume, whereas storing per SKU is also tested against an increase of SKUs.
- All quantitative and qualitative results from the simulation model are summarized in one large table per intervention, displayed in Section 6.6.
- To implement storage per order or per SKU, a road map has been made consisting of six overlapping phases: make a decision and form a project team, look for a software provider, make the transition in the current system, identify risks and mitigate them, make feasible in the new ERP system, and continuous improvement. In each phase, a central question should be answered and multiple tasks should be performed.
- To make a small sidestep, a short discussion about the impact of automatization has been added.

7. Conclusions and Recommendations

This section poses the conclusions that can be drawn from all results mentioned above. Moreover, recommendations are given to the board of VMI, after which the limitations of this thesis and guidelines for further research are outlined. Lastly, the contribution to both practice and theory is displayed.

7.1. Conclusions

At the start of this research, VMI wanted to know if their way of processing materials based on the current storage policy is still adequate. There are four key reasons why VMI wanted to know this: developments over the past twelve years, the ERP system, doubts about the adequacy of the current system, and uncertainty about the future. An alternative storage and picking policy should be as effective and efficient as possible, but it should also be robust for changes in the future. This eventually led to the following main research question: *What is an **efficient and effective storage and picking policy** for the VMI warehouse that can cope with the **long-term changing environment?*** To answer this question, multiple sub-questions were formulated. Per sub-question, the key findings are presented here.

1. *What are the characteristics of the current warehousing process?*

The VMI warehouse has to store and receive items, that have to be delivered to production, customers, or other warehouses. This delivery is done via production, sales, and warehouse orders. The warehouse currently has five storage zones based on the size of items. Within these zones, two storage policies are applied: 'project' and 'anonymous' storage. In the project storage, items are stored per order. In the anonymous storage, items are stored per SKU. The project storage zones are the red box (RB), euro pallet (EP), steel pallet (SP), and self-carrying (ZD) zones. The anonymous storage zones are the standard grey bin (ST-GB), standard euro pallet (ST-EP), and the standard lean lift (ST-LL) zones. The ST-GB zone is part of the red box zone, whereas the ST-EP zone is part of the EP zone. Currently, anonymous items are picked days in advance if they are needed for a production order soon. In that case, they are picked, and put away in the project storage, and stored per order again. To deliver the items to production, a tugger train system is used.

2. *What are alternative storage policies for the VMI warehouse?*

Based on the literature, a storage policy tries to find a solution to the storage location assignment problem (SLAP), which is the problem "to assign incoming products to storage locations in storage departments/zones in order to reduce material handling cost and improve space utilization" (Gu et al., 2007). The SLAP is NP-hard. In literature, many storage policies are described, which can be allocated to three groups: shared, dedicated, and random storage strategies.

3. *How should a proper simulation study be conducted?*

Based on literature, a simulation model imitates the real-world system, via a set of assumptions about the system it tries to describe, expressed as mathematical and logical relations between objects within the system (Winston, 2004). Before and during the programming of the model, the model should be defined on paper and communicated with relevant stakeholders. During model construction, the model should be constantly verified and validated. To acquire proper simulation output, the initialization bias should be removed, and the run length and number of replications should be determined using formal procedures. Lastly, statistical procedures should be used to analyze simulation output.

4. What are interesting alternatives and scenarios to test in the simulation model?

After identifying the important stakeholders for this research and KPIs in the VMI warehouse, solutions were generated for the SLAP. By brainstorming, interviewing, and sending a questionnaire to twelve important stakeholders, solutions were generated. In this questionnaire, respondents could give their opinion on already existing ideas and provide new ideas. This resulted in a long list with alternative storage policies, improvements for the current scenario, and scenarios against which these should be tested.

5. What are the scenarios and interventions that should be tested in the simulation model?

With the key stakeholders, all alternatives have been scored and weighed on four criteria: simulation effort, relevance for the research question, potential efficiency gains, and support from the questionnaire. Eventually, the following alternatives were tested in the simulation model:

- The current situation (as a benchmark)
- Doing anonymous picks simultaneously with project picks (in contrast to days in advance)
- Storage per SKU
- Storage per train
- Procuring more SKUs anonymously

These alternatives were tested against a scenario in which the volume increases. Moreover, storage per SKU and the current situation were also tested against a scenario in which more SKUs arrive.

6. What does the simulation model of the VMI Holland warehouse look like?

To test these scenarios and interventions, a simulation model has been made that includes all key warehouse processes of the VMI warehouse. First, the model was written down on paper and communicated with the stakeholders, after which it could be implemented in a program. The chosen interventions and scenarios were judged on multiple time- and productivity-related metrics. To be able to construct the model, multiple assumptions and simplifications have been made. The model has been verified using several techniques of Law (2015). The model has been validated by looking at the arrival of parts, utilization levels, and time measures. It was decided to use a warm-up period of 100 days, a run length of 700 days, and five replications for each experiment.

7. What are the results from the simulation model?

From the simulation model, multiple quantitative results have been acquired regarding each intervention.

1. Doing anonymous picks simultaneously

When anonymous items are picked simultaneously with project items (in contrast to days in advance) one pick and put-away step can be saved. As a nice catch, on average 68.31 locations in the RB zone (≈1.24%) and 25.68 locations in the EP zone (≈0.78%) can be saved. Moreover, based on the saved pick and put-away time, approximately 0.7 FTE per day can be saved. However, the time to pick one train increases. When volume increases, these savings become even larger.

2. Storage per SKU

When storing per SKU, more locations are needed compared to the current situation. On average, approximately 1107 more locations (≈11.19%) are needed. This number increases when the volume of items arriving increases. Since in this intervention, items do also not have to be picked and put away twice, the total put-away time is shorter. However, the time to pick all items increases since they are not put away per order. This causes that, on average, 0.28 FTE per day more are needed. Also, the time to pick one train increases. However, when volume increases, the FTEs needed when storing per SKU or in the current scenario are almost equal. Lastly, if the number of SKUs that arrive increases, more locations are needed, and pick times increase when storing per SKU. The current scenario is robust to this change in SKUs and barely shows any differences in results.

3. Storage per train

When storing per train, approximately 454 locations less (≈4.59%) are needed compared to the current situation. Put-away times slightly increase. However, the time to pick all items decreases, on average saving 0.22 FTE per day. Moreover, the time to pick one train also decreases. When volume increases, these savings become larger.

4. Buying more SKUs anonymously

For interventions 1 (doing anonymous picks simultaneously), 2 (storage per SKU), and the current scenario, it has been tested what the effect of procuring more SKUs anonymously is. When more SKUs are bought anonymously, more locations are needed for each intervention since the sojourn time of these items is longer. For the current scenario, more FTEs are needed. For interventions 1 and 2, fewer FTEs are needed if more SKUs are procured anonymously. This is since procuring more items anonymously decreases total put-away time. However, in the current scenario, these items are picked and put away twice, so, there, no gain is acquired. Lastly, by procuring more SKUs anonymously, the average dock-to-stock time can substantially be decreased.

Next to these quantitative arguments, multiple qualitative arguments can be formulated for or against each intervention. Think about the ease of implementation in the ERP system, complexity of having more than one storage policy, flexibility, or certainty about the availability of items. A full overview of all qualitative and quantitative arguments is displayed in Section 6.6.

So, to answer the main question: *What is an efficient and effective storage and picking policy for the VMI warehouse that can cope with the long-term changing environment?* It is as usual: it depends.

Regarding the quantitative arguments, storage per train or doing anonymous picks simultaneously (or a combination thereof) seems like the best alternative regarding efficiency. Moreover, both are even more efficient when the volume is increased and are likely also robust to an increase of SKUs since they are similar to the current scenario.

Looking at qualitative arguments, storage per train seems like a difficult policy to implement in an ERP. Moreover, it results in a large decrease in flexibility. Hence, this alternative does not seem to be that interesting. So, currently, the best alternative regarding efficiency seems to be the current scenario while doing the anonymous picks simultaneously with the project picks.

However, in the future, a new ERP system will be introduced at VMI. Hence, everything (even the current storage policy) will need to be reprogrammed. This is relatively expensive. Therefore, the cost and savings mentioned above have been estimated to euros per year, by assuming a price for m^2 and FTE per year. Based on this estimation, storing items with the current storage policy saves approximately €*xx,xxx* per year (assuming a volume of 1.5x more orders than in 2020) compared to storing per SKU. If the anonymous picks are done simultaneously this amount even becomes approximately €*xx,xxx* per year. In a new ERP system, storage per SKU is the standard. Hence, VMI should consider if it is worthwhile to reprogram the current storage policy in this new ERP system. This reprogramming requires an investment in IT. Hence, if this investment is lower than the net present value of €*xx,xxx* per year over the lifetime of the ERP system, VMI should invest in this reprogramming regarding costs. Vice versa, if this investment is higher than the net present value of €*xx,xxx* per year over the lifetime of the ERP system, it is not worthwhile. In that case, storage per SKU remains. Next to the costs involved, some other arguments can be given for or against a certain storage policy. Storage per SKU is not that efficient nor robust against a change in volume or an increase of SKUs. However, it is robust when more SKUs are anonymously procured. Furthermore, storage per SKU has multiple qualitative advantages: it reduces complexity since one storage policy is used, most ideas from literature are applicable, anonymous items do not have to be picked in advance, and no separate (project/anonymous) storage zones need to be maintained.

To implement either storage per order (with doing anonymous picks simultaneously) or storage per SKU, a road map has been made consisting of six partially overlapping phases. These phases should be executed from now until after December 2023. This road map is summarized in Table 7-1.

Table 7-1: A summary of the road map created to implement the chosen storage strategy (per SKU or the current situation). The road map consists of six phases, in which a key question is answered by performing several tasks.

Phase	**Key question**	**Result**
Decision and forming a project team	*Are we willing to invest in reprogramming the current storage policy in the new ERP system?*	A decision on which storage policy to implement and a project team.
Look for and choose a software provider	*Which software provider can provide the way of storing per SKU or storing per order?*	A strategic software partner that can implement the storage policy in Epe and globally.
Make transition in the current system	*Is our physical process capable of storing items in the preferred way?*	A view on if the new storage policy is feasible in the physical warehouse.
Identify risks and mitigate them	*What are immediate risks that can harm the flow of goods and how can we solve them?*	List of risks and how to mitigate them.
Continuous improvement	*How can the chosen storage policy become more effective and efficient?*	n.a.
Make feasible in the new system	*How should the new storage policy be implemented in the new ERP system?*	Implemented storage policy in the new ERP system.

7.2. Recommendations

Combining all qualitative and quantitative arguments and comparing both road maps, my recommendation would be to reprogram the current way of working (storage per order) in the new ERP system. However, I would in that case, also make sure that anonymous items are picked simultaneously with the project items. A few arguments why:

- It is more efficient regarding the time per day and average space needed compared to storing per SKU. I think the higher investment costs into the ERP system are recovered by the efficiency gains made when storing per order. Storage per train is even more efficient (while possibly doing anonymous picks simultaneously), but I think that the losses in flexibility and extra programming work make this scenario too difficult to implement right now.
- VMI is expecting … [*information censored for public version].*
- The strategic direction in which VMI is heading, … [*information censored for public version].*
- Programming in the ERP system will be more problematic when storing per order. Nevertheless, the implementation plan for storing per order (also when doing anonymous picks simultaneously) seems easier in the physical warehouse. For example, when storing per SKU, a completely new way of working has to be introduced, also in the current ERP system. It

can be questioned if this is worthwhile since this system will stop functioning soon. However, if this is not done, the change might be too big to handle.
- At the moment … [*information censored for public version].*
- While storing per order, especially when doing anonymous picks simultaneously, flexibility is maintained since items can be stored anonymously per SKU and per order in the project storage. In this way, VMI can shift volume back and forth between warehouses. This is more difficult when storing per SKU that only provides one way of storing.
- More volume is shifted … [*information censored for public version].*
- The implemented storage policy will perhaps also be used in the Yantai and Leszno warehouses. In that case, the efficiency gains of storage per order are also acquired there and, hence, are bigger. In addition, when storage per order has been programmed for the Epe warehouse, it is believed that this can more easily be implemented at those sites too. So, both the efficiency gains become larger, and the costs of programming become relatively lower when looking at it from a global perspective.

Possible improvements of storing per order are displayed in Section 6.7. The road map to introduce this scenario is also displayed in that section. I would recommend using this road map when implementing storing per production order into the new ERP system. If storage per order is not desired by VMI, I would recommend storing per SKU. For both options, storage per SKU and per order, multiple advantages and disadvantages can be formulated.

Additional recommendations

Next to the recommendation on which storage policy to use, some additional recommendations not directly related to the research question can be given.

- Generate more metrics from the ERP system based on time, productivity, costs, and quality to create a better overview of current warehouse performance.
- Time measurements from the scan application are not as reliable as intended. It might be worthwhile to explain when exactly items should be scanned to acquire proper timestamps.
- After the decision for the storage policy, further research on route optimization and order batching can be done to decrease walking distances.
- Start formal procedures to when and how items can be removed from the warehouse if they are present for too long. Currently, a lot of items that barely move occupy quite some space.
- If possible, try to schedule picks of sales and warehouse orders on fixed days. In that case, the capacity needed per day is more predictable. However, this will increase the lead time for these orders. It can be questioned if that is desired by the sales and purchasing departments.
- Give order pickers information about the locations in which an order is located and not only about the last active location. In this way, order pickers can look if the item they want to store fits in the already occupied locations instead of always looking for a new one.
- Currently, the train leads the picking process. The train macro is designed for efficiently using the train. However, it turns out that the train is not that much of a bottleneck. Therefore, this train macro could perhaps be rebuilt with the perspective of efficiently picking all orders instead of efficiently using the train itself.

7.3. Limitations and further research

During this research, some assumptions had to be made. Moreover, some things could not be done to make sure this research stayed within the specified time frame of this research. Based on this, a few limitations can be mentioned:

- The way anonymous items are modeled in the simulation model is simplified. The use of order quantities, lead times, etc. can lead to some different results. After an initial storage policy has been chosen, it can be investigated if this storage policy is still performing as expected when this part is modeled in detail.
- In this research, a dataset of 2020 is used. 2020 was not the best of years for VMI. This has been considered by increasing the volume of items for each intervention. However, the mix of items might also be quite different if another period had been taken. Therefore, the model could again be tested with data from a completely different period.
- This research only includes the warehouse in Epe. If the new ERP system (with corresponding storage policy) is also used at other sites, for example, in Leszno or Yantai, it should be checked if the storage policy is also suitable for those sites.
- In this research, item sizes have been assumed. These item sizes are believed to be quite accurate. However, these can perhaps be validated more thoroughly.
- In this research, the time to pick and put away items has been assumed. Moreover, these are deterministic. It is believed that these times are quite accurate. However, these can perhaps be validated more thoroughly.
- Not all scenarios or interventions of Chapter 4 could be tested. Some interesting scenarios (like the mix of items) or interventions (like lean lifts next to the train) could be tested.
- This research only focuses on the Epe warehouse. If the chosen storage policy is also implemented at the VMI sites in Yantai and Leszno, the efficiency gains or losses become bigger. Moreover, if a storage policy is already programmed in Epe, it is easier to also apply it at these sites. Taking this perspective, the amounts in Section 6.5 are perhaps too conservative.

Next to some further investigation into these limitations, some other suggestions for further research can be given. This research gives guidelines about which storage policy to select. After the selection of a storage policy, multiple other decisions within this policy should be taken. Guidelines for further research could be:

- When storing per SKU, what storage policy should be used?
- Should a separate reserve area be used?
- When storing per order, how can storage of ‘orders’ be further optimized?
- What routing should be used?
- How should orders be batched?
- How can the lean lift be further optimized? How can the possible new lifts help?
- What are the savings or costs looking at it from a multi-site perspective?

However, many more directions for further research can be posed.

7.4. Ethical point regarding the FTEs needed

The results of Chapter 6 are about savings in “FTEs needed” when picking and putting away items. This thesis does by no means intend to discharge people from their functions at VMI. However, this thesis tries to indicate how many people will be needed when using the one or the other storage policy. When VMI decides to store per SKU, this might even create more job opportunities.

However, even when the number of people needed is less than in the current situation, for example, because one of the improvements has been implemented, I (the author) still think this is ethically justifiable because:

- These people can possibly work in many other places at VMI, even within the warehouse. Examples of the past have already shown this. For example, the current warehouse data specialist also started as order picker.
- To implement and maintain the possible improvements, people are needed, providing new job opportunities (see the road maps in Chapter 6).
- Currently, … [*information censored for public version].*
- Looking at it from a bigger perspective, VMI itself becomes more competitive regarding its warehouse processes. The more competitive VMI is, the more job opportunities VMI can provide to society.

In my belief, it is more about looking where people are needed, instead of looking if people are needed.

7.5. Contribution to literature and practice

This thesis contributes to the various articles about warehousing or more specifically the SLAP. When reviewing literature about the SLAP, not many articles were found about engineer- and make-to-order environments, where it is already known in advance when and how the items will be needed. This thesis at least contributes to this literature by posing some practical solutions for these companies. By testing various interventions in a simulation model, quantitative and qualitative arguments are given which these companies can evaluate for themselves. Hence, this research tries to fill this gap in literature a little bit.

For VMI, this thesis supports the decision on which storage policy to use. As shown, this decision has a big impact on the number of locations and FTE needed. It, therefore, helps to decide if an investment into implementing a certain storage policy in the new ERP system is needed or not. It does not only consider qualitative arguments, but it shows the quantitative impact of these policies. Moreover, this thesis also shows where problems occur, or savings can be acquired. Therefore, it also guides into decisions to tackle these for the eventual solution chosen. For this, a road map has been outlined for storage per order and SKU.

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Appendix A Current situation

This appendix describes all relevant data and information needed to describe the current situation at VMI in the first two chapters of this report.

Appendix A.1 Organogram

Censored for public version

Figure A 1: Organogram of VMI Holland B.V and the location of this research (Feb 2021).

Some abbreviations are used:

- CEO: chief executive officer
- COO: chief operations officer
- CFO: chief financial officer
- CCO: chief commercial officer
- QESH: quality, environment, safety, and health
- R&D: research and development
- ICT: information and communications technology
- HRM: human resource management
- SQA: supplier quality assurance

Appendix A.2 Current warehouse process

Censored for public version

Figure A 2: The warehouse process flow with relevant Infor statuses and locations.

Appendix A.3 Pictures of storage options

Lean lift

Figure A 3: Lean lifts in use at VMI (Pannekoek, 2020). Four lifts can be observed.

Figure A 4: Sorting per PO after picking from the lean lift. To easily sort the orders, a picker-to-light system is used.

Red box zone

Figure A 5: Red box zone at VMI (Pannekoek, 2020).

Euro pallet zone

Figure A 6: Euro pallet zone at VMI (Pannekoek, 2020). The picture shows half and full pallet locations.

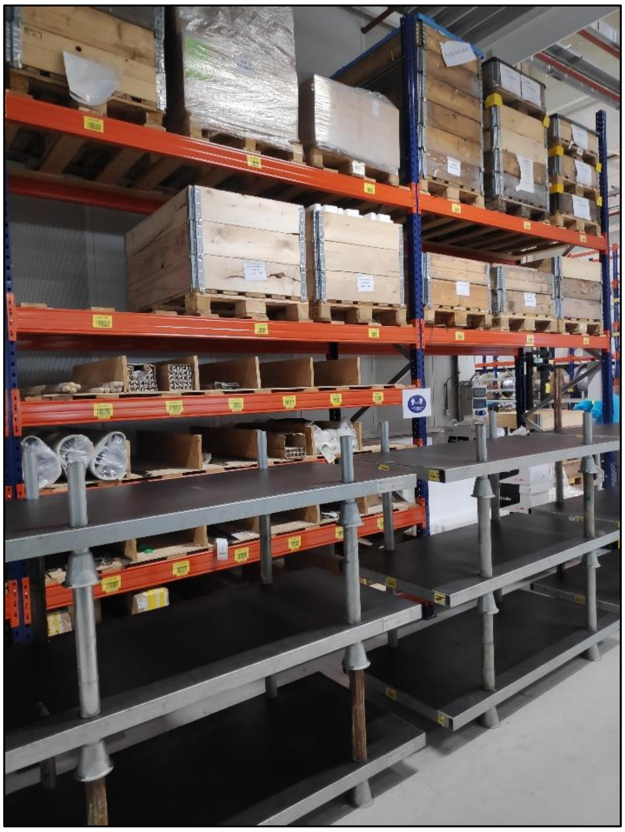

Figure A 7: EP zone "AJ" location (behind the steel pallets). Note that these spaces are different than in the 'normal' EP zone.

Steel pallet zone

Figure A 8: Steel pallet zone at VMI (Pannekoek, 2020). Note the differences in stacking height.

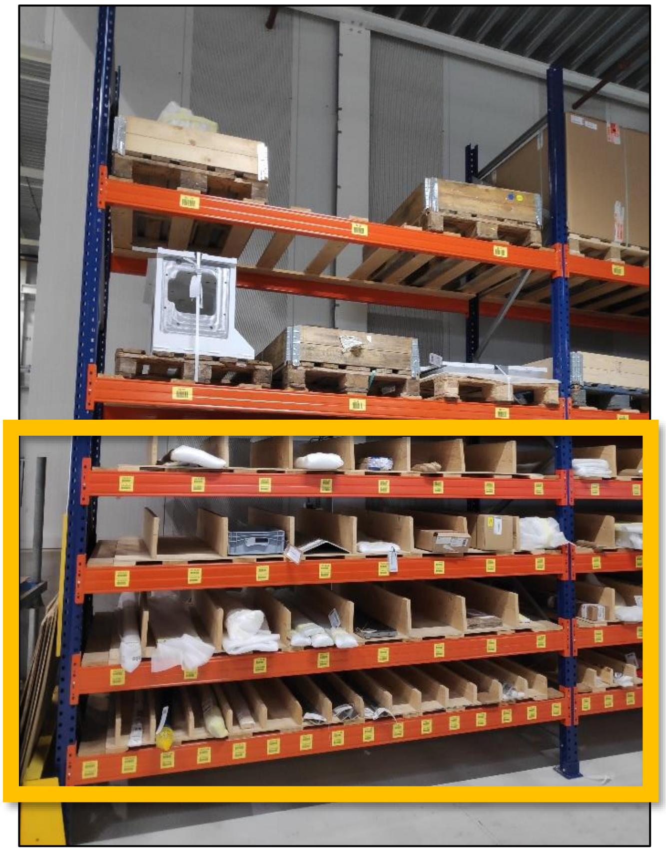

Figure A 9: Steel pallet zone in the euro pallet rack. Note the smaller compartments.

Self-carrying zone

Figure A 10: Self-carrying item zone: large steel pallets (Pannekoek, 2020). Again, note the differences in stacking height.

Figure A 11: Self-carrying item zone: cantilever (Pannekoek, 2020).

Figure A 12: Self-carrying item zone: floor location.

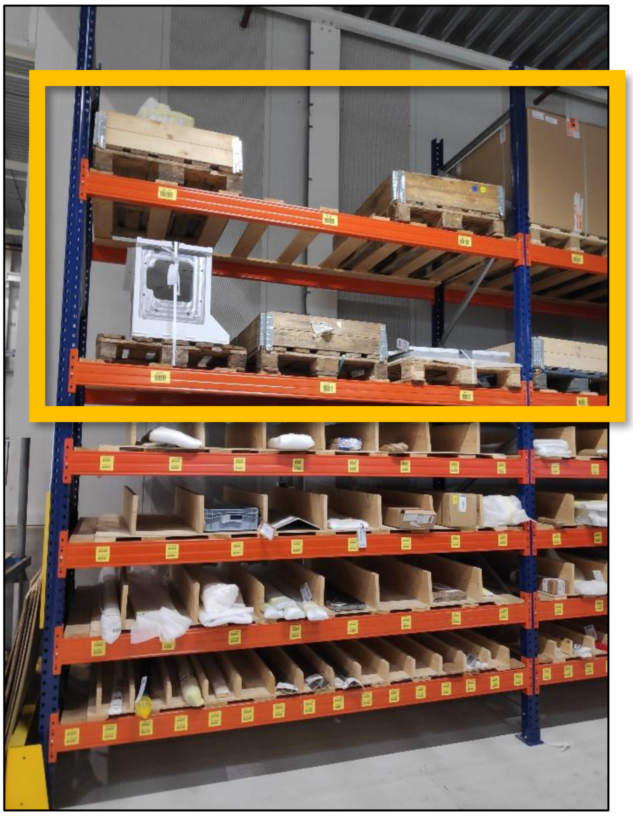

Figure A 13: Self-carrying zone in euro pallet rack. Note the height and weight of the items.

Appendix A.4 Lean lift allocation

Table A 1: Lean lift allocation (Luigjes, 2020). The sizes of locations, names, and the number of locations are given.

Size	Name in lean lift	Length (cm)	Width (cm)	Total locations
Small (½ grey box)	AAA	7.5	7.5	**852**
	CJA	26	11.8	**2040**
	CJB	26	11.8	**296**
	DAA	7.5	15	**1041**
	DEA	15	15	**1267**
	EGA	17.8	20	**68**
	EGB	17.8	20	**20**
	EJA	26	17.8	**888**
	EJB	26	17.8	**157**
	GGA	30	20	**439**
	GGB	30	20	**110**
Total small	**11 types**			**7178**
Big (grey box)	FMA	40	23.8	**112**
	FMB	40	23.8	**16**
	FQA	82.5	23.8	**287**
	FQB	82.5	23.8	**248**
	GLA	30	29.8	**876**
	GLB	30	29.8	**219**
	GMC	30	40	**130**
	HOD	60	40	**140**
	MQD	65.8	82.5	**89**
	MQF	65.8	82.5	**6**
Total big	**10 types**			**2123**
Total	**21 types**			**9301**

Appendix A.5 Seasonality in item arrival and demand

Item arrival per day of the week

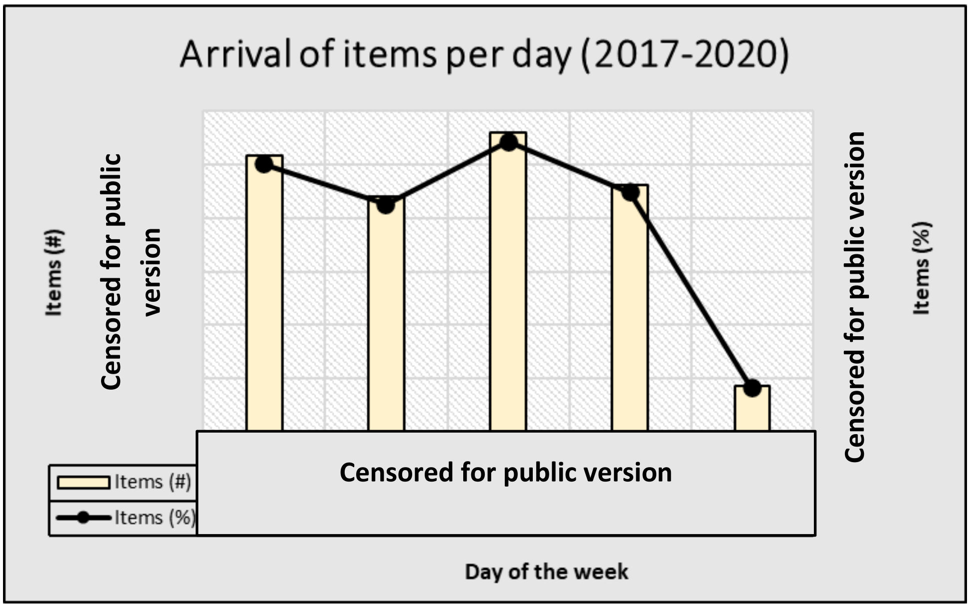

Figure A 14: Seasonality in the arrival of items per day (2017-2020). Note the large dip on Fridays.

Item arrival per month of the year

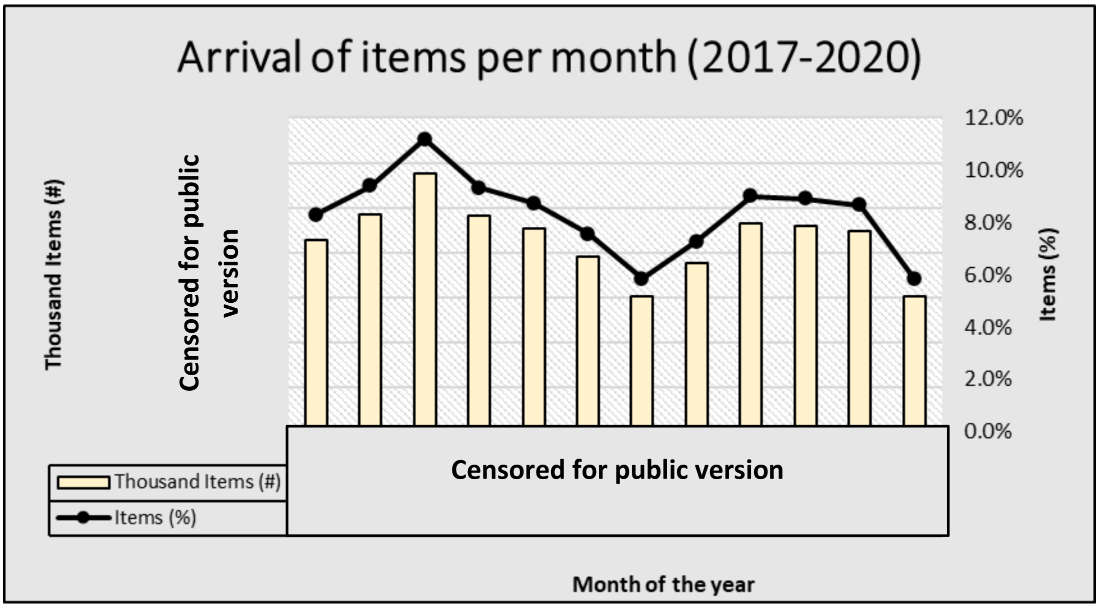

Figure A 15: Seasonality in the arrival of items per month (2017-2020), indicating seasonality in holiday months.

Item demand per day of the week

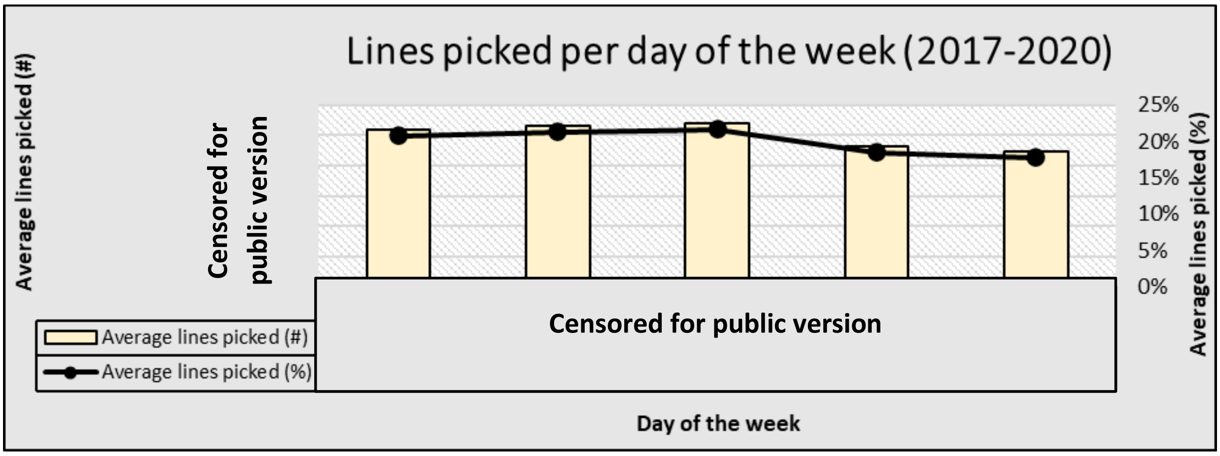

Figure A 16: Seasonality in demand for items per day of the week (2017-2020). No real seasonality can be observed.

Item demand per month of the year

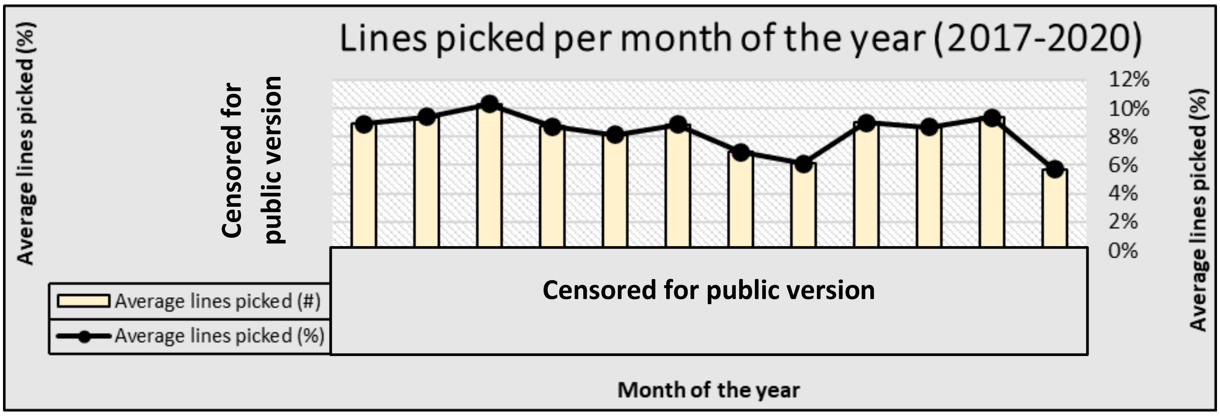

Figure A 17: Seasonality in demand for items per month of the year (2017-2020). Again, note the dips in holiday months.

Appendix A.6 Orders

Items per order

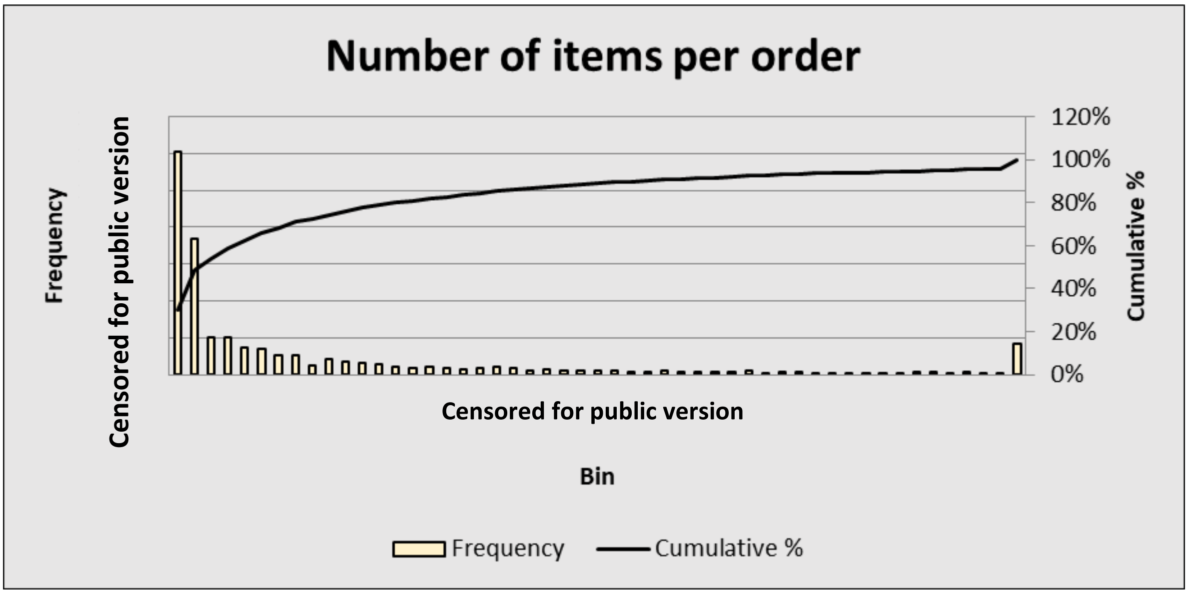

Figure A 18: Number of items per order (PO/WO/SO). Note the large peak at 1, but also how many orders have more than 50 items.

Warehouse, sales, and production orders per day

Empirical distribution of sales orders

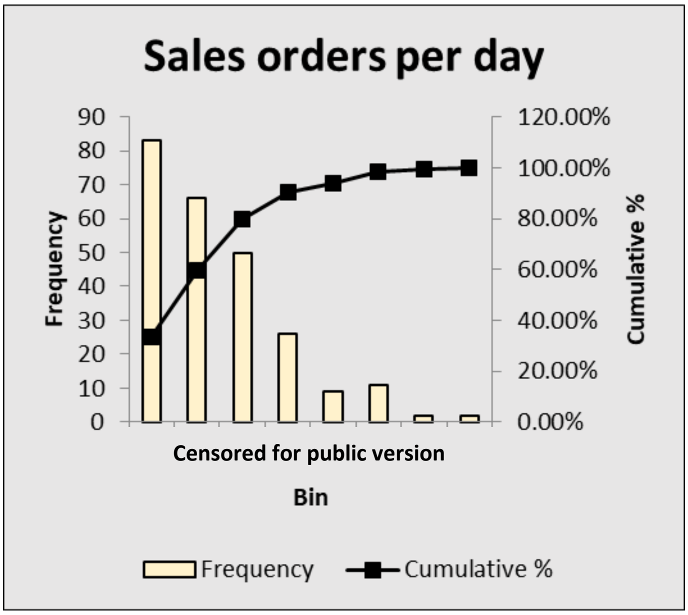

Figure A 19: Empirical distribution of the number of sales orders per day. Notice that the peak is at '0'.

Empirical distribution of warehouse orders

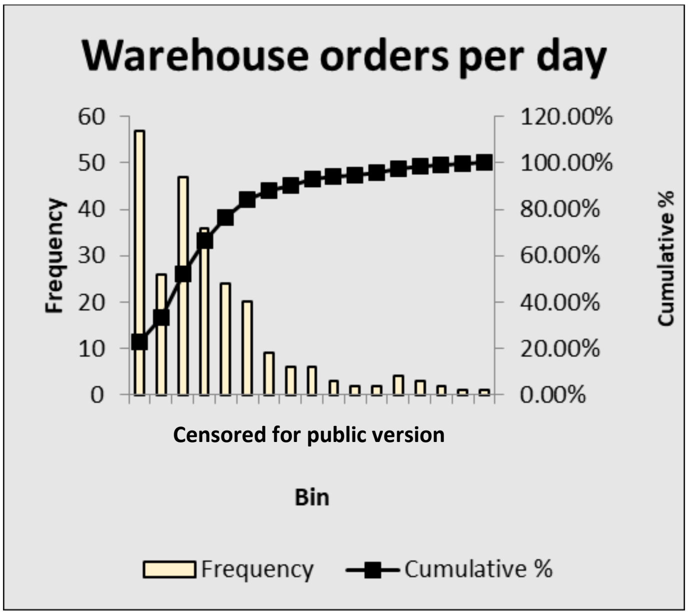

Figure A 20: Empirical distribution of the number of warehouse orders per day.

Empirical distribution of production orders

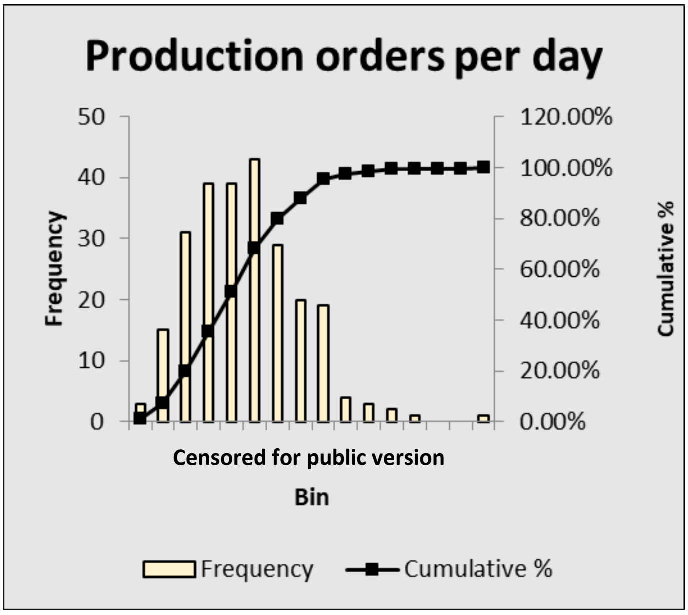

Figure A 21: Empirical distribution of the number of production orders per day.

Appendix A.7 Chi-square independence test

The number of POs, WOs, and SOs picked on a day should be independent. If a low number of production orders indicates a high number of warehouse orders or sales orders (and vice versa), this should be considered. For this, a Chi-square independence test is performed, using a contingency table. However, since the order data is quantitative and contingency tables begin with qualitative data, the order data has been reduced to "high" or "low" per day for sales, warehouse, and production orders per day, just like in Case Study 10.5.2 of Larsen and Marx (2012). A high value is above its average per day, whereas a low value is below its average per day. The null hypothesis states (H_0): [Variable 1] is independent of [Variable 2] against the alternative hypothesis (H_1): [Variable 1] is not independent of [Variable 2].

Using SPSS, the following tests are performed, with corresponding P-values.

Table A 2: Results of the Chi-square independence test between POs, WOs, and SOs.

Variable 1	Variable 2	P-value	Test statistic value
POs per day	WOs per day	0.898	0.017
POs per day	SOs per day	0.536	0.383
WOs per day	SOs per day	0.148	2.092

Bar charts and crosstabulations for each test are displayed below. Using significance level α = 0.05 (or critical value $\chi^2_{0.95,1}$= 3.841), the null hypothesis cannot be rejected for each statistical test. To conclude, there is not enough evidence to suggest an association between the number of production orders, warehouse orders, and sales orders per day. To underline these formal tests, two more arguments can be given for independence:

- Physical argument: sales and warehouse orders are triggered by different departments than the warehouse. These departments do not have a direct view on how busy the warehouse is. They simply fulfill customer demands and ask the warehouse to pick these orders (regardless of how busy they are).
- Population correlation coefficient: using the bivariate Pearson correlation to construct a population correlation coefficient, no significant correlations (two-tailed test) are found (see next pages). Note, independence implies correlation zero, but not the other way around.

All in all, it is assumed that POs, WOs, and SOs per day are independent of each other.

Calculations for the Chi-square independence test

Production orders vs. warehouse orders

Table A 3: Number of cases used for the Chi-square test (249 working days - POs vs. WOs).

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Production * Warehouse	249	100.0%	0	0.0%	249	100.0%

Table A 4: Crosstabulation of production vs. warehouse orders per day.

Production * Warehouse Crosstabulation

			Warehouse		
			High	Low	Total
Production	High	Count	45	73	118
		Expected Count	45.5	72.5	118.0
		Residual	-.5	.5	
	Low	Count	51	80	131
		Expected Count	50.5	80.5	131.0
		Residual	.5	-.5	
Total		Count	96	153	249
		Expected Count	96.0	153.0	249.0

Table A 5: Chi-square test results (production vs. warehouse orders).

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	.017[a]	1	.898		
Continuity Correction[b]	.000	1	1.000		
Likelihood Ratio	.017	1	.898		
Fisher's Exact Test				1.000	.501
N of Valid Cases	249				

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 45.49.

b. Computed only for a 2x2 table

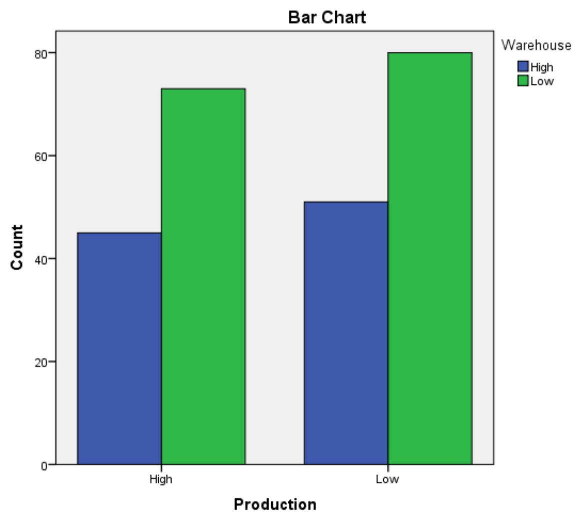

Figure A 22: Bar chart of high and low number of orders per day (production vs. warehouse orders).

<u>Production orders vs. sales orders</u>

Table A 6: Number of cases used for the Chi-square test (249 working days – POs vs. SOs).

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Production * Sales	249	100.0%	0	0.0%	249	100.0%

Table A 7: Crosstabulation of production vs. sales orders per day.

Production * Sales Crosstabulation

			Sales		Total
			High	Low	
Production	High	Count	45	73	118
		Expected Count	47.4	70.6	118.0
		Residual	-2.4	2.4	
	Low	Count	55	76	131
		Expected Count	52.6	78.4	131.0
		Residual	2.4	-2.4	
Total		Count	100	149	249
		Expected Count	100.0	149.0	249.0

Table A 8: Chi-square test results (production vs. sales orders).

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	.383[a]	1	.536		
Continuity Correction[b]	.239	1	.625		
Likelihood Ratio	.383	1	.536		
Fisher's Exact Test				.605	.313
N of Valid Cases	249				

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 47.39.

b. Computed only for a 2x2 table

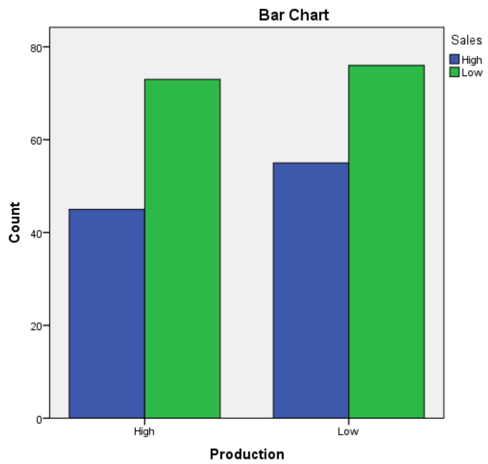

Figure A 23: Bar chart of high and low number of orders per day (production vs. sales orders).

<u>Warehouse orders vs. Sales orders</u>

Table A 9: Number of cases used for the Chi-square test (249 working days – WOs vs. SOs).

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Warehouse * Sales	249	100.0%	0	0.0%	249	100.0%

Table A 10: Crosstabulation of warehouse vs. sales orders per day.

Warehouse * Sales Crosstabulation

			Sales High	Sales Low	Total
Warehouse	High	Count	44	52	96
		Expected Count	38.6	57.4	96.0
		Residual	5.4	-5.4	
	Low	Count	56	97	153
		Expected Count	61.4	91.6	153.0
		Residual	-5.4	5.4	
Total		Count	100	149	249
		Expected Count	100.0	149.0	249.0

Table A 11: Chi-square test results (warehouse orders vs sales orders).

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	2.092[a]	1	.148		
Continuity Correction[b]	1.726	1	.189		
Likelihood Ratio	2.084	1	.149		
Fisher's Exact Test				.184	.095
N of Valid Cases	249				

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 38.55.

b. Computed only for a 2x2 table

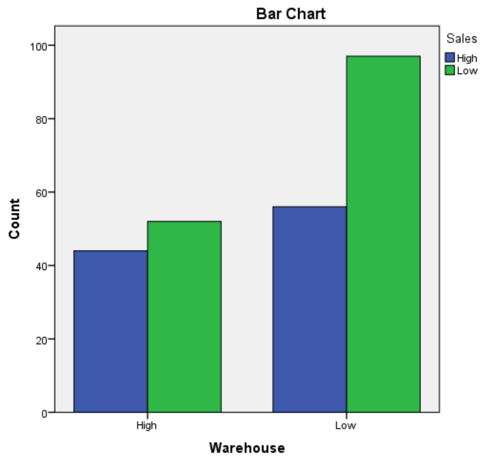

Figure A 24: Bar chart of high and low number of orders per day (warehouse vs. sales orders).

Population correlation coefficients

Table A 12: Pearson correlation test results.

		Warehouse	Sales	Production
Warehouse orders per day	Pearson Correlation	1	0.065	-0.031
	Sig. (2-tailed)		0.306	0.623
	N	249	249	249
Sales orders per day	Pearson Correlation	0.065	1	-0.059
	Sig. (2-tailed)	0.306		0.354
	N	249	249	249
Production orders per day	Pearson Correlation	-0.031	-0.059	1
	Sig. (2-tailed)	0.623	0.354	
	N	249	249	249

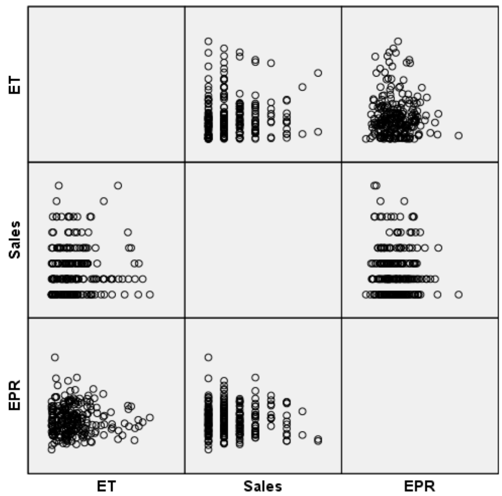

Figure A 25: Scatter plots of the number of orders per day (ET = WOs, EPR = POs, and Sales = SOs).

Appendix A.8 Fitting a Gamma distribution to the number of POs per day

For POs, the Gamma distribution seems to describe the number of POs per day quite well. This is underlined by the summary statistics, QQ-plot, PP-plot, and the histogram of the data and the Gamma distribution, which can be found on the next pages. The Gamma distribution is a continuous function, whereas our data is discrete. However, since '*n*' (the number of days) is quite large (249), not much is lost by approaching our discrete data with a continuous one. Also, the Gamma distribution can give problems when modeling discrete data if a significant portion of low values (close to zero) is present in the data. However, this is not the case in the dataset, where only 1.2% (3 of the 249 observations) of the values is lower than *xx* per day. Hence, it is decided to continue with the Gamma distribution. To properly use it in the simulation model, decimal values are rounded to the nearest integer value. Using the method of moments, the scale (θ) and the shape (*k)* can be estimated from the data, where $\theta = \frac{Var(X)}{E(X)} \approx xx$ and $k = \frac{E(X)^2}{Var(X)} \approx xx$.

Finally, a goodness-of-fit test is performed with the Chi-square test (again, see Section 3.2.2). In this test, the expected frequencies (using the Gamma distribution) are compared to the observed frequencies in an interval. The null hypothesis states (H_0): there is no significant difference between the expected and observed frequencies, whereas the alternative hypothesis (H_1): states that there is a difference that cannot be due to chance alone. The intervals are determined such that each interval has the same probability (using the inverse of the CDF). In total $ceil(\sqrt{n}) = ceil(\sqrt{249}) = 16$ bins are used, making the expected number of observations in each interval 15.5625. Then, using the test-statistic $\chi^2 = \sum_{j=1}^{k} \frac{(N_j - np_j)^2}{np_j}$, where *j* is the interval number, *k* is the number of intervals (16), N_j is the observed number of observations in the interval, and np_j is the expected number of observations in the interval. The calculated test statistic was $\chi^2 = 11.18$ (for computations see below). The critical value is $\chi^2_{0.95,15} = 24.996$. Hence, the H_0 should not be rejected. It cannot be proven that there is a significant difference (significance level 5%) between the expected and observed frequencies. Note, H_0 is not proven. However, based on the goodness-of-fit test, together with the QQ-plot, PP-plot, and histogram, the Gamma distribution seems to be a good fit for the number of production orders per day.

Calculations for the goodness-of-fit test

Table A 13: Summary statistics of the number of POs per day.

Summary statistics	
Mean	A
Standard Error	B
Median	C
Mode	D
Standard Deviation	E
Sample Variance	F
Kurtosis	G
Skewness	H
Range	I
Minimum	J
Maximum	K
Sum	L
Count	M

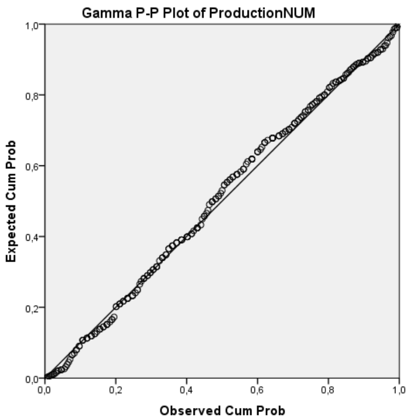

Figure A 26 PP-plot: number of production orders per day vs. Gamma distribution.

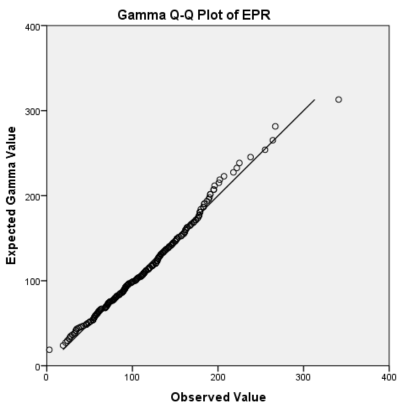

Figure A 27: QQ-plot: number of production orders per day vs. Gamma distribution.

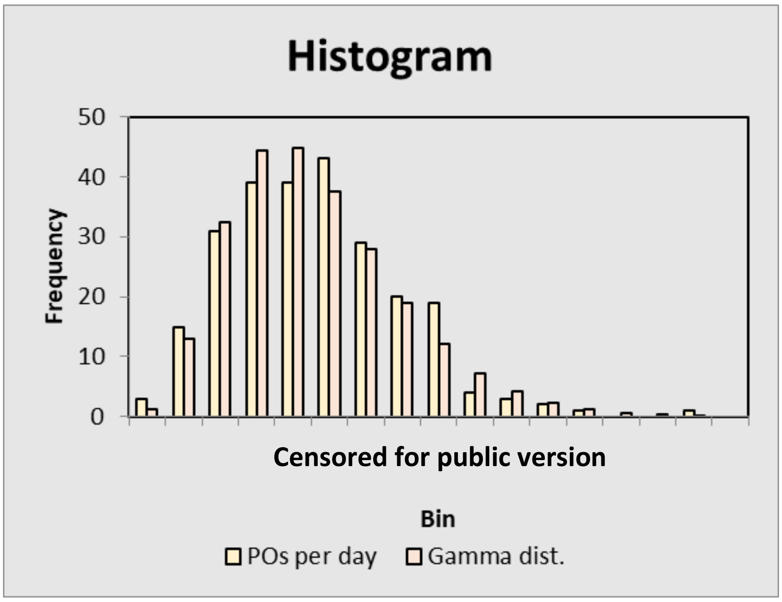

Figure A 28: Histogram: number of production orders per day vs. Gamma distribution.

Table A 14 Computations of the Chi-square test for fitting the Gamma distribution.

Bin Number (x)	***Probability (x/16)***	***Bin (Inverse Gamma CDF)***	***Observed frequency***	***Expected frequency***	$\frac{(N_j - np_j)^2}{np_j}$
1	0.06	A	A	A	0.38
2	0.13	B	B	B	0.01
3	0.19	C	C	C	0.02
4	0.25	D	D	D	0.13
5	0.31	E	E	E	1.34
6	0.38	F	F	F	0.16
7	0.44	G	G	G	0.76
8	0.50	H	H	H	2.77
9	0.56	I	I	I	0.82
10	0.63	J	J	J	0.13
11	0.69	K	K	K	0.38
12	0.75	L	L	L	0.01
13	0.81	M	M	M	0.13
14	0.88	N	N	N	0.13
15	0.94	O	O	O	2.66
16	1.00	P	P	P	1.34
				Total	11.18

Appendix A.9 Tugger train

Table A 15: Summary statistics of the number of POs per train.

Summary Statistics	
Mean	A
Standard Error	B
Median	C
Mode	D
Standard Deviation	E
Sample Variance	F
Kurtosis	G
Skewness	H
Range	I
Minimum	J
Maximum	K
Sum	L
Count	M

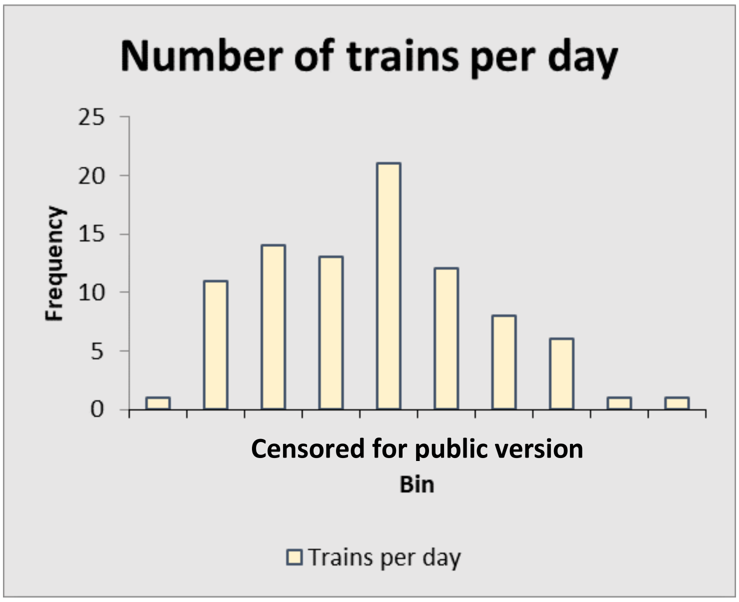

Figure A 29: Distribution of the number of trains per day.

Appendix A.10 Throughput times

Table A 16: Summary statistics of the inbound throughput time for RB/EP/LL items.

Summary Statistics	
Mean	A
Standard Error	B
Median	C
Mode	D
Standard Deviation	E
Sample Variance	F
Kurtosis	G
Skewness	H
Range	I
Minimum	J
Maximum	K
Sum	L
Count	M

Table A 17: Summary statistics of the inbound throughput time for SP/ZD items.

Summary Statistics	
Mean	A
Standard Error	B
Median	C
Mode	D
Standard Deviation	E
Sample Variance	F
Kurtosis	G
Skewness	H
Range	I
Minimum	J
Maximum	K
Sum	L
Count	M

Table A 18: Summary statistics of the sojourn time in working days.

Summary Statistics	
Mean	A
Standard Error	B
Median	C
Mode	D
Standard Deviation	E
Sample Variance	F
Kurtosis	G
Skewness	H
Range	I
Minimum	J
Maximum	K
Sum	L
Count	M

Table A 19: Summary statistics of the sojourn time in days.

Summary Statistics	
Mean	A
Standard Error	B
Median	C
Mode	D
Standard Deviation	E
Sample Variance	F
Kurtosis	G
Skewness	H
Range	I
Minimum	J
Maximum	K
Sum	L
Count	M

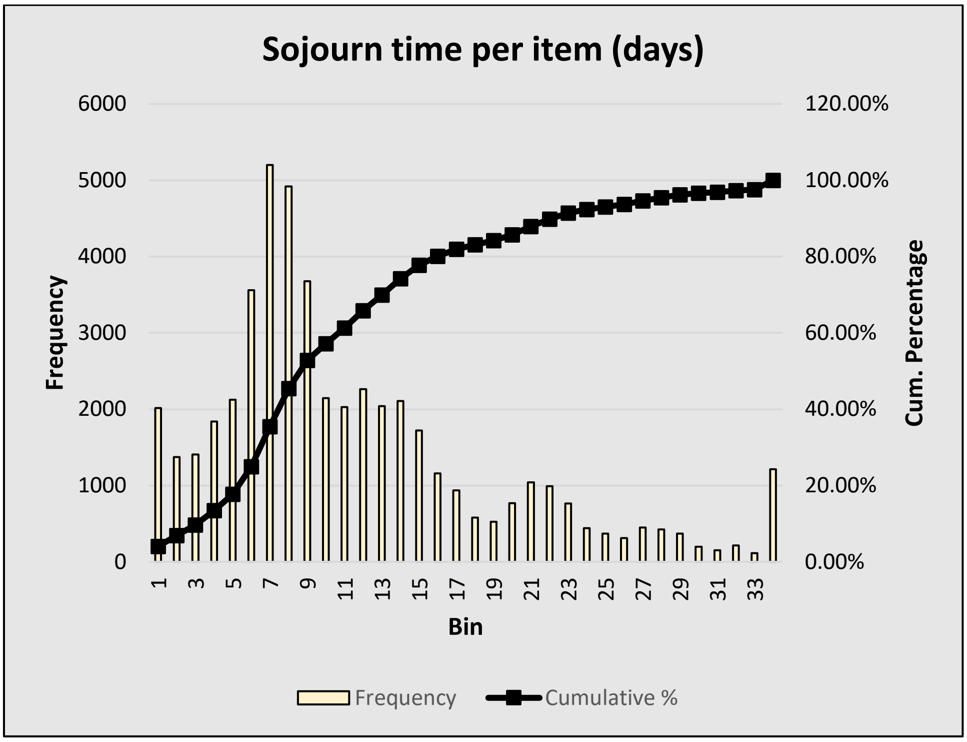

Figure A 30: Distribution of the sojourn time (days). Note these are not working days. Notice the peak around 7 or 8 days.

Appendix B Performance indicators from literature

This section covers the facility-related metrics used in Chopra and Meindl (2015) and the direct and indirect warehouse indicators as described by Staudt et al. (2015).

Appendix B.1 Facility-related metrics

Table B 1: Facility-related metrics (Chopra & Meindl, 2015).

Metric	**Definition**
Capacity	The maximum amount the facility can process.
Utilization	Fraction of capacity currently being used.
Processing/setup/down/idle time	Fraction of time the facility was processing units, setting up to process units, unavailable or idle.
Production cost per unit	The average cost to produce one unit of output.
Quality losses	Fraction of production lost due to defects
Theoretical cycle time	Time required to process a unit if there are absolutely no delays at any stage.
Actual cycle time	The actual cycle time (theoretical cycle time + delays).
Flow time efficiency	Ratio theoretical flow to the actual average flow time.
Product variety	Number of products or product families processed.
Volume contribution of top 20 percent SKUs and customers	Fraction of total volume processed by the top 20 percent of SKUs.
Average production batch size	The average number of units produced in each production batch.
Production service level	Fraction of production orders completed on time and in full.

Appendix B.2 Direct warehouse indicators found in literature

Table B 2: Direct warehouse indicators (Staudt et al., 2015).

Dimensions	Indicator name	Number of publications
Time	Order lead time	9
	Receiving time	5
	Order picking time	4
	Delivery lead time	3
	Queuing time	2
	Put-away time	2
	Shipping time	2
	Dock-to-stock time	2
	Equipment time	1
Quality	On-time delivery	10
	Customer satisfaction	8
	Order fill rate	5
	Physical inventory accuracy	5
	Stock-out rate	4
	Storage accuracy	4
	Picking accuracy	3
	Shipping accuracy	2
	Delivery accuracy	2
	Perfect orders	2
	Scrap rate	2
	Orders shipped on-time	1
	Cargo damage rate	1
Cost	Inventory cost	7
	Order processing cost	3
	Cost as % of sales	3
	Labor cost	2
	Distribution cost	2
	Maintenance cost	2
Productivity	Labor productivity	11
	Throughput	10
	Shipping productivity	7
	Transport utilization	5
	Warehouse utilization	4
	Picking productivity	3
	Inventory space utilization	3
	Outbound space utilization	3
	Receiving productivity	2
	Turnover	2

Appendix B.3 Indirect warehouse indicators found in literature

Table B 3: Indirect warehouse indicators (Staudt et al., 2015).

Indicator theme	Number of publications
Labor	7
Value-added logistics activities	4
Inventory management	4
Warehouse automation	4
Customer perception	3
Flexibility	3
Maintenance	1

Appendix C Solution generation

This appendix shows the questionnaire used to gather opinions of stakeholders in Appendix C.1. Appendix C.2 shows the resulting long list of alternatives.

Appendix C.1 Questionnaire (Dutch)

Due to copying and pasting of the questionnaire in this appendix, the layout of the questionnaire changed. The actual questionnaire was distributed digitally, with a different layout. Nevertheless, the questions are the same. The questionnaire was in Dutch.

Afstudeeropdracht: opslagmethodieken voor het VMI magazijn

Jesper Rensen

* Required

Welkom!

Als ik jou deze enquête toegezonden heb zou ik graag je mening willen meenemen in mijn afstudeerproject. Hoofdvraag van mijn project is: wat is een effectieve en efficiënte opslagmethodiek voor het VMI-magazijn die tegelijkertijd robuust is voor de lange termijn? De opslagmethodiek is de beslissing die bepaald aan welke fysieke opslag we welke items gaan toewijzen. Daardoor heeft de opslagmethodiek vooral invloed op het aantal ruimte dat items in beslag nemen en de handelingstijd (wegleggen/order picken). Naast deze twee hoofdpunten zijn er vele neveneffecten zoals drukte in gangpaden, implementatie in een ERP systeem, affiniteit van order pickers met locaties, robuustheid, etc.

Maandag 22 maart hebben Bob, Berthold, Henk en ik gebrainstormd over diverse opslagmethodieken en scenario's. Graag hoor ik jullie mening over de alternatieven die we gegenereerd hebben. Wellicht heb je hier zelf ook nog ideeën over. Ook deze kun je toevoegen in de enquête.

Hopelijk willen jullie de tijd nemen om deze enquête in te vullen. In ieder geval al heel erg bedankt.

De enquête bevat 4 secties:

1. Alternatieve opslagmethodieken
2. Verbeteringen huidige situatie
3. Scenario's
4. KPI's (waarvan het laatste deel optioneel)

Aan het eind van iedere sectie is er de mogelijkheid om je eigen input te geven en/of commentaar toe te voegen.

Verwachte duur: 30 min.

Alle resultaten zullen anoniem verwerkt worden (maar ik kan wel zien wie wat heeft ingevuld)!

1. Wat is je naam? *

2. Wat is je functie? *

De eerste sectie gaat over het alternatieve opslagmethodieken. Welke alternatieve opslagmethodieken zijn er in plaats van de manier waarop we het nu doen (combinatie van project en anonieme opslag)? Graag hoor ik jouw mening over de volgende types. Daarbij kun je aan het eind nog commentaar toevoegen en zelf alternatieven aandragen.

Alternatieve opslagmethodieken

Alles per item-type opslaan

In deze methodiek slaan we inkomende items per item-type op voor elk artikel, zoals we nu doen in het anonieme magazijn. Dus elk artikel heeft eigen unieke locatie(s).

Voordelen:

- Makkelijk te implementeren in ERP systemen
- Veel ideeën over hoe het beste items weg te leggen in literatuur - Meest gebruikte manier van opslaan Nadelen:
- Meer looptijd tijdens orderpicken doordat je meerdere locaties langs moet t.o.v. het alleen maar lopen naar enkele projectlocaties.

De invloed op het aantal benodigde locaties is mij onduidelijk. Aan de ene kant zal je meer plekken nodig hebben, want je legt niet meer verschillende items bij elkaar, maar tegelijkertijd leg je ook items van hetzelfde type bij elkaar die nu uit elkaar liggen in de projectopslag.

3. Alles per item-type opslaan *

Mark only one oval per row.

	1 - Tijdverspilling	2 - Niet zo interessant	3 - Neutraal	4 - Interessant	5 - Zeer interessant
Dit testen vind ik	⬭	⬭	⬭	⬭	⬭

Per uitrijdatum

In deze methodiek veranderen we de projectopslag. De projectopslag zal niet meer per productieorder zijn, maar per uitrijdatum dat PO's naar de productie worden uitgereden.

Voordelen:

- Op een uitleverdag hoef je alleen maar op en af te lopen naar een (setje) locatie(s) die bij elkaar zitten
- In principe zal je minder plekken nodig hebben omdat je meer artikelen bij elkaar legt in de projectopslag - Meerdere anonieme pickacties kunnen gebundeld worden Nadelen:
- Extra sorteerwerk t.o.v. huidige situatie
- Herplanningen zullen problematischer zijn dan in de huidige situatie
- De opdeling tussen anoniem en, in dit geval, per projectdatum opslaan blijft bestaan

4. Per uitrijdatum opslaan *

Mark only one oval per row.

	1 - Tijdverspilling	2 - Niet zo interessant	3 - Neutraal	4 - Interessant	5 - Zeer interessant
Dit testen vind ik	⬭	⬭	⬭	⬭	⬭

Per trein opslaan

Een variant op de voorgaande. In deze methodiek veranderen we de projectopslag. De projectopslag zal niet meer per productieorder zijn, maar per trein dat PO's naar de productie worden uitgereden.

Voordelen:

- Op een dag hoef je alleen maar op en af te lopen naar een (setje) locatie(s)
- In principe zal je minder plekken nodig hebben omdat je meer artikelen bij elkaar legt
- Om een trein te picken hoef je alleen maar naar enkele locaties te lopen die bij elkaar liggen - Opnieuw kun je anonieme pickacties bundelen Nadelen:
- Extra sorteerwerk t.o.v. huidige situatie
- Je moet de trein al van tevoren plannen (en niet op de dag zelf)
- Herplanningen zullen problematischer zijn dan in de huidige situatie
- De opdeling tussen anoniem en, in dit geval, per trein opslaan blijft bestaan

5. Per trein opslaan *

Mark only one oval per row.

	1 - Tijdverspilling	2 - Niet zo interessant	3 - Neutraal	4 - Interessant	5 - Zeer interessant
Dit testen vind ik	⬭	⬭	⬭	⬭	⬭

Haaksbergen/TKH magazijn

Gelinkt aan het per item opslaan, is het opslaan zoals ze in Haaksbergen doen. Daar slaan ze op per inkomende orderregel in de miniload. Ze slaan dus artikelen per regel op de binnenkomende pakbon in.

Voordelen:

- Snelle weglegstap, de orderregel kan gebracht worden naar de dichtstbijzijnde open locatie.
- Doordat item types verspreid liggen zal er in principe altijd ééntje dichtbij moeten zijn tijdens het orderpicken.

Nadelen:

- Je zult meer plekken nodig hebben dan per item opslaan.
- Als het aantal benodigde artikelen in één locatie niet toereikend is moet je naar nog een locatie lopen.
- Sowieso meer looptijd doordat je langs meerdere locaties moet lopen t.o.v. de huidige situatie.

Het verschil met het per item opslaan is dus dat je in deze methodiek zelfs meerdere item types verspreid hebt liggen.

6. Haaksbergen/TKH magazijn *

Mark only one oval per row.

	1 - Tijdverspilling	2 - Niet zo interessant	3 - Neutraal	4 - Interessant	5 - Zeer interessant
Dit testen vind ik	⬭	⬭	⬭	⬭	⬭

En wat wil jij?

Had je zelf nog ideeën over mogelijke alternatieven? Dan kun je deze hier invullen. Alles is welkom!

7. Ik dacht zelf aan...

____

____

____

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Opmerkingen

Heb je nog opmerkingen over bepaalde vragen in deze sectie, dan kun je deze hieronder kwijt.

8. Verder nog opmerkingen?

____

____

Verbeteringen huidige situatie	Ten tweede, naast complete alternatieven zijn er ook nog verschillende verbeteringen denkbaar binnen de huidige situatie. Graag hoor ik jouw mening over de volgende types. Daarbij kun je, net als in de vorige sectie, aan het eind nog commentaar toevoegen en zelf alternatieven aandragen.

Anonieme pickstap tegelijkertijd

In het huidige systeem picken we de anonieme artikelen 3/5 werkdagen van te voren (LL/BL). Na het picken van de anonieme artikelen worden ze weer achter de baan gelegd waarnaar ze vervolgens worden weggelegd bij de bijbehorende productie orders. Hierdoor hebben we eigenlijk een extra pick én weglegstap. We zouden kunnen kijken wat ervoor nodig is om de anonieme pickstap tegelijk te doen met wanneer de gehele productie order gepakt wordt. Dus wanneer de productie order uitgereden moet worden, worden de anoniem gepickte artikelen aan de trein toegevoegd. Wat zou dit dan opleveren? Wat is hier voor nodig? Dat is waar deze interventie om draait.

9. Anonieme pickstap tegelijkertijd *

Mark only one oval per row.

	1 - Tijdverspilling	2 - Niet zo interessant	3 - Neutraal	4 - Interessant	5 - Zeer interessant
Dit testen vind ik	⬭	⬭	⬭	⬭	⬭

Meerdere uitgaande stromen naar productie

In de huidige situatie hebben we twee uitgaande stromen naar productie: ZD's apart en SP's, EP's en RB's via de trein. Maar wat als we het aantal uitgaande stromen nu vergroten? Wat als we dit vergroten naar bijvoorbeeld drie stromen: ZD, project, en anoniem? Of wat als we deze stromen nog verder opdelen naar vier: bijvoorbeeld per zone. Het voordeel hiervan is dat je een groter cluster tegelijk kan picken in één bepaalde zone. Het nadeel is uiteraard dat het aantal stromen naar productie vergroot wordt.

10. Meerdere uitgaande stromen naar productie *

Mark only one oval per row.

	1 - Tijdverspilling	2 - Niet zo interessant	3 - Neutraal	4 - Interessant	5 - Zeer interessant
Dit testen vind ik	⬭	⬭	⬭	⬭	⬭

Lean liften naast de trein

In de toekomst zullen de lean liften vervangen moeten worden. Wat als de trein nou eerst langs de lean liften rijdt en de items hieruit verzameld en toevoegt aan alle projectorders die al op de trein zitten. Het voordeel hiervan is dat de artikelen niet apart gepakt en weggelegd hoeven te worden. Het nadeel is dat de trein een vertraging heeft omdat hij eerst moet wachten totdat alles gepickt is. Dit alternatief was ook een aanbeveling van een eerdere student (Elles de Rooij).

11. Lean liften naast de trein *

Mark only one oval per row.

	1 - Tijdverspilling	2 - Niet zo interessant	3 - Neutraal	4 - Interessant	5 - Zeer interessant
Dit testen vind ik	⬭	⬭	⬭	⬭	⬭

Outsourcen

Er is ook altijd nog de mogelijkheid om opslag te outsourcen, dus dat we delen en artikelen opslaan bij een externe partner in plaats van in ons eigen magazijn. Vraagstukken zouden kunnen zijn: wat zal er gebeuren als onze totale anonieme opslag geoutsourced wordt? Of als de opslag van grote delen totaal geoutsourced wordt? Wat levert dit dan op? Hiermee zou een vergelijking gemaakt kunnen worden: wat mag het outsourcen dan kosten?

12. Outsourcing *

Mark only one oval per row.

	1 - Tijdverspilling	2 - Niet zo interessant	3 - Neutraal	4 - Interessant	5 - Zeer interessant
Dit testen vind ik	⬭	⬭	⬭	⬭	⬭

En wat wil jij?

Had je zelf nog ideeën over mogelijke alternatieven? Dan kun je deze hier invullen. Alles is welkom!

13. Eigen alternatieven?

Opmerkingen
Heb je nog opmerkingen over bepaalde vragen in deze sectie, dan kun je deze hieronder kwijt.

14. Verder nog opmerkingen

Scenario's	Hierboven hebben we het gehad over diverse alternatieven en/of verbeteringen op de huidige situatie. Deze alternatieven zullen getest moeten worden tegen diversie situaties (naast de huidige!), om te kijken hoe ze dan standhouden. Dit is waar deze sectie om draait: welke scenario's willen we testen?

Volume
Wat als het volume ineens groter wordt? Wat als het volume ineens krimpt? En wat als het volume enorm fluctueert over de jaren.

15. Volume *

Mark only one oval per row.

	1 - Tijdverspilling	2 - Niet zo interessant	3 - Neutraal	4 - Interessant	5 - Zeer interessant
Dit testen vind ik	◯	◯	◯	◯	◯

Aankomst grote/kleine delen
Wat als de verhouding ZD, SP, EP en RB nou verandert t.o.v. de huidige situatie? Wat als er ineens meer kleine artikelen binnen komen? Wat als er ineens meer grote artikelen binnenkomen?

16. Aankomst grote/kleine delen *

Mark only one oval per row.

	1 - Tijdverspilling	2 - Niet zo interessant	3 - Neutraal	4 - Interessant	5 - Zeer interessant
Dit testen vind ik	⬭	⬭	⬭	⬭	⬭

Meer anonieme inkoop

Wat zal er gebeuren als we meer anoniem inkopen? In dat geval hoeven we minder vaak verschillende delen weg te leggen. Bijvoorbeeld een item dat per maand 5x binnenkomt zou in dit geval maar 1x ingeboekt te worden, hoeft maar 1x over de baan, etc. Daarbij, mochten we per item type opslaan zou dit ook betekenen dat je maar naar één locatie hoeft te lopen bij het wegleggen. Bijkomend voordeel zouden orderkosten reducties kunnen zijn.

17. Meer anonieme inkoop *

Mark only one oval per row.

	1 - Tijdverspilling	2 - Niet zo interessant	3 - Neutraal	4 - Interessant	5 - Zeer interessant
Dit testen vind ik	⬭	⬭	⬭	⬭	⬭

Meer project inkoop

Wat zal er gebeuren als we meer projectmatig inkopen? In dat geval zullen we vaker artikelen apart weg moeten leggen. Echter, we hoeven niet meer anonieme artikelen apart te picken. Kanttekening hierbij is dat we lang niet alles projectmatig kunnen inkopen (denk aan kleine stickers, schroefjes etc.). Een bijkomend nadeel is extra orderkosten.

18. Meer project inkoop *

Mark only one oval per row.

	1 - Tijdverspilling	2 - Niet zo interessant	3 - Neutraal	4 - Interessant	5 - Zeer interessant
Dit testen vind ik	⬭	⬭	⬭	⬭	⬭

Aankomst verschillende/dezelfde delen

Wat als er ineens veel dezelfde delen aankomen (omdat we dezelfde machines verkopen) of wat als er ineens veel verschillende delen aankomen (omdat we allemaal verschillende machines verkopen)?

19. Aankomst verschillende/dezelfde delen *

Mark only one oval per row.

	1 - Tijdverspilling	2 - Niet zo interessant	3 - Neutraal	4 - Interessant	5 - Zeer interessant
Dit testen vind ik	⬭	⬭	⬭	⬭	⬭

Yantai

Door de tijdsrestrictie kunnen we Yantai niet ook helemaal simuleren. Maar, door de inspectietijd te vergroten en meer grote delen te genereren zouden we kunnen testen hoe een opslagmethodiek zou kunnen werken binnen de karakteristieken van Yantai.

20. Yantai *

Mark only one oval per row.

	1 - Tijdverspilling	2 - Niet zo interessant	3 - Neutraal	4 - Interessant	5 - Zeer interessant
Dit testen vind ik	⬭	⬭	⬭	⬭	⬭

Herplanningen

Het aantal herplanningen heeft invloed op de verblijftijd van bepaalde artikelen. Als project vaker geherpland worden zal dit invloed hebben op hoe lang locaties bezet zullen zijn.

21. Herplanningen *

Mark only one oval per row.

	1 - Tijdverspilling	2 - Niet zo interessant	3 - Neutraal	4 - Interessant	5 - Zeer interessant
Dit testen vind ik	⬭	⬭	⬭	⬭	⬭

Geen restricties

Out-of-the-box: wat als er ineens restricties die we nu hebben, wegvallen? Hierbij moet je echt denken aan de verre toekomst. Denk hierbij aan bijvoorbeeld het opheffen van de volgende drie restricties:
1. Geen doorlooptijd: wat als picktijd ineens minder wordt of helemaal wegvalt door bijvoorbeeld automatisering? 2. Oneindige capaciteit: wat als we ineens een oneindige magazijncapaciteit hebben door andere manieren van opslaan? Wat zal je dan willen doen en hoeveel plekken zijn er daadwerkelijk bezet?
3. Wat als we ineens geen order pickers meer nodig hebben door bijvoorbeeld de hulp van robots?

Het opheffen van deze restricties kan andere zaken aan het licht stellen. Waar loop je dan tegen aan? Dit zal vervolgens weer interessante nieuwe inzichten kunnen geven.

22. Geen restricties *

Mark only one oval per row.

	1 - Tijdverspilling	2 - Niet zo interessant	3 - Neutraal	4 - Interessant	5 - Zeer interessant
Dit testen vind ik	◯	◯	◯	◯	◯

En wat wil jij?

Had je zelf nog ideeën over mogelijke alternatieven? Dan kun je deze hier invullen. Alles is welkom!

23. Eigen alternatieven?

Opmerkingen

Heb je nog opmerkingen over bepaalde vragen in deze sectie, dan kun je deze hieronder kwijt.

24. Verder nog opmerkingen

KPI's

Met de opslaginrichtingen, scenario's, en verbeteringen op zak, is het tijd om te kijken op welke KPIs we de verschillende uitkomsten willen meten. Dat is waar deze sectie over gaat. Aan het eind kun je weer commentaar toevoegen en zelf alternatieven aandragen.

Magazijn KPI dimensies

Magazijn KPI's kunnen we grofweg opdelen in vier dimensies:

- Tijd: zoals: order lead time, weglegtijd, order picktijd, wachttijd, etc.
- Kwaliteit: zoals: compleetheid PO niveau, compleetheid PO regels, klanttevredenheid, etc.
- Kosten: personeelskosten, proceskosten, onderhoudskosten, etc.
- Productiviteit: rendement op arbeid, throughput, utilisatie, etc.

Graag zal ik willen weten wat voor gewicht jij hangt aan elk van deze dimensies.

25. Dit vind ik van de dimensie: *

Mark only one oval per row.

	1 - Onbelangrijk	2 - Engizins belangrijk	3 - Redelijk belangrijk	4 - Belangrijk	5 - Zeer belangrijk	Geen mening
Tijd	◯	◯	◯	◯	◯	◯
Kwaliteit	◯	◯	◯	◯	◯	◯
Kosten	◯	◯	◯	◯	◯	◯
Productiviteit	◯	◯	◯	◯	◯	◯

KPI's per dimensie (OPTIONEEL)

DEZE SECTIE IS OPTIONEEL, MOCHT JE GEEN TIJD MEER HEBBEN DAN KUN JE DIT OVERSLAAN.

Binnen deze dimensies zijn er verschillende KPI's waarmee deze gemeten worden. De onderstaande komen uit een wetenschappelijk artikel. Zou je diegene die jij belangrijk vindt willen aankruisen? Onder elke dimensie kun je nog een alternatief toevoegen. Mocht je nog meer willen toevoegen, of heb je iets dat niet in een dimensie past dan kun je onderaan nog weer alternatieven invoeren. Daarbij kun je natuurlijk ook weer opmerkingen toevoegen.

26. Dimensie tijd

Check all that apply.

- [ ] Order lead time: tijd tussen wanneer een order geplaatst wordt en een order geshipped wordt.
- Putaway time: tijd om producten weg te leggen.
- [ ] Dock to stock time: tijd van aankomst van een artikel totdat het op de plank ligt.
- [ ] Order picking time: tijd om een order/orderregel te picken.
- [ ] Queueing time: tijd dat een product in het gehele proces aan het wachten is.
- [ ] Receiving time: tijd om een truck te lossen
- [ ] Shipping time: tijd om een trein te laden
- [ ] Delivery lead time: tijd tussen dat een artikel uit het magazijn vertrekt en aankomt in productie.
- [ ]

Other:

- [ ] ______________________

27. Dimensie kwaliteit

Check all that apply.

- [ ] Storage accuracy: de juiste producten worden in de juiste locaties opgeslagen.
- [ ] Physical inventory accuracy: is de systeemvoorraad gelijk aan de fysieke opslag?
- [ ] Stock-out rate: aantal producten dat we moesten leveren, maar niet konden leveren doordat de voorraad niet toereikend was.
- [ ] Picking accuracy: accuraatheid van het order pick process
- [ ] Shipping accuracy: aantal orders dat zonder fouten wordt verstuurd.
- [ ] On-time delivery: aantal orders dat op tijd wordt ontvangen door productie.
- [ ] Order line fill rate: aantal orderregels dat op tijd wordt ontvangen door productie.

Other: [ ] ______________________

28. Dimensie kosten

Check all that apply.

- [ ] Voorraadkosten: het voorraadniveau (in waarde)
- [ ] Order processing cost: totale kosten om orders te picken, weg te leggen, etc./aantal orders (lees gedeeld door)
- [ ] Labor cost: kosten van personeel dat ingezet wordt.
- [ ] Onderhoudskosten: kosten voor onderhoud van het opslagsysteem.
- [ ] Kosten als percentage van verkoop: totale magazijnkosten t.o.v. totale verkoop van VMI

Other: [ ] ______________________

29. Dimensie productiviteit

Check all that apply.

- [ ] Labor productivity: totaal aantal items verwerkt / werkuren (lees gedeeld door)
- [ ] Throughput: aantal items dat het warehouse verlaat per uur
- [ ] Warehouse utilization: het gemiddelde aantal magazijncapaciteit in gebruik per tijdseenheid
- [ ] Inventory space utilization: aantal plekken bezet / aantal plekken (dit kun je verder opdelen per bijvoorbeeld zone: RB, EP, etc.) (lees gedeeld door)
- [ ] Turnover: aantal producten verkocht / gemiddelde voorraad (lees gedeeld door)
- [ ] Picking productivity: aantal producten gepicked / werkuren (lees gedeeld door)
- [ ] Transport utilization: aantal plekken op de trein bezet / aantal plekken (lees gedeeld door)
- [ ] Shipping productivity: Totaal aantal producten dat verstuurd wordt per tijdseenheid

Other: [ ] ______________________

Andere KPI's of dimensies

Heb je nog KPI's die niet in een dimensie passen? Dan kun je hieronder nog weer alternatieven invoeren.

30. Andere KPI's of dimensies

____

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Opmerkingen
Heb je verder nog opmerkingen over de KPI sectie?

31. Opmerkingen

Bedankt voor je tijd!
Heel erg bedankt voor het invullen van de enquête. Vergeet hieronder niet op 'submit' te drukken, anders zie ik de gekozen resultaten niet terug en dat zal toch zonde zijn!

Appendix C.2 Brainstorming long list

Alternative storage policies

1. **Storing per SKU**
   In this alternative, all items are stored per SKU, like in regular warehouses and the current anonymous storage. Each SKU has a unique location.
   Advantage(s): it is easy to implement in an ERP system, many ideas from literature are applicable, it is the most used way of storing, simplicity due to having only one storage strategy, a decrease of sojourn times is possible for anonymous items, and fewer storage zones are needed since the project and anonymous storage zones can be added together.
   Disadvantage(s): longer walking distances when picking orders, it is more difficult to oversee if a project is complete, and items can easier be 'stolen' for a different project than in the current scenario. Regarding the latter, currently, an employee has to overbook items, physically move them, etc. When storing per SKU, this is not needed.
   The influence on the number of storage locations is a bit unclear. On the one hand, you will need more space because you do not store multiple different items together, however, at the same time you store the same items together.
2. **Storing per date of delivery to production**
   In this alternative, the project storage will not be done per production order, but per date of delivery to production.
   Advantage(s): On the date of delivery you only have to walk towards a small set of locations, that are close to each other. You will need less space since more articles are stored together. More anonymous pick actions can be bundled.
   Disadvantage(s): You will need to sort the POs when picking these locations. Rescheduling of POs will be more problematic than in the current situation. The current situation with two types of storage keeps existing.
3. **Storing per train**
   Related to storing per date, it is also possible to store per train. The storage will not be per production order, but per train on which it will be delivered to production.
   Advantage(s): Same as storing per date. Also, when picking the train, you only have to walk towards that location (instead of different locations).
   Disadvantage(s): Same as storing per date. Also, the train itself needs to be generated before storage. Currently, this is done on the day of delivery.
4. **Storing like the TKH warehouse in Haaksbergen**
   In the TKH warehouse in Haaksbergen, VMI stores per line of incoming goods. So, they store per line on the packing slip. It is good to note that the TKH warehouse uses a mini-load, which is a big difference from the warehouse in Epe.
   Advantage(s): Quick put away in the closest open location. Due to scattered storage, items should always be somewhere close.
   Disadvantage(s): You will need more space than storing per SKU. If the number of articles in one location is not sufficient, you will need to walk to another one. The order picking time will increase in comparison to the current situation.
5. **Looking at a production order as a 'superSKU'**
   Since VMI stores per production order, you can also look at it as a 'superSKU'. This superSKU contains all items from a production order. This SKU needs a certain number of places, will be needed for production at some time, and will arrive partially per item. By looking at a

production order in this way, the storage policies from literature can also be used for the project storage. Especially interesting are the following (also see Section 2.2):

a. **Duration of stay (DoS):** where items that arrive, and that are not needed for the production order soon, are placed in less favorable locations, such that items that arrive and are needed sooner are placed in the more favorable locations. In this way, the favorable locations are emptied earlier which would decrease order picking and put-away time.
b. **Cube-per-order-index (COI):** the cube-per-order index ranks SKUs on the ratio of the number of needed storage locations to the number of trips per period. The number of trips per period is one for each project. Therefore, this measure is only dependent on the number of needed locations. The projects that need multiple locations are stored in less favorable locations such that most production orders can be picked from favorable locations.
c. **Object-oriented slotting (OOS):** tells us that production orders that are needed together, should be stored together. This is basically what storing per delivery date or per train tries to achieve.

6. **Horizontal carousel/racks on wheels**
   In this approach, production orders are stored in racks on wheels. By doing this, production orders are stored on a rack close to the inbound department. When time passes, these racks are pushed forward such that, when they are needed, are close to the outbound department. They empty this location and put the empty rack back in the inbound department. A similar effect can be created by using a horizontal carousel.
7. **Hybrid form**
   In this form, items from the two most sold machines are stored per SKU, whereas the others are still stored via a production order.
8. **Storing per transport carrier**
   In this approach, items are stored on steel pallets and in racks. These two storage options can be transported on the train. In this way, you do not have to pick the items again.

Improvements to the current situation

1. **Anonymous picks simultaneously**
   In the current situation, anonymous items are picked several working days before production needs the order, dependent on the storage zone (LL or EP/RB). After picking anonymous items, the articles are put away behind the tracks in the inbound department, who subsequently put away the articles in the project locations. Therefore, these items are picked and put away twice. In this alternative, it will be investigated what will be needed to perform this anonymous pick at the same time as the production order is picked and what savings can be made. The advantage is that one put-away and pick step can be saved. Moreover, the sojourn time of anonymous items can be shortened, saving places. However, it puts more pressure on the date of delivery, and if it turns out that anonymous stock is not sufficient, you are too late.
2. **Increasing the flows to production**
   In the current situation, there are two flows to production: items from the ZD zone separate, and items in the SP, EP, and RB zone together on the train. What if this is increased to, for example, three: one for ZD's, one for anonymous items, and one for production order items? Or perhaps even four, one flow per zone? The advantage is that one larger cluster can be picked per zone. The disadvantage is the increase of flows to production, which is not desired.

3. **Lean lifts next to the train**
   In the future, the current lean lifts will have to be replaced by new ones. What if these new ones are placed next to the train? In this way, items from the lean lift can be added when the corresponding production orders are already on the train. In this way, items from the lean lift will not have to be picked and put away twice. This was also a recommendation of another student, Elles de Rooij (2020).
4. **Outsourcing**
   What if more parts of the warehouse are outsourced? For example, what if all large items are stored at an external partner? Or what if all anonymous items are stored in an external warehouse? What will this yield? This can be used as a comparison to the cost of outsourcing to see if this is an interesting alternative.
5. **Procuring more SKUs anonymously**
   Procuring more SKUs anonymously means that items are not procured for a specific production order. By procuring more SKUs anonymously, SKUs can be procured together and come in together, instead of coming in separately. Advantage one is that there is only one booking, inspection, and put away for all items that come in together. Two, the procuring department could attain ordering cost reductions. Three, when storing per SKU, this also means walking to a location only once when putting away the items. A disadvantage is an extra pick and put-away step with the current storage policy. Also, it is not possible for all SKUs, especially not the larger SKUs in the ZD and SP zone, like frames. Lastly, some accounting reasons also make this alternative less attractive.
6. **Procuring more per production order**
   In contrast to the former, what if more SKUs are procured attached to a production order? The put-aways will increase. Also, ordering costs will likely increase since more one-offs are ordered. However, the extra pick and put-away steps are not needed for these items. A side note is that not all SKUs can be procured in this way, think about bolts, nuts, or stickers.
7. **No restrictions**
   A bit out-of-the-box: what if current restrictions are left out? This scenario is about the long-term (let's say more than 10 years in the future). Think about especially the following three restrictions:
   a. No picking or put-away time due to automation.
   b. Unlimited storage capacity due to different ways of storing.
   c. What if order pickers are not needed, for example, due to robots?

   Forgetting about these restrictions can highlight other problems, gaining new insights.

Scenarios

1. **Volume**
   What if the number of arriving items increases? This scenario should acquire insight into where bottlenecks will occur when volume increases. What will be the critical areas of the warehouse? Also, when volumes are increased, one scenario can be better than the other, for example, because one alternative needs more space. Or perhaps the outbound department cannot deal with all order requests since one alternative will increase picking times. Hence, altering the volume is seen as an interesting scenario to test the alternatives against.
2. **Arrivals large/small parts**
   What if more large parts arrive? What if more small parts arrive?
3. **Arrival of more/fewer SKUs:** what if more SKUs arrive, while the volume remains the same? And what if fewer SKUs arrive? For example, when storing per SKU, more locations are needed

if more SKUs arrive, whereas this is not the case for storing per production order or per train. However, this is still needed in the anonymous storage, and perhaps problems occur there. So, this scenario influences all alternatives and hence it is also considered.

4. **Rescheduling**
   What if a lot of projects are rescheduled? These items occupy space for a longer time in the warehouse. What will happen with each intervention if more projects are rescheduled?
5. **Yantai**
   Due to the time limits of this research, Yantai cannot fully be simulated too. However, by increasing the throughput time of the inspection step and mainly generating large items, the characteristics of Yantai can be imitated. In this way, results can superficially be checked for the situation in Yantai.

Appendix D Simulation Modeling

This appendix contains more details about the simulation model used, regarding its contents, verification, validation, assumptions and simplifications, and the number of replications chosen. Hence, it is recommended to first read Chapter 5 before reading this appendix.

Appendix D.1 Detailed description of the simulation model

In the simulation, on a day, three things happen. 1. Orders and trains are generated, and item arrivals are scheduled for the future (see Section 5.5). 2. The items that were scheduled to arrive on this day, physically arrive in the warehouse and are put away. 3. Trains and anonymous items are picked. These components are outlined here.

1. Order generation

Dataset used

The dataset used is based on production, warehouse, and sales orders picked in the second half of 2020. In the dataset, orders which contain items that go to locations that are not considered in this research, are completely deleted to not create orders that contain too few items. Also, only items that follow the 'official route' are considered. So, anonymous items that went to the anonymous storage first, and after that to the project storage. Or project items that went directly to production via the project storage. The items that went directly from the anonymous storage to production or expedition are filtered out. The dataset is validated in Section 5.7. This dataset is loaded into the simulation such that this only has to be done once. By loading the dataset into the simulation model, all items, and attributes of these items from these orders are grouped per order and combined in a sub-table such that these are easily accessible when generating items.

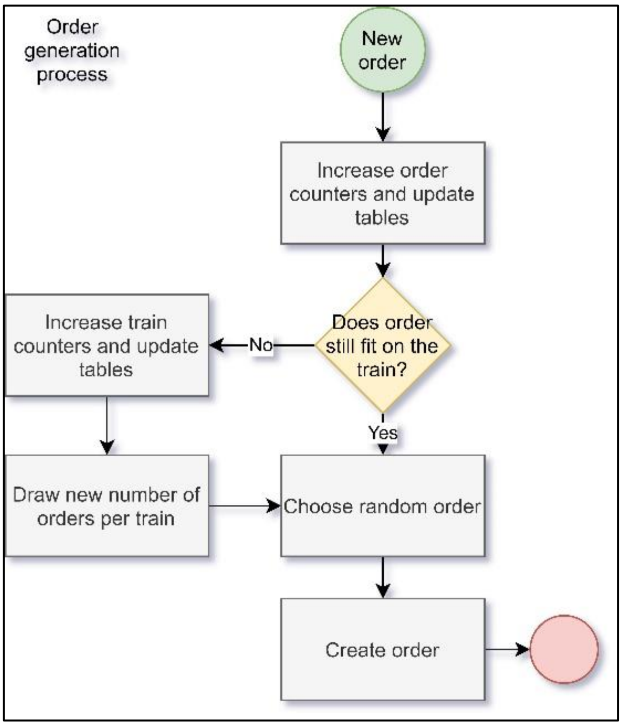


Figure D 1: Generating orders and adding them to trains.

Number of POs, WOs, SOs, and trains

Each day POs, WOs, and SOs are drawn from the Gamma (for POs) and empirical distributions (WOs and SOs), based on Section 2.4.5. Also, the number of orders per train is drawn from the empirical distribution displayed in Section 2.5. When the number of orders on a train is reached, a new train is created and a new number of orders per train is drawn. This train is subsequently filled with orders. This process continues until all orders on a day are planned. Also, see Section 5.5.

Order generation process

Subsequently, for each PO, WO, and SO that should be created, Figure D 1 is followed. One random order is drawn from the full list of POs if it is a PO (and of course from the lists of WOs for a WO/SOs for a SO). Then for all contents in this production order, project and anonymous items are scheduled for arrival.

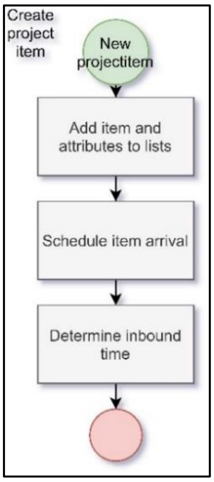


Figure D 2: Scheduling project items.

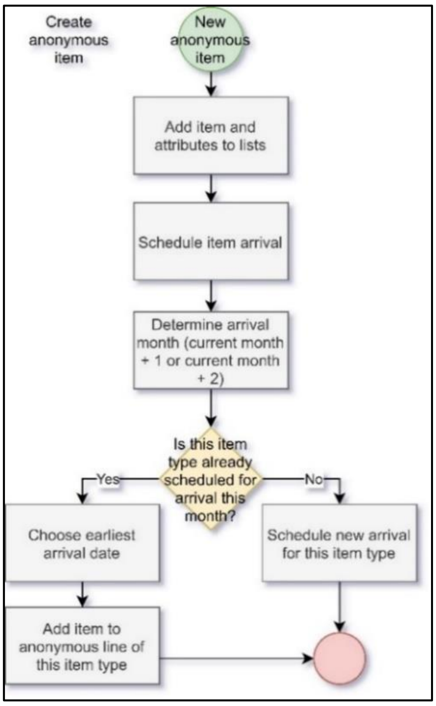


Figure D 3: Scheduling anonymous items.

Create project items

When a project item in an order is created, it is scheduled in several lists to store its attributes, order date, arrival date, and inbound time. A project item has the following attributes:

Table D 1: Attributes of an item in the simulation model.

Attribute	Data type	Description	Example
ItemID	Integer	Unique item ID within the simulation	3257
Item_string	String	Item number at VMI	"K.259.0534"
Description	String	Brief description of the item	"Cover"
Inboundtime	Time	Process time at inbound	2:08:33 (DD:HH:MM:SS)
Arrivaltime	Time	Time of arrival of the item	31:10:52:44
Order_date	Time	Pick date of the order to which it belongs	48:00:00:00
Order_string	String	Original order number of VMI to which the item belonged	"EPR497357"
OrderNum	Integer	Unique order ID within the simulation	533
Storage_zone	String	Zone in which the item needs to be stored	"ZD"
Storage_destination	String	Destination within the zone (only for SP/ZD)	"ZD-ZDFloor"
TrainNum	Integer	Unique train ID within the simulation	73
Size	Real	Fraction of a location the item occupies in its storage zone	0.4

The inbound times and sojourn times are based on the empirical distributions displayed in Section 2.6. The arrival date of an item is determined via the sojourn time distribution and subtracting this from the planned order pick date (see Figure D 4). This order pick date is set 46 days ahead in the future.

Create anonymous items

Anonymous items are created according to Figure D 3. When an anonymous item in an order is created, it is scheduled in several lists to store its attributes, order date, arrival date, and inbound time. Its attributes are the same as for project items. Though, anonymous items come into the system as one line per month per SKU. That means that all items of a certain type that were scheduled to arrive in one month, are combined into one anonymous line. This line gets the earliest arrival date of that SKU in that month. This line stays together until items are put away on location. The arrival date of an individual item is determined via the sojourn time distribution and subtracting this from the planned order pick date, see Section 5.5, just like for project items. This order pick date is, again, set 46 days ahead in the future.

The arrival of anonymous and project items is visualized in Figure D 4. Also, days are added to the sojourn time distribution, to follow the fixed schedule explained later in the assumptions and simplifications.

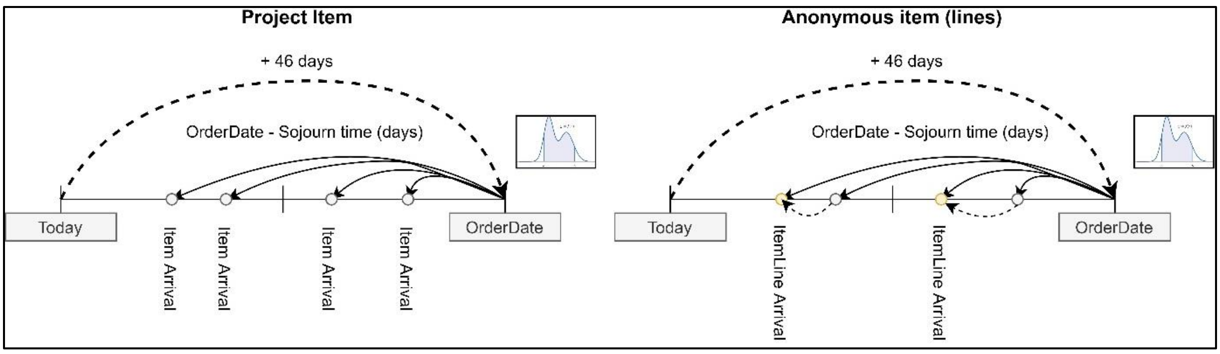


Figure D 4: Scheduling anonymous and project item lines.

An anonymous line has the following attributes:

Table D 2: Attributes of an anonymous line.

Attribute	Data type	Description
ItemLineCode	String	Unique item line ID within the simulation
Contents	Table	Table of individual anonymous items contained in this line.
Item_String	String	Item number at VMI
Item_Description	String	Brief description of the item
Arrivaltime	Time	Time of arrival of the item line
Inboundtime	Time	Processing time at the inbound department
Size	Real	The size of the item (based on its storage zone)
Storage_zone	String	Zone in which the item needs to be stored
StorageDestination	String	Destination within the zone in which the item needs to be stored

2. Item arrival and the put-away process

Item arrival

After item arrivals are scheduled, they are physically created in the model. All items that were scheduled to arrive on a day, both anonymous lines and project items, are created. These items arrive in random order. Item arrival is equally spread out over the day, based on how many items should arrive on that day. Items that are created arrive at the inbound department and are inspected for a certain time, based on the attribute 'inbound time', which was assigned during the item creation. After inspection, the items are put away. The inbound department works from 7:30 to 16:15, with the breaks from 9:30-9:45 and 12:30-13:00.

Storage zones

Items are put away in different storage zones, based on the attribute 'storage_zone' which was assigned during the item creation. The storage zones and number of individual locations are the same as mentioned in Section 2.2.1. Anonymous item lines are stored in the ST-EP, ST-GB, and ST-LL zones. Project items are stored in the ZD, SP, EP, and RB zones. In the ZD-zone, a distinction is made between rack locations, floor locations, XL locations, cantilever locations, and the public warehouse. The latter three have an infinite capacity in the model (see assumptions). In the SP-zone, a distinction is made between the rack and floor locations. An item that cannot be stored in its storage zone is being put away on the public warehouse location (see Section 2.5.4). At this location, items are stored that are delivered to and received from the public warehouse. It is assumed that the public warehouse has an infinite capacity for items that could not be stored too. Items that are not being put away in their zone are counted. This can be seen as a penalty for that particular scenario.

Figure D 5: One RB or GB.

Item put-away

Put-away capacity

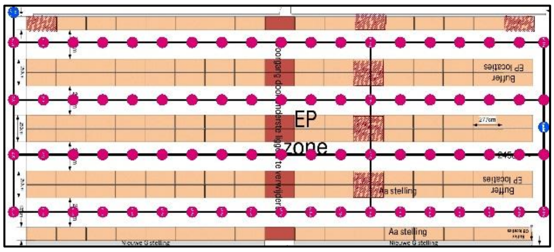
The put-away capacity is eight items when putting away items in the RB or EP zone. The put-away capacity is eight item lines in the ST-EP and ST-GB zone. Lastly, when items are picked from the lean lift or the ST-GB zone, they return to the RB zone. When these items are picked, they are sorted per order into multiple RBs. For this put-away, the capacity is eight RB per route. The put-away has been set to eight for the following reasons:

- This capacity is a trade-off between traveling time and processing time. By increasing the capacity, more items can be picked in one tour, decreasing traveling time. On the other hand, with more capacity, the probability of mistakes is larger, items need to be sorted, damages are more likely, etc. VMI has determined to set this trade-off to eight.
- The current scanner application can process only eight items per scan turn. In the case of the RBs, it can handle eight RBs.

The put-away capacity is one by one in the SP and ZD zone since these items are heavier and larger. Item put-away consists of four components: travel time, search time, set-up time, and handling time.

- *Travel time*

Unfortunately, no reliable data is present about the time it takes to put away items in each zone, let alone in a location. Hence, assumptions need to be made. For this, distance grids are drawn over the warehouse map for each zone, where coordinates are drawn over the warehouse map. This is displayed in Appendix D.5. By doing so, the Manhattan distance between each coordinate can be calculated, and by subsequently assigning each location to a coordinate, the Manhattan distance between each location can be calculated. This results in a symmetric distance matrix per zone between each location.



$$D = \begin{pmatrix} 0 & d_{01} & d_{02} & \cdots \\ d_{10} & 0 & d_{12} & \\ d_{20} & d_{21} & \ddots & \\ \vdots & & & 0 \end{pmatrix}$$

Figure D 6: Distance grids to distance matrix.

By using the dimensions displayed on the floor plan, travel distances could be computed in meters by assuming an x and y distance in meters. Finally, to assign times to the put-away process, a speed has to be assumed. For this, the travel speed used is 2.4 km/h. This is based on the average speed used in the three articles of Ruben and Jacobs (1999), Schrotenboer et al. (2017), and Roodbergen (2012). Based on the height of a location, also a vertical travel time is incurred. This travel time is based on Veldhuis (2016). Veldhuis is an employee of VMI who researched the EP zone at VMI.

Table D 3: Assumed vertical travel time (Veldhuis, 2016).

Pallet Height Code	Vertical travel time
1	0
2	0
3	0
4	50
5	64
6	78
7	92

These speeds have been validated by taking a pallet truck and measuring the speed in the VMI warehouse.

- *Handling time*

Based on the same journal articles, the handling time has been set to 20 seconds per item. However, this differs across zones. For the RB, EP, and SP-rack zones, it is 20 seconds per item. For the ST-GB and ST-EP zones, it is 20 seconds per visited location. This is done since you fill these locations with incoming item lines until it is full, and then visit the next one. Also, when a location is full, you have to check this, find the new one, indicate that it was full, etc. For the SP floor, ZD rack, ZD floor, and ZD other, the put-away time has been set to 36.7 seconds since these items are heavier and bigger and, thus, more difficult to handle.

- *Search time*

Search time is the time needed to search for locations. So, this is incurred for every location visited. This is set to 26.67 seconds per location visited. This number is based on the chosen handling time of 20 seconds per item and the distribution of an order picker's time, as described by Tompkins et al. (2003).

- *Setup time*

Setup time is the time to set up a picking route. This has been set to 13.33 seconds. Again based on the chosen handling time of 20 seconds per item and the distribution of an order picker's time, as described by Tompkins et al. (2003).

Put-away in the lean lift

Put-away for the lean lift is done twice per day, once at 9:41 and once at 14:03. These times are chosen such that between each put away an equal amount of time is present (4:22/4:23). During these put-aways, all items on the pallet are delivered to the lean lift.

Put-away in the RB and EP zone

If eight items are present in the put-away bin for project items that go to the RB or EP zones, the put-away bin is being put away. This is also done for all remaining items in the bin at the end of the day, such that the schedule is not distorted (see assumptions). The basic process is displayed in Figure D 7. A few things to point out:

1. When a new location is selected because the other location is full, the closest open location is selected. When the order does not have a storage location yet, the open location with the highest y-coordinate (so closest to the I-point) is chosen.
2. In the EP zone, the difference between half and full pallet locations is considered. Hence, if an item needs a full pallet location, but only half pallet locations are available, it cannot be stored. Also, the differences between the sizes of these locations have been considered.
3. When items cannot be stored because there are no more open locations, they are stored at the public warehouse.
4. The route eventually only visits unique locations.
5. When an item does not fit into a project location, it is added to a new location. The old order location is indicated as full. This means that any other (perhaps smaller) item cannot be stored in the older location anymore too. The new location becomes the new order location.

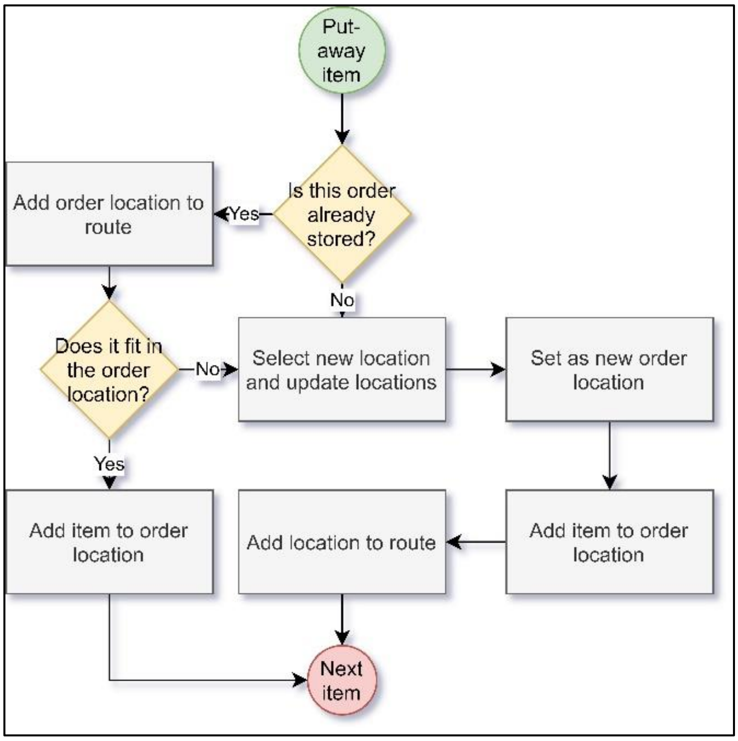


Figure D 7: Flowchart for putting-away project items.

Put-away in the ST-GB zone and ST-EP zone

If eight item lines are present in the put-away bin for anonymous items that go to the ST-EP/ST-GB zone or it is the end of the day, the items are put away. The basic process is displayed in Figure D 9 (below). To summarize this process: it is checked if this SKU already has a location or not. If not, a new location is created for this SKU, and all individual items are added to this location, as long as it fits. If it does not fit anymore, another new location is created until all items have a location. If an SKU already has one or multiple locations, it is checked for each item line if it fits in any of the already created locations. If not, new locations are added, and items are added to that location.

A few things to point out:

1. Points 1-4 mentioned above are also implemented here.
2. In the ST-EP zone, an ABC classification is used. The ABC classification is made by calculating the usage per SKU in the used simulation dataset, where usage is the number of times that SKU occurs in the dataset. This is plotted against the cumulative percentage of SKUs. Approximately 25% of the SKUs define 80% of usage. These SKUs are allocated to the A-class. The 33% of SKUs that define 15% of usage thereafter are allocated to the B-class. Lastly, the 42% of SKUs that define the last 5% of usage are allocated to the C-class.
   Regarding the locations, all locations on picking height are allocated to the A-class. All locations on height 4 or 5 are allocated to the B-class, and locations with a height of 6 or higher are allocated to the C-class. By doing so, 53%, 31%, and 16% of the locations are allocated to respectively the A, B, and C classes. If B items cannot be stored in their own zone, they are allocated to the C-class, and then to the A class.
   Perhaps, the number of classes, sizes of classes, locations assigned to classes, items assigned to classes, etc. could be further optimized. However, that is outside the scope of this research.

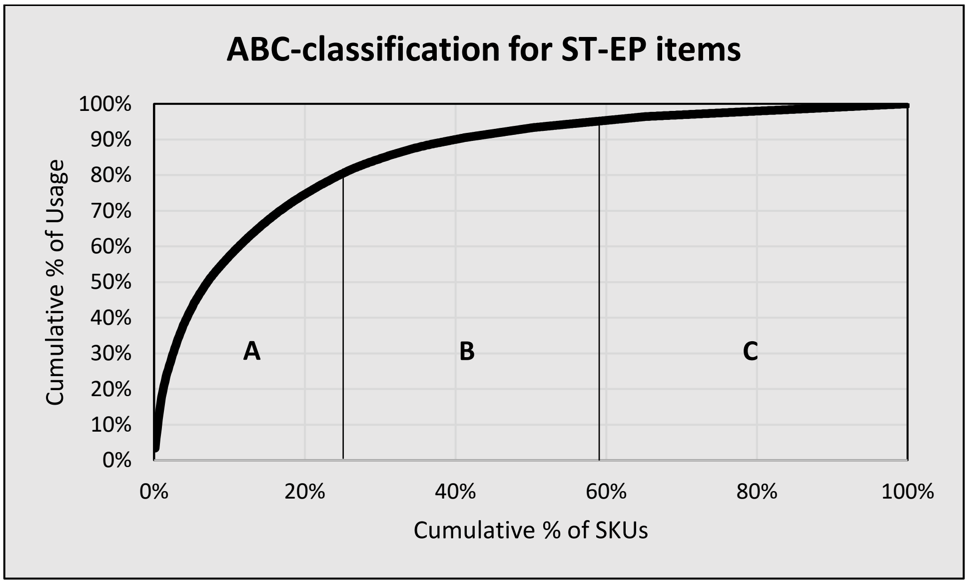


Figure D 8: ABC classification in the ST-EP zone.

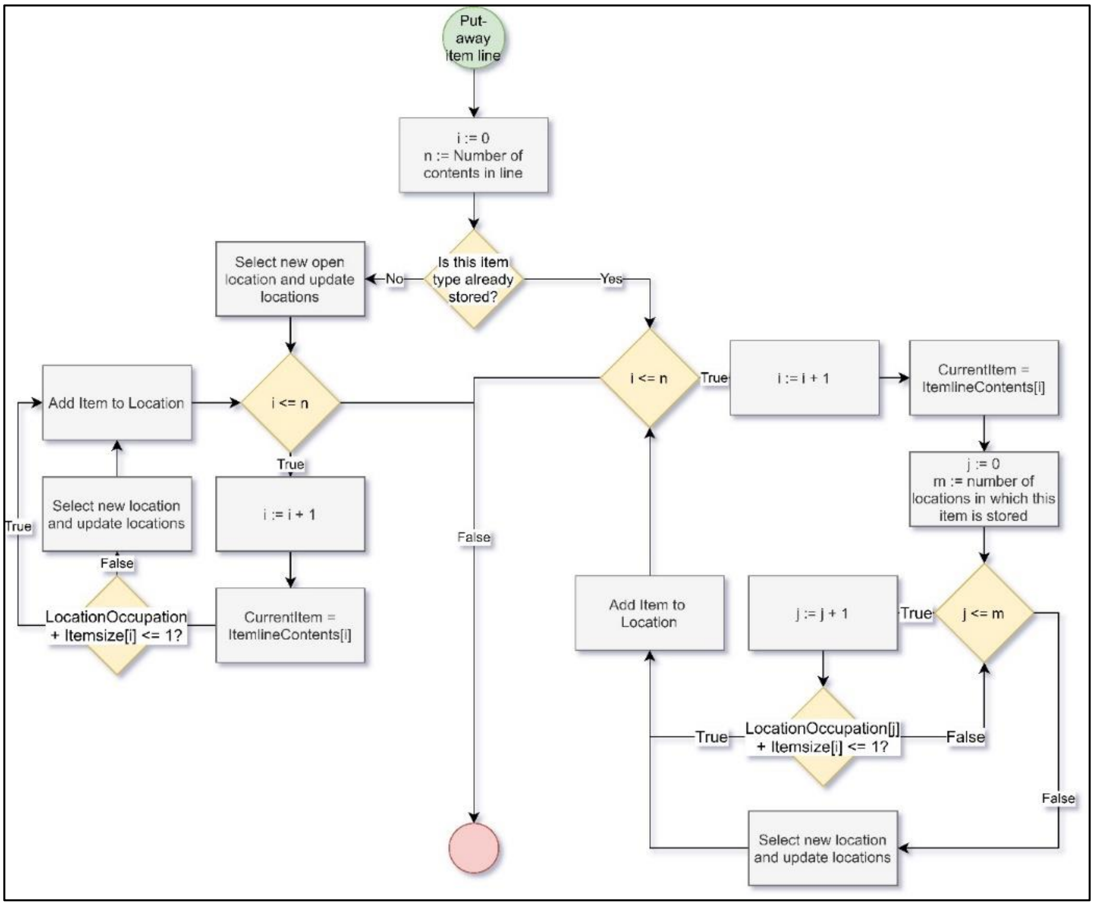


Figure D 9: Putting away anonymous items.

Put-away in the SP and ZD zone

Putting away items in the SP and ZD zones is done as displayed in Figure D 7. A few points:

1. Put-aways are done item for item.
2. Points 1, 3, and 5 at "*Put-away in the RB and EP zone"* also hold here.
3. The SP-zone consists of the rack locations and floor locations. Stacking on floor locations are considered as well as that some rack locations have the size of 3/8th pallet locations and others have the size of 3/16th pallet location.
4. The ZD-zone consists of rack locations, floor locations (on which stacking has been considered), XL locations, cantilever locations, and public warehouse locations.

Routing

Since putting away is done for multiple items in the RB, EP, ST-EP, and ST-GB zones, a route has to be created. This routing is based on the current routing in the scan application of VMI. Routing in the ST-GB and RB zones is based on the y-coordinate of the locations that need to be visited. The locations with the highest y-coordinate are visited first. In the ST-EP and EP zones, the route is based on the x-coordinate and y-coordinate. The locations with the highest x-coordinate are visited first (AA, AB, AC, etc. locations), if this is equal, the locations are sorted on the highest y-coordinate (AA.01., AA.07., AA.31., etc.). Also, when the same locations have to be visited for multiple items, this location is only visited once. A put-away route starts from the I-point and ends at the I-point (see distance grids). Note that put-away routes in other zones are one by one, so the route only consists of I point – location – I point.

Table D 4: Set-up, handling, and searching times incurred together with the picker's capacity per zone.

Put-away										
Time	**RB**	**EP**	**ST-GB**	**ST-EP**	**SP rack**	**SP floor**	**ZD rack**	**ZD floor**	**ST-EP (2)*** **	**ST-GB (2)**
Hand-ling	Item (20)**		Location (20)		Item (20)	Item (36.7)			Item (20)	GB (20)
Travel capac-ity	Route per 8 items		Route per 8 lines		Per item	Per item			Route per 8 items	Route per 8 GB
Pick										
Time	**RB**	**EP**	**ST-GB**	**ST-EP**	**SP rack**	**SP floor**	**ZD rack**	**ZD floor**	**ST-EP (2)**	**ST-GB (2)**
Hand-ling	GB (20)	Per item (20)				Loc* (36.7)		Item (36.7)	n.a.	
Travel capac-ity	Route per 8 GB	Route per 8 items	Route per 8 GB	Route per 8 items	Route per location visited				n.a.	
General										
Set-up	Per route									
Search	Per location visited									

**Loc: per location visited.*
*** Handling time incurred in seconds.*
**** Put-away in project storage, after anonymous items have been picked.*

Note that the lean lift is not added since only travel time is incurred for bringing items to and from the lean lift. Also, storage in the other ZD locations (cantilever, XL, and public warehouse) is not included. Handling is incurred per item for these locations, together with a set-up time and travel time per route and a search time per location visited. The same goes for items that were delivered to the public warehouse because they could not be stored in their own zone. ST-EP (2) and ST-GB (2) include the put-away after ST-EP and ST-GB items have been picked from the anonymous storage and need to be put away in respectively the EP and RB zone in the project storage.

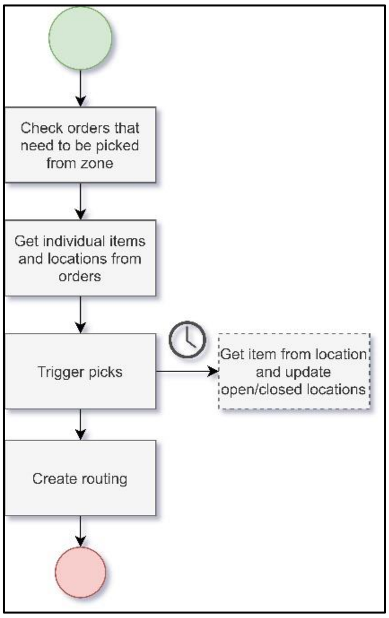


Figure D 10: Trigger pick actions.

3. Train picks and anonymous picks

Next to the arrival of items and scheduling items and orders for the future, all trains and anonymous items are picked on the day they are needed. Each day, the anonymous picks in the ST-GB, ST-EP, and ST-LL, are triggered, as well as the trains that need to be picked. These are triggered as such, such that the item picks are spread out over the entire day.

Picking capacity

Since the put-away capacity is eight for EP and RB items, the picking capacity has also been set to eight. Otherwise, one alternative might be more interesting because it favors the one process over the other. Note that this means that RBs and ST-GBs are picked per 8 RB. EPs and ST-EPs are picked per 8 items, and the SP floor, SP rack, ZD rack, and ZD floor are picked per location on which the items are stored. When items are picked from the other ZD locations or the public warehouse, they are handled one by one (see Table D 4).

Travel, handling, set-up, and search times for the picking process

The travel, set-up, and search times are the same as for the put-away process. The handling time is different. For the EP, ST-EP, ST-GB, SP rack, and ZD floor, the handling time is per item since you have to manually pick one by one from these locations. For the RB zone, this is per RB since you can pick the entire RB from the location and pick it. For SP floor and ZD rack locations, the handling time is per location since you can pick the entire pallet location.

Routing

Since picking is done for multiple items in the RB, ST-GB, EP, and ST-EP zone, a route has to be created. This routing is based on the current routing in the scan application of VMI. Routing in the RB zone is again based on the y-coordinate, where the highest y-coordinate is visited first. Routing in the ST-GB zone is first based on the order you are picking for and then ordered based on the y-coordinate (highest first). So, it could be that you travel to the same location twice (no order batching is applied), however, this is currently also true at VMI. In the EP zone, the routing is based on the x and y coordinate, where the location with the highest x-coordinate is visited first. If this is equal for some locations, the highest y-coordinate is visited first. Routing in the ST-EP zone is first based on the order for which you are picking, then on the x-coordinate, and then on the y-coordinate (again highest first). A picking route for anonymous items starts at the I-point and ends at the I-point. Picking for project items starts at the O-point and ends at the O-point. Note that picking in the other zones is per location, or one by one, so this only consists of one location visit. This item routing can probably be improved regarding distance minimization. However, it is the current way VMI works. Routing optimization is not part of this research.

Locations

When items are picked from the location, they are deleted from that location. If this item is the last item of an order location, this order location becomes free and is available for any new order. The same goes for item locations: when an item is the last item for an item location, it becomes free for any new SKU.

Appendix D.2 Model assumptions and simplifications

This section outlines the assumptions and simplifications made in the simulation model.

Assumptions

1. **Item sizes:** At VMI, no data is present about the sizes of items. This is an essential part of this research since it determines when locations are full or not. So, an assumption has to be made. For this, a dataset of all items picked in the project zones, from January 2020 to April 2021, is used (approximately *xxx,xxx* records). Using this dataset, the number of items picked from a location on a day is counted. Then, per SKU, it is calculated with how many items on average, this item key was stored. Then, the reciprocal of this number yields the average item size. So, for example, if an item key once was stored with 4 other items, and once with 2 other items in the EP-zone. On average, this item key takes $\frac{1}{\frac{(5+3)}{2}} = \frac{1}{4}^{th}$ fraction of an EP location. This was eventually done for each item key in the dataset.
   Taking the minimum does not yield the right result. For example, if a big item was stored, let's say, an item that takes 0.75^{th} RB, and 5 items from the lean lift are added, that all take 0.05^{th} RB, this item would, by taking the maximum, take $\frac{1}{6}^{th}$ RB, whereas its actual size was 0.75. Similarly, the maximum also does not yield the right result. For example, when one lean-lift item was present in a sales order, that takes 0.05^{th} RB, this item would be stored in 1 RB, without adding any other item. Then, this item would, by taking the maximum, get the size of 1 RB. The one method overestimates the item size (maximum), whereas the other underestimates the item size (minimum). Hence, the average is taken.
   A problem is that some item keys are sometimes stored in one zone, whereas, at other times, they are stored in another zone. For these item keys, the size from the zone is chosen in which it was stored most often. Also, a distinction has been made in the EP zone between half pallet locations and full pallet locations, and between the different storage options in the SP and ZD zone.
   Another problem is the fact that one item line in some cases contains a larger item quantity than at other times. However, it is decided to not take this into account. When validating the item size assumption, it turned out that not considering the item quantity yields better results. Eventually, the following average sizes were obtained for each storage type.

Table D 5: Average sizes of items per zone.

Zone	Average Size	Standard deviation	Unit
EP	0.246	0.182	EP
RB	0.185	0.202	RB
SP rack	0.771	0.215	SP (rack)
SP floor	0.632	0.239	SP (floor)
ST-EP	0.238	0.161	EP
ST-GB	0.166	0.125	RB
ST-LL	0.097	0.081	RB
ZD rack	0.729	0.341	ZD (rack)
ZD floor	0.475	0.221	ZD (floor)

To validate these sizes, two things are done. First, the project manager has measured 30 items for a certain project in the past. The measured volumes and surfaces were compared to the calculated fractions. Then, by using this fraction to calculate its expected volume and surface, based on the surface and volume of a location in that zone, a comparison is made. On average, the deviation was 10.4% regarding its volume and 14.4% regarding its surface. Second, per order, it has been counted how many locations it had occupied. Then, by summing per order how many locations you would expect it to occupy by summing the assumed item sizes per zone, per order, the expected number of locations was obtained. From this analysis, the ZD-zone was deleted since the XL and cantilever locations have an infinite capacity in the simulation model. The expected number of locations was compared to the actual number of locations occupied per order in the SP, EP, and RB zone. In total, of the *xx,xxx* orders considered, *xx,xxx* (80.3%) orders had an equal number of actual and expected locations in each zone. Of the *x,xxx* (19.7%) orders of which the actual number of locations was unequal to the expected number of locations, *x,xxx* orders (40.2%) only deviated one location. Of course, there is a danger of putting too much confidence in these results due to overfitting. This since the validation data was also part of the original dataset.

All in all, the assumption made is not perfect, but it is not bad. However, an assumption has to be made about the item sizes. Another approach could be measuring some items currently in the warehouse and extrapolating this. However, this takes quite some time, and it can be questionable if this yields better results than the current approach. Moreover, in each experiment in the simulation model, the same items come into the warehouse. As long as these are the same for each experiment, it does not matter that much which exact sizes are used, as long as they contain the characteristics of the actual system.

2. **Public warehouse (see Section 2.5.4):** All items that cannot be stored in their destined zones are stored in the public warehouse. This is on a fixed location, in the top left corner of the warehouse. In reality, items are picked up or delivered to this location by the public warehouse. The number of items that were not stored per zone is counted, which should be seen as a penalty for that particular scenario. Since it is not known what the capacity of this public warehouse is, an infinite capacity is assumed.
3. **Deterministic search time, set-up time, handling time, and speed.** In reality, times for searching for items, handling them, setting up the routing, and even walking itself, are stochastic variables. However, since data about these times is not present, and to properly compare the differences between scenarios, it is assumed that the mentioned times are deterministic.
4. **Stacking height:** The stacking height in the SP and ZD zone depends on how large the items are and on if stacking posts are used or not. Unfortunately, since item heights are unknown and to simplify the model, an assumption has to be made here. The stacking height is important since on a floor location multiple orders can be stored based on the stacking height (in contrast to, for example, an EP-location). Therefore, multiple production simulation runs have been made with different stacking heights for the SP and ZD floor locations, and the utilization has been computed. Unfortunately, no utilization levels are known from the past. Hence, these have been proposed to the warehouse manager, compared to the utilization levels of other zones. He decided that the stacking height for the SP floor should be 3 and the stacking height should be 3.5 for the ZD floor. A stacking height of 3.5 can be created by giving half of the ZD floor locations a stacking height of 4, whereas the other half gets a stacking height of 3.

Table D 6: Utilization levels for the SP floor and ZD floor based on different stacking heights.

Stacking height	Utilization SP floor	Utilization ZD floor
1	80.4%	97.7%
2	40.8%	85.5%
3	**27.1%**	**63.2%**
4	20.2%	**46.6%**
5	16.7%	37.7%
6	13.8%	31.6%

5. **Fewer locations for the ST-GB and ST-EP zones.** In the ST-EP and ST-GB zones, some locations have been deleted. This is done since the utilization levels in some production runs were quite low for these zones. Locations that have been deleted, are locations on which items were present that did not move (so no picks or put-aways) for half a year. This is done since these items are not present in the simulation model dataset, which is only a dataset of half a year. For the ST-EP zone, this means that 538 locations have been deleted, and in the ST-GB zone 940 locations have been deleted. The exact locations that have been deleted are the same as in reality.
6. **Order picker's utilization:** The utilization of an order picker has been set to 70%. This has been set by communicating with the warehouse foremen, warehouse manager, and SCI manager. By outlining the expected time an order picker is doing other tasks and comparing this to the eight working hours, 70% seemed like a reasonable number. Moreover, when comparing the pick and put-away times to the FTE needed, 70% also seemed like a good estimation.

Simplifications

1. **Working days:** Only working days are simulated, weekends and holidays are not simulated since during those days no items are processed. Items are only processed between 7:30 and 16:15 (the working times of the warehouse). The inbound department has breaks between 9:30-9:45 and 12:30-13:00. For put away and picking, items are put away and picked during the entire day. Here, breaks are not considered. However, this is accounted for when calculating the FTE needed.
2. **Backorders:** Backorders are not considered. Of the *xxx,xxx* lines picked from the project storage, these only accounted for approximately 4% of the items. Also, see Table D 7. This table was obtained by comparing the actual pick date with the minimum pick date of the order of which it was part.

Table D 7: Number and percentage of items backordered (ERP, inventory transaction history, 2020).

	Items	Percentage of items	Percentage of orders that contained a late item
Not on time	A	3.92%	8.31%
On time	B	96.08%	91.69%
Total	**C**	**100%**	**100%**

3. **Infinite capacity:** Multiple storage locations have an infinite capacity in the simulation model. The lean lift has infinite capacity since the alternative storage assignment policies do not affect the put-aways, utilization levels, and picks from the lean lift. The outsourcing company has infinite capacity since it is not known what its capacity is, and this company is outside the scope

of this research. The XL locations and cantilever also have an infinite capacity in the simulation model to speed up the model construction. This is done because the item sizes of these items were difficult to determine and because these items only consist of respectively 0.75% and 0.06% of the items.

4. **Sojourn time:** The sojourn time is truncated at 20 working days (one month) to prevent having to schedule ahead for three months. In this way, the simulation model only has to schedule ahead for two months. This is also done to prevent extreme values. On average, only 3.76% of the values for the sojourn times would be larger than 20 working days. For the same reason, the minimum sojourn time for lean lift items has been set to 6 days since with a sojourn time of five or less, items are scheduled three months ahead. This does not affect any utilization levels since the lean lift has infinite capacity and lean lift items are only entering the RB zone two days before the production start date.
5. **Anonymous items:** In reality, anonymous items come into the system based on reorder points and order quantities. In the model, these are not individually programmed per SKU. However, to create the effect of items coming into the system together, all arrivals in a month are combined into one line, as explained above.
6. **Fixed schedule:** Days are added to the sojourn times. This is done to make sure that the put-away and pick schedule is attained. This schedule is displayed in Table D 8. To also prevent that items are not put away before picking starts, the inbound times of Section 2.6 have been truncated at eight hours and the relative frequencies have been altered such that they still add up to 100%. This shortens the average inspection time for SP and ZD inspection by approximately 26 minutes and the average inspection times for RB, EP, and LL items by 5 minutes. Note that the minimum inbound time has already been set to 10 minutes in Section 2.6. The inbound time includes unloading, booking, inspection, and all buffers between these processes. Therefore, it is assumed that the inbound has an infinite capacity. Finally, at the end of the day, all the items still present behind the tracks, are being put away in their designated zones. This is (again) done to follow the schedule below.

Table D 8: Fixed schedule followed in the warehouse.

Time (working days)	Activity to be performed	Latest date for:
t=8	Production start date	
t=7	Train pick date	
t=6	Put away lean lift	(Put away project items)
t=5	Pick lean lift	Arrival Project items
t=4		(Put away lean lift items)
t=3	Put away ST-GB and ST-EP	Arrival lean lift items
t=2	Pick ST-GB and pick ST-EP	
t=1		(Put away ST-GB/ST-EP items)
t=0		Arrival ST-GB/ST-EP items

In reality, this schedule is not always followed, for example, when it is quite busy. However, the intention is to always follow this schedule.

7. **Seasonality:** As shown in Sections 2.3 and 2.4, there is daily/monthly seasonality in the arrivals and picks of items. This is not implemented in the model since most seasonality is due to holidays and only working days are simulated. To simplify the model, the lower arrivals on Friday are not considered.

8. **ABC classification/random storage (see Section 5.5):** In the ST-EP zone, an ABC classification is used since maintenance cannot be used like in reality. This is also done to prevent that popular items are stored in unfavorable locations. When an item location is full, and a new location needs to be visited, still the closest open location is chosen to add the items to. So, in that case, the ABC classification is not considered. In the ST-GB zone, a random storage policy is used since no maintenance can be done to open and close locations within the model. For the ST-LL, an infinite capacity is assumed. Hence, no storage policy is implemented in the lean lift.
9. **All orders on the train:** In the simulation model, all orders leave the warehouse per train and, thus, are picked per train. Currently, only production orders are transported on the train. However, also not all types of production orders are delivered by train yet. Nevertheless, soon, the plan is to transport all types of orders via the train. Of course, ZD items are still being transported one by one since these do not fit on the train. However, a problem occurs for the train capacity, which is measured in production orders per train. For this, the average item size per order is compared (based on Table 2-6, so including zones not considered in the model). A PO is approximately four times larger than an SO, whereas a PO is two times larger than a WO. Hence, when an SO is added to the train, the number of orders on the train is increased by 0.26, whereas when a WO is added to the train, the number of orders on a train is increased by 0.12.

Table D 9: Items per order (ERP, transaction history, 2020).

Order type	Items per order	Items per PO / Items per SO or WO
PO	A	1.00
SO	B	3.83
WO	C	8.45

Note that in reality, the train is not computed per order but is composed based on different item sizes, routing, etc.

7. **Order pickers do not make mistakes:** In the model, it is assumed that order pickers do not make mistakes when putting away and picking items. In reality, order pickers can put away the items in the wrong locations, pick the wrong items, damage them, etc. To not overcomplicate the model, this is not considered.

Appendix D.3 Model verification and validation

This section outlines the model verification and validation.

Verification

The model is continuously verified during model construction. To do so, all eight techniques of Law (2015) are used, also see Section 3.2.4:

1. **Writing the program in modules and subprograms and debug:** the model consists of multiple frames, methods, and lists. These frames are based on function, while methods and lists are mostly divided per storage zone and activity. This is done to maintain a clear overview of processes and functions within the model.
2. **Let more than one person review the program:** the SCI manager and warehouse manager are involved in model construction (as well as validation and verification of the model). By stepping through the model during multiple meetings, they are closely involved in model construction.
3. **Run the model on a variety of settings:** think about increasing volumes, using smaller datasets at the start, smaller storage space, etc. This is done to check if the model behaves as expected.
4. **Use a trace:** using the interactive debugger in the simulation program, each possible programming path has been examined and checked during its construction.
5. **Run the model under simplifying assumptions:** used to a lesser degree, but especially at the start, modeling has been done in separate files and has later been implemented in the model. In this way, it has been checked if small subsystems behave as they should.
6. **Observe animations:** also used to a lesser degree since animation is not a strict requirement for this research. However, from the observation, it can be observed that the parts follow the path displayed in Section 5.5.
7. **Compare means and variances of probability distributions**: before each probability distribution or empirical distribution was implemented in the model, it was checked if this distribution behaved as it should in a separate, simplified model.
8. **Use a commercial simulation package to reduce programming effort:** the simulation model is created in Tecnomatix Plant Simulation 13 of Siemens.

Next, the model needs to be validated to acquire credible results.

Validation

Validating the model is done in two steps, namely by checking data and showing the model to the stakeholders. First, the arrival of items is checked. Second, the utilization levels are compared. Finally, the put-away and pick times are constructed. To validate the model, production runs are made with the model, so without a formally defined number of replications, warm-up period, and run length. These comparisons are also shown to the SCI-manager, and the warehouse manager.

1. Validating the arrival of items

The first step of this validation section starts by outlining the number of orders generated per day since this is the basis for how many orders arrive in the simulation model. To get an average from the simulation model, three replications were used where on average 1,320,992 days were simulated. The results are displayed in Table D 10.

Table D 10: Orders per day (history vs. simulation model).

Orders	History (2020)		Simulation model		
	Average orders per day	Standard deviation	Average orders per day	Standard deviation per run	Deviation from reality (%)
SOs	A	A	A	A	+0.01%
WOs	B	B	B	B	-0.73%
POs	C	C	C	C	-0.19%
Total avg.	**D**	**D**	**D**	**D**	**-0.33%**

Indicating only a small deviation in average orders per day. To simulate orders, a dataset of *xx,xxx* orders is used. This dataset is based upon orders from July 2020 until December 2020. This dataset is compared to the number of items picked in the second half-year of 2020.

Table D 11: Items picked (07-01-2020-31-12-2020) vs. the dataset used in the simulation model.

Storage Zone	Items Picked 2020	% Of zone (project/ anonymous)	Dataset used	% Of zone (project/ anonymous)	Deviation (Col. 2 – Col. 4)
Project storage (P)					
EP	A	23.55%	A	22.93%	2.70%
RB	B	64.90%	B	65.80%	-1.37%
SP	C	5.17%	C	5.23%	-1.15%
ZD	D	6.38%	D	6.04%	5.61%
Total (P)	**E**	**61.33%**	**E**	**60.69%**	**0.00%**
Anonymous storage (A)					
ST-EP	A	18.86%	A	19.02%	-0.76%
ST-GB	B	9.02%	B	9.32%	-3.14%
ST-LL	C	72.12%	C	71.66%	0.74%
Total (A)	**D**	**38.67%**	**D**	**38.65%**	**0.10%**
Total (P+A)	**E**	**100.00%**	**E**	**100.00%**	**-1.04%**

A small deviation over zones can be observed. This is since, in the dataset, it is assumed that each SKU has a fixed storage zone, based on where it was stored most often. This was done to simplify the arrival of parts. In reality, the person who puts away the item chooses the storage zone. The absolute deviations are due to the filters used (see model contents above).

Next, the simulation test runs are compared to the dataset and the picked orders in the second half of 2020. To do so, the generated number of orders per day generated has been lowered to *xxx* per day. This is done since the average number of orders in the first half of 2020 was *xxx* whereas the average number of orders in the second half of 2020 was *xxx*. In the test runs, a small warm-up period of 60 days has been used (since in the first 45 days no items are picked yet) and three replications are used. The results are displayed below.

Table D 12: Simulation production run results, compared to the dataset and the items picked.

Storage Zone	Simulation model	Standard deviation	% of zone (project/ anonymous)	Deviation from dataset	Deviation from picked orders
Project storage (P)					
EP	A	A	22.69%	-1.35%	1.31%
RB	B	B	65.76%	-2.31%	-3.65%
SP	C	C	5.39%	-5.33%	-6.42%
ZD	D	D	6.15%	-4.09%	1.29%
Total (P)	**E**	**E**	**60.97%**	**-2.37%**	**-2.37%**
Anonymous storage (A)					
ST-EP	A	A	19.04%	-4.07%	-4.80%
ST-GB	B	B	9.38%	-4.58%	-7.58%
ST-LL	C	C	71.57%	-0.05%	-3.12%
Total (A)	**D**	**D**	**39.03%**	**-1.24%**	**-3.86%**
Total (P+A)	**E**	**E**	**100.00%**	**-1.93%**	**-2.95%**

Only (again) indicating a small deviation, which could be due to the stochasticity involved. As a final note, the dataset used should not be compared to Table 2-5 and Table 2-6 of Chapter 2. There are multiple reasons for this: 1. The current dataset is a half-year dataset of the second half of 2020 whereas the tables in Chapter 2 are based on the entire year 2020. 2. The number of orders per day in the second half-year is lower than in the first half-year of 2020 (see Table 2-7). 3. In the dataset, orders which contain items that go to locations that are not considered in this research are completely deleted, to not create orders that contain too few items. An example of such a location is the locker location zone in the RB zone. 4. In the simulation dataset, the anonymous picked lines are not double-counted for project picks. 5. In the dataset, only items that follow the 'official route' are considered. So, anonymous items that first went to the anonymous storage and after that to the project storage. The items that went directly from the anonymous storage to production or expedition are filtered out. This is done since backorders are not considered in the model. Also, if an item is broken or rejected, it can be that it was directly picked from the anonymous warehouse. Since the volume of items is an experimental factor anyhow and more items can be created by increasing the number of orders per day, multiple item arrival volumes can be tested in the model relatively easily. The most important thing is that the dataset represents the right order size together with the right allocation of items to zones.

These numbers are also showed to the warehouse manager and SCI manager. It is believed that the arrival numbers are sufficiently reliable to continue.

2. Utilization per zone

With the number of arrived lines validated, it is time to check the utilization levels acquired from the model. For the real-world system, only the utilization in the RB and EP zone is known. This is defined as the number of occupied locations divided by the total number of locations in that zone. This is measured weekly. However, comparing the data to this is problematic due to a couple of reasons:

- The locations in the warehouse have changed over time. For example, the EP zone had 2062 locations around July 2020, whereas there were 1630 locations at the start of 2021. Moreover, in Infor, some locations are still missing or are not updated (for example, a full pallet location has become a half pallet location), resulting in fewer locations. For the simulation model, the physical locations around March 2021 have been counted and used.

- As explained, an assumption is made for the item sizes. However, real item sizes can differ, resulting in different utilization levels.
- Certain incoming items do not follow the official routing as intended, for example, when there is a large urgency to get the items from the warehouse.
- Rescheduling of projects is not modeled.

However, to check the results from the model, the following four steps are conducted, for only the project storage. In these steps, Little's law is used (7).

$$L = \lambda * W \tag{7}$$

Where L is the average number of items in the system, λ = the average arrival rate of items into and out of the system, and W = the average time an item spends into the system.

1. Determine the simulation results

Based on three replications, an average run-time of 300 days and a warm-up period of 160 days (so a total run length of 460 days), the following results are obtained for the average utilization levels per zone:

Table D 13: Production run results: utilization levels per storage zone.

	RB	ST-GB	EP	ST-EP	SP-Floor	ZD-Floor	SP-Rack	ZD-Rack
Avg. Utilization	30.45%	13.34%	46.35%	44.72%	25.87%	51.12%	22.75%	19.87%
St. dev	0.74%	0.14%	0.91%	0.38%	0.93%	0.76%	0.36%	0.56%

2. Determine a lower bound for the simulation results

To determine a lower bound for the number of locations needed, the average item size in a zone ($ItemSize_z$) was multiplied by the average number of items in that zone ($\#Items_z$). Dividing this by the number of simulation days (360) yields the arrival rate of 'locations per day'. Then multiplying this by the sojourn time of items in a zone ($Sojourn\ time_z$) yields the average WIP (Little's Law). In formula form:

$$WIP_z = \frac{\#Items_z * ItemSize_z * Sojourn\ time_z}{360} \tag{8}$$

Where z ϵ {RB, ST-GB, ST-EP, EP, ST-LL, SP-Rack, SP-Floor, ZD-rack, ZD-rack}. The sojourn times differ for project items and anonymous items. The anonymous items are only present in the project storage after they are picked from the anonymous storage and have been put away in the project storage. This is done a few days in advance of the order pick date, resulting in a shorter sojourn time for these items. For each storage zone, the WIP is divided by the number of locations in that zone. However, for the RB zone, the WIP of the RB, ST-GB, and ST-LL zone should be added and, similarly, the WIP for the EP and ST-EP zone should be added to determine a lower bound for the utilization. This is a lower bound since the sizes of items are added up, whereas in reality items are also divided per order, resulting in more locations.

3. Determine an upper bound for the simulation results

To determine an upper bound for the simulation results, (9) is used for the WIP.

$$WIP_z = \frac{\#Items_z * Sojourn\ time_z}{360} \qquad (9)$$

Where the zones, number of items, and sojourn times are the same as in the calculation for the lower bound. These WIP levels are subsequently divided by the number of locations in that zone to determine an upper bound for the utilization. This is an upper bound since each item occupies one full location, whereas in reality multiple items are put together when they are from the same order.

4. Predict the utilization based on the dataset

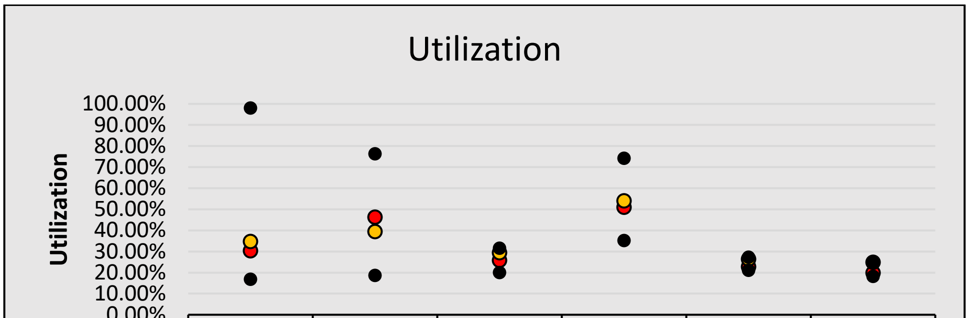
To predict the utilization based on the dataset, the number of items per zone (the zones *z* are the same zones as mentioned above) per order is counted ($IteminZone_z$) in the dataset used. This is subsequently multiplied by the average item size ($ItemSize_z$) in that zone. By eventually rounding this number per zone up, the number of locations per order *o* per zone *z* needed is obtained (10). This is summed per type of order (11) to acquire the number of locations per zone needed for all order types, indicated with *type* (production, warehouse, and sales orders). However, the dataset contains much more orders per type ($OrdersInDataset_{type}$) than arrive per day. Hence this is normalized to the number of orders per day ($Ordersperday_{type}$). This results in the number of needed storage locations per zone per day per type of order ($Locations_{type,z}$). Then by again using Little's Law, the WIP per zone is determined by multiplying this number with the sojourn time per zone per type of order. By eventually summing over the order types, the WIP per zone is obtained. (12). Dividing the WIP per zone by the number of locations per zone yields the expected utilization based on the dataset.

$$NeededLocations_{z,o} = \lceil IteminZone_{z,o} * ItemSize_{z,o} \rceil\ for\ each\ z\ and\ o \qquad (10)$$

$$Locations_{type,z} = (\sum\nolimits_o NeededLocations_{z,o}) * (\frac{\#OrdersPerDay_{type}}{OrdersInDataset_{type}})\ for\ each\ z\ and\ type \qquad (11)$$

$$WIP_z = \sum\nolimits_{type} Locations_{type,z} * Sojourntime_z\ for\ each\ z \qquad (12)$$

Again the WIP should be added for the RB, ST-GB, and ST-LL zones and the ST-EP and EP zones to acquire the right utilization levels for the RB and EP zone respectively. The results of steps one to four are compared below:



	RB	EP	SP floor	ZD floor	SP rack	ZD rack
Simulation	30.45%	46.35%	25.87%	51.12%	22.75%	19.87%
Prediction	34.82%	39.54%	29.55%	54.11%	26.47%	24.98%
LB	16.95%	18.67%	20.03%	35.29%	21.15%	18.29%
UB	98.15%	76.34%	31.69%	74.27%	27.42%	25.09%
Deviation	4.37%	-6.81%	3.68%	2.99%	3.73%	5.12%

Figure D 11: Comparison of the LB, UB, prediction, and simulation results for the utilization levels.

All zones are within the lower and upper bounds. However, these bounds do not provide much insight for the RB, EP, and ZD floor zones. The deviation between the expected (predicted) value and the simulation results, is also quite small. The biggest relative deviation can be observed for the ZD rack location and the EP zone. The ZD rack zone only has 72 locations, so this deviation only corresponds to 3.75 locations. However, in the EP zone, this deviation corresponds to 140 locations. This difference is observed since in the simulation model always first the half-pallet locations are filled if the item size is $\leq$ 0.5 EP, occupying more locations. This is not considered in the prediction.

When showing the utilization levels to the SCI manager and the warehouse manager, the utilization for the project-storage zones is considered realistic. Nevertheless, the utilization rates from the model in the anonymous storage are not an accurate representation of reality due to the following reasons (also see Section 5.5):

- The general validation issues like item sizes and changes in locations over the years.
- Maintenance in the model is continuously done instead of periodically (like in reality).
- Not all items currently present in the anonymous storage, are also present in the used dataset. Some items occupy a location for more than a year. This is considered by deleting the locations occupied by these items. However, it is believed that this is not completely accurate due to the reliability of the data. Hence, there are still some more locations occupied.
- As mentioned above, anonymous items come in together with multiple order quantities. The fact that they come in together has been simulated using the current approach. However, in reality, at times, multiple items remain in the warehouse, due to the fixed order quantities. These items will occupy space. How many items these exactly are, depends on the order quantities themselves. However, these quantities are also varying.

It is believed that modeling these things per anonymous SKU specific was too complex for the simulation model at hand. Moreover, would it be that relevant? The main point of interest is the number of locations the incoming items occupy using the one or the other storage policy. For all policies chosen, the anonymous storage remains per SKU. In addition, the incoming items remain the same for each scenario, with a fixed storage zone. Consequently, it is investigated what happens in each zone, instead of, for example, putting the ST-EP and EP zones together.

All in all, in consultation with the key stakeholders, it is agreed to continue with a more simplified approach of anonymous items and anonymous storage since it can still provide the right insights for the problem at hand. However, to prevent that popular items are stored in unfavorable locations, in the ST-EP zone, an ABC storage policy is used. This is also underlying the current dedicated storage. The lean lift has an infinite capacity in the model, hence no storage policy is implemented there.

Note that later on, a formally defined number of replications, different random number seeds, and a different warm-up period have been used to conduct experiments. This led to slightly different utilization levels.

3. Pick and put-away times

For the pick and put-away times, no data is present. So, the total pick and put-away times were shown to the SCI manager, warehouse manager, and all warehouse foremen and their assistants. These times were based on five replications, a run length of 600 days, and a warm-up period of 100 days. To properly compare this to the current situation, the number of orders per day has been increased by 69%. This is done since currently (June 2021) the warehouse processes 69% more orders than in 2020. At this moment, the warehouse has 7 FTE who are only putting away and picking items. The simulation runs resulted in the following pick and put-away times per day:

Table D 14: Total time per day needed for picking and putting away items.

	Time
Put-away (hour)	29.17
Pick (hour)	24.51
Total (hour)	**53.68**
FTE (100% utilization)	6.71
FTE (70% utilization)	9.59

"I think you are not far from reality."
– Warehouse outbound foreman

Putting away items takes more time than picking items, however, it is a bit unclear how much this should exactly be because:

1. Putting away takes more time since you have to visit multiple locations per route. Picking can just pick the project location (in the project storage).
2. Picking usually needs to walk further because put-away priorities make sure that putting away items is done close to the inbound department.
3. Picking is done across zones, whereas putting away is done per zone.
4. While picking, you are can carry more items since you are carrying multiple RBs, whereas the inbound department has to put away items in bins one by one.
5. The picker's capacity is not always utilized while picking due to the way trains are scheduled. Put away only starts when there are enough items to be put away or when it is the end of the day.

All things combined, it is believed that the put-away side should be the busiest. The division of time per day for putting away items (left) and picking them (right) per zone is displayed in Figure D 12.

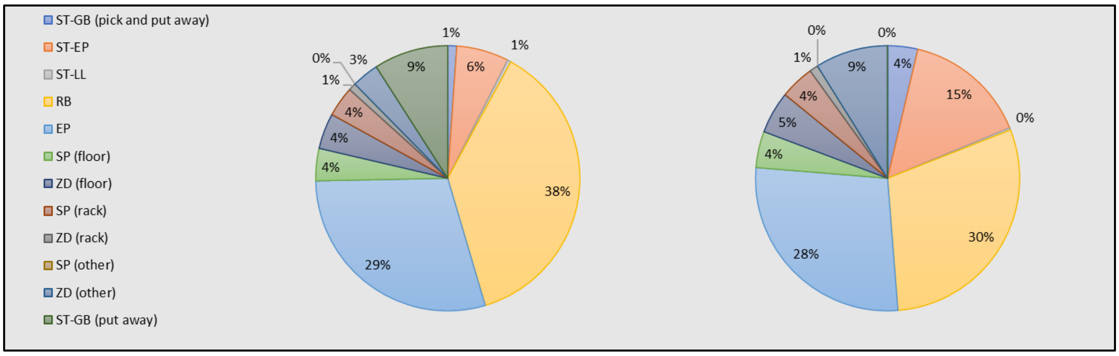


Figure D 12: Division of time per day for putting away items (left) and picking them (right) in/from each zone.

As expected by the warehouse foremen, most time is spent picking and putting away items in the RB and EP zone since most items go to that zone. Note that for the lean lift, only delivering items from and to the lean lift has been considered. The FTEs at the lean lift are beyond the scope of this research. Note, the ST-GB (put away) only includes putting away the RBs in the project zone.

To compare the outcomes of the model, multiple questions have been asked to the warehouse foremen. As a rule of thumb, the outbound department uses 1 FTE per *xxx* project item lines, and 1 FTE per *xxx* anonymous item lines. Note that the outbound department also puts away anonymous items in the storage zones. Unfortunately, the inbound department does not have a rule of thumb. However, assuming that this also holds for the inbound department (which is not completely accurate), Table D 15 is created.

Table D 15: The rule of thumb applied to the number of item lines picked and put away.

	Lines	FTE (rule of thumb)
Project (inbound + outbound)	A	A
Anonymous (inbound + outbound)	B	B
Total lines and FTE	**C**	**10.1**

"Those numbers do not sound crazy at all!" – Warehouse outbound foreman assistant

Which is close to the 9.59 FTE from the simulation model (5.71%). It is believed that this could be true for the current situation in the warehouse. However, the question arises: if the warehouse needs 10.1 FTE, why did they only have 7 FTE? Well, currently it is hard to get personnel for the warehouse. Therefore, not all work (as intended) is currently being done. Anonymous picks are done later than intended, warehouse support and foremen are helping in picking and putting away items, and even some trains are not leaving the warehouse on time.

Comparing this to the model, the model also needed 7 FTE to do all the work, namely 6.71 FTE. However, this is when order pickers would have utilization of 100%. Of course, this is unrealistic. When discussing with all the foremen about what this should be, the utilization level has been set to 70%. This is done because the order picker is also busy preparing its order picks, taking steel pallets, scanning, next to other tasks that are unrelated to work. Using this utilization level, the model indicates a need for 9.59 FTE.

> *"I am FTEs short for RB and EP put-aways"* – Warehouse outbound foreman assistant

Zooming in a bit closer, the model indicates a workload of 22.1 hours per day for putting away project items in the RB and EP zone. When using the utilization of 70% this would correspond to 3.9 FTE. This also underlines the quote mate by the warehouse foreman, who would like to have one or two FTE more, next to its current two FTE for putting away items in the RB and EP zone. The outbound department in the simulation model indicates a workload of 23.12 hours per day for picking items and putting away items in the anonymous zones. This corresponds to 4.13 FTE. This is a bit less than the outbound foreman assistant would expect. However, when, for example, the inbound department gets more FTE and finishes its work, it can also help the outbound and vice versa. The other 1.51 FTE needed to get to the total of 9.59 in Table D 15 is for putting away items in the SP and ZD zone.

> *"Ideally, I would have liked to have two FTE more, but at least one more would have been nice."* – Warehouse inbound foreman

Splitting these times out per item across zones, Table D 16 can be made.

Table D 16: Average time per item for picks and put-aways in seconds.

Average time per item (s)	Total put-away time (s)	Total pick time (s)	Total time (s)
ST-GB (anonymous put-away and pick)	70	57	**127**
ST-EP	317	113	**430**
RB	61	23	**84**
EP	90	71	**161**
SP floor	162	154	**316**
ZD floor	166	165	**331**
SP rack	148	141	**289**
ZD rack	238	231	**470**
ZD other	126	285	**411**
ST-GB (project put-away)	19	0	**19**

Put-aways and picks from the SP and ZD zones are longer since these are one by one. Bringing items to and getting items from SP and ZD floor locations almost takes an equal amount of time. This is slightly shorter for the SP floor since item handling is one by one for ZD items, and per location for SP items. The ZD rack items take more time to pick and put away since you need to travel vertically to put away items on the ZD rack locations. Comparing the RB and EP zone, the EP items take more time since you also need to travel a vertical distance. The pick time per item in the RB zone is low since you can pick full RBs (locations). For the same reason, ST-GB project put-aways are relatively short. Anonymous put-aways in the ST-GB and ST-EP zones are longer than in the RB and EP zones since you need to visit multiple locations when a location is full. All in all, pick time per item per zone is in line with expectations.

Lastly, the simulation output numbers have been compared to the literature of Tompkins et al. (2003). Their indication of the distribution of an order picker's time is displayed in Section 3.1.1. The distribution of an order picker's time in the simulation model is displayed in Figure D 13. This was obtained by dividing the travel, search, pick, and set-up by the total pick time for each zone and by weighing this with the time per zone and the total pick time. These numbers are also relatively close to each other.

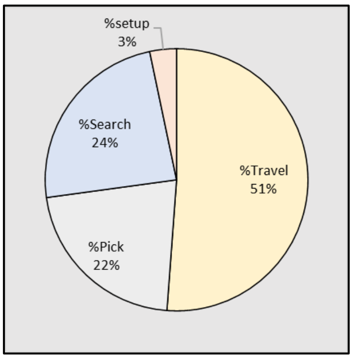


Figure D 13: Distribution of an order picker's time in the simulation model.

The put-away and travel times were difficult to get right in the simulation model, compared to reality. Especially since no data is present about this. Hence it also was a point of discussion in multiple validation meetings. Eventually, it is believed that with a utilization of 70%, the simulation model is sufficiently accurate to describe reality.

Appendix D.4 The number of replications

The number of replications is decided by estimation and using the sequential procedure, as described in Section 3.2.5. The relative error chosen is 0.05. So, the estimation of the relative error should be smaller than $\gamma' = \frac{\gamma}{1+\gamma} = \frac{0.05}{1.05} = 0.0476 \ldots \approx 0.048$. The chosen significance level has been set to α = 0.05. Then, by making *n*=10 runs, an estimation is made for the number of replications needed, to see if γ' is not chosen too small. For the estimation of the number of replications, again two utilization and two time measures are chosen. In this case, four different KPIs than for the warmup period are used. The sequential procedure is applied to the utilization in the RB zone, the utilization in the ST-EP zone, total put-away time per day, and dock-to-stock time. The estimated results did not result in an unrealistic number of replications (see below). Hence, it is decided to continue with the sequential procedure. For the sequential procedure, the same α and γ' are used. The total sequential procedure for each KPI is displayed below. The summarized results are displayed in Table D 17.

Table D 17: Nr. of replications needed according to the estimate and the sequential procedure.

	Utilization ST-EP	Utilization RB	Put-away time per day (hour)	Dock to stock time
Nr. of replications estimate	$\lceil 0.25 \rceil$=1	$\lceil 0.38 \rceil$=1	$\lceil 0.36 \rceil$=1	$\lceil 0.05 \rceil$=1
Nr. of replications sequential procedure	2	3	3	3

So, the maximum number of replications needed is 3, for the utilization in the RB and the put-away time per day (hour). However, since the sequential procedure has not been applied to each KPI and experimental setting, it is decided to use *n* = 5 replications. As Robinson (2014) advises, it is, in that case, good to overestimate the number of replications a little bit. Moreover, Law and McComas (1990) also advise suing at least 3 to 5 replications.

Below, the full sequential procedure and estimate are shown.

Table D 18: Sequential method applied to four KPIs, together with an estimate for the number of replications

Settings						
α	0.05	γ	0.025	$\gamma/1+\gamma$	0.02439	
Put-away time						
n	KPI	Average	Variance	*T*-value	Error	Estimate based on *n*=10
1	15.85					0.36
2	16.18	16.02	5.29E-02	12.71	0.129	
3	16.16	16.06	3.32E-02	4.30	0.028	
4	16.30	16.12	3.56E-02	3.18	0.019	
5	15.75	16.05	5.42E-02	2.78	0.018	
6	16.23	16.08	4.90E-02	2.57	0.014	
7	16.21	16.10	4.34E-02	2.45	0.012	
8	16.32	16.13	4.32E-02	2.36	0.011	
9	16.44	16.16	4.89E-02	2.31	0.011	
10	16.52	16.20	5.65E-02	2.26	0.010	
Dock-to-stock time						
n	KPI	Average	Variance	*T*-value	Error	Estimate based on *n*=10
1	2.88					0.05
2	2.86	2.87	3.27E-04	12.71	0.057	
3	2.88	2.88	2.15E-04	4.30	0.013	
4	2.86	2.87	2.20E-04	3.18	0.008	
5	2.90	2.88	2.94E-04	2.78	0.007	
6	2.89	2.88	2.59E-04	2.57	0.006	
7	2.87	2.88	2.23E-04	2.45	0.005	
8	2.87	2.88	1.95E-04	2.36	0.004	
9	2.86	2.88	1.96E-04	2.31	0.004	
10	2.90	2.88	2.45E-04	2.26	0.004	

Utilization RB						
n	KPI	Average	Variance	*T*-value	Error	Estimate based on *n*=10
1	0.31					0.38
2	0.31	0.31	1.50E-05	12.71	0.113	
3	0.31	0.31	1.17E-05	4.30	0.027	
4	0.32	0.31	1.69E-05	3.18	0.021	
5	0.31	0.31	2.07E-05	2.78	0.018	
6	0.32	0.31	1.94E-05	2.57	0.015	
7	0.32	0.31	1.84E-05	2.45	0.013	
8	0.32	0.31	1.74E-05	2.36	0.011	
9	0.32	0.31	1.88E-05	2.31	0.011	
10	0.32	0.31	2.20E-05	2.26	0.011	
Utilization ST-EP						
N	KPI	Average	Variance	*T*-value	Error	Estimate based on n=10
1	0.46					0.25
2	0.46	0.46	9.94E-07	12.71	0.020	
3	0.46	0.46	9.30E-06	4.30	0.017	
4	0.46	0.46	1.69E-05	3.18	0.014	
5	0.45	0.46	5.25E-05	2.78	0.020	
6	0.46	0.46	4.39E-05	2.57	0.015	
7	0.46	0.46	3.94E-05	2.45	0.013	
8	0.46	0.46	3.77E-05	2.36	0.011	
9	0.46	0.46	3.41E-05	2.31	0.010	
10	0.46	0.46	3.06E-05	2.26	0.009	

Appendix D.5 Distance grids

EP Zone

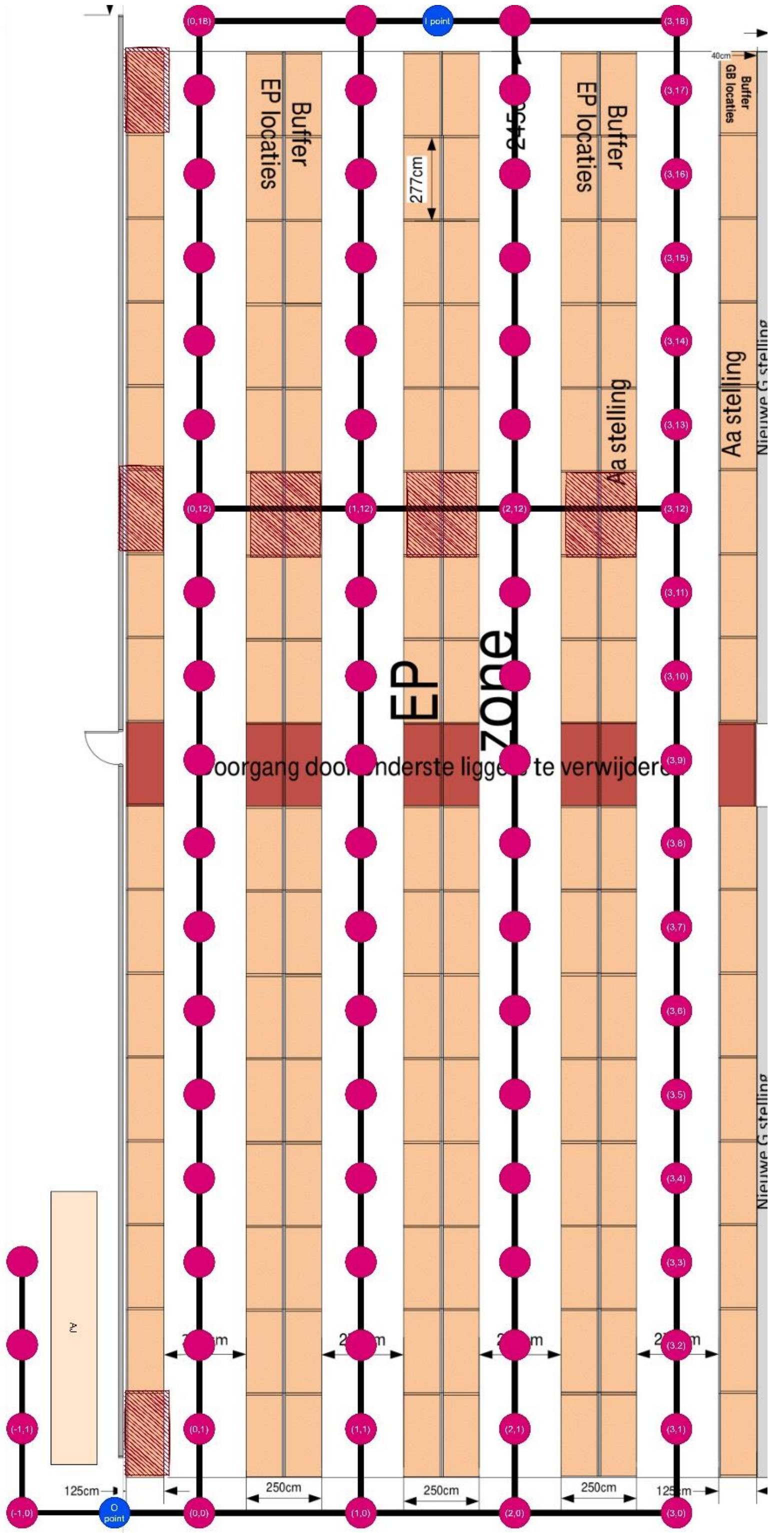


Figure D 14: Distance grid in the (ST-)EP zone.

RB Zone

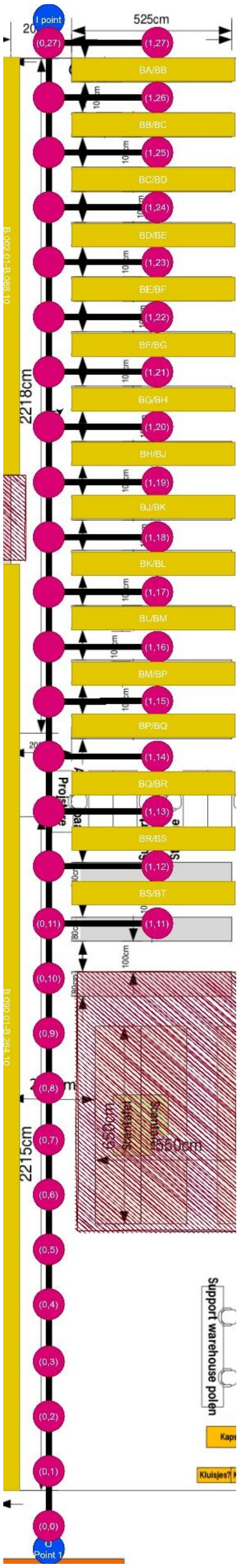


Figure D 15: Distance grid in the RB/ST-GB zones.

SP zone

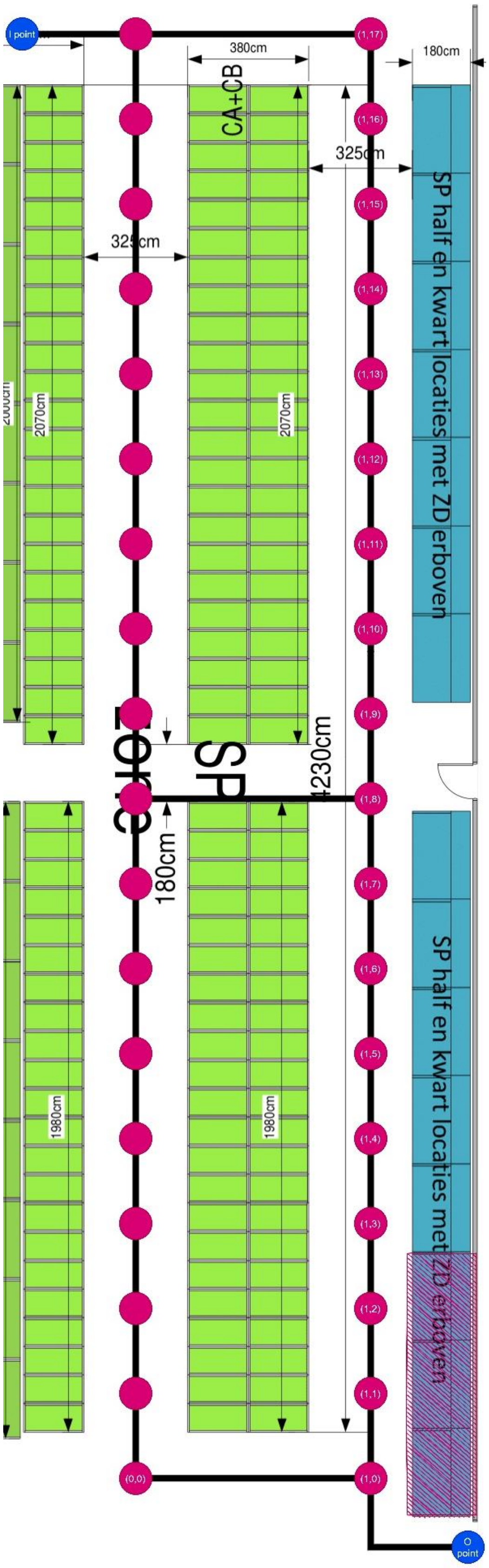


Figure D 16: Distance grid in the SP zone.

ZD zone

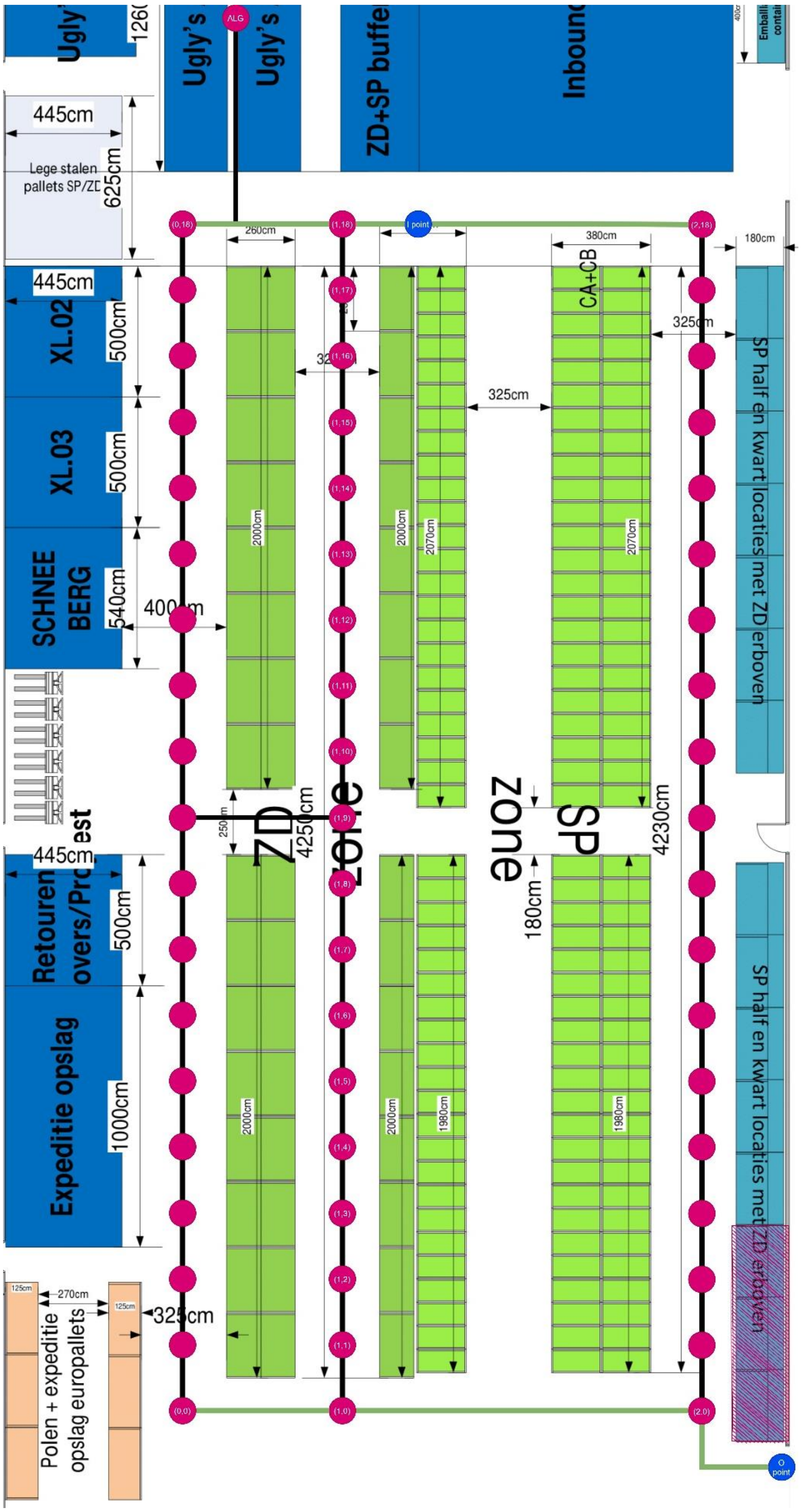


Figure D 17: Distance grid in the ZD zone.

Lean lift and the public warehouse

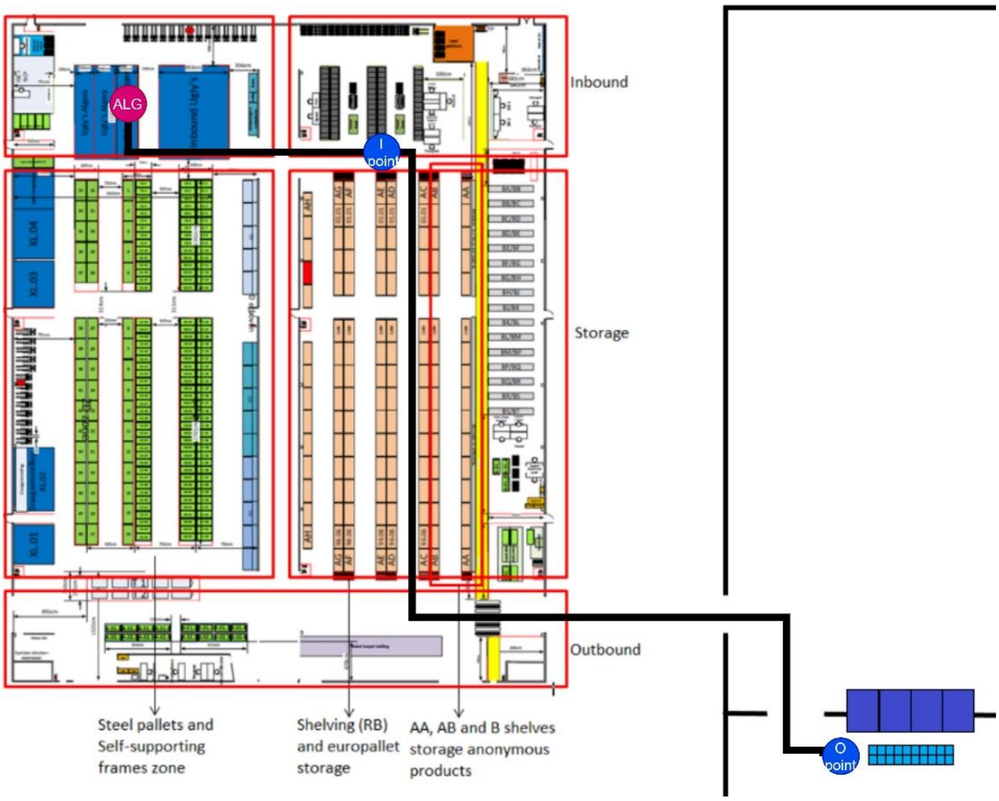


Figure D 18: Bringing items to the lean lift or the public warehouse.

Appendix D.6 Screenshots of the simulation model

This appendix shows some screenshots of the simulation model explained in Chapter 5. This is by no means a complete overview of all detail contained in the model. The purpose of this section is to indicate what the simulation model looks like.

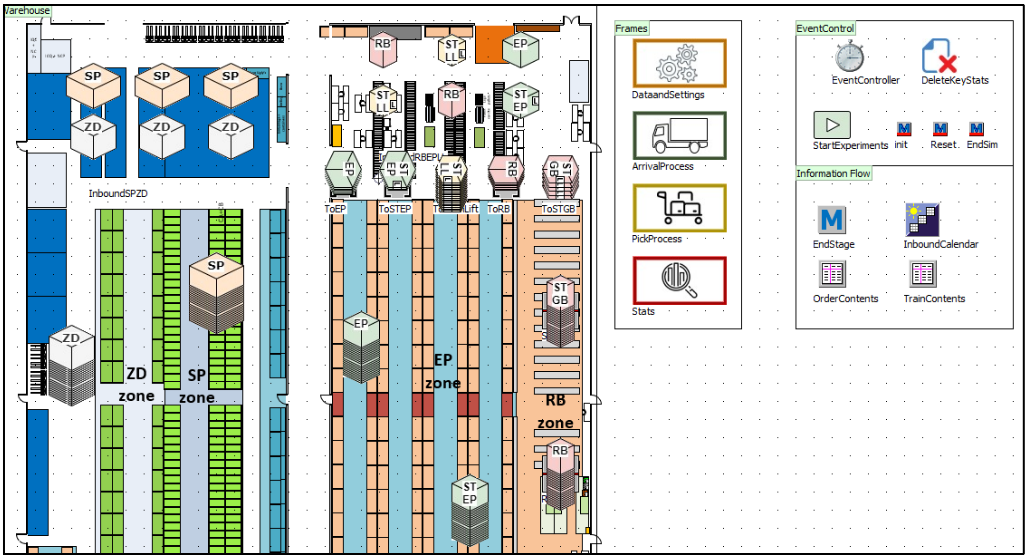


Figure D 19: Part of the mainframe of the simulation model.

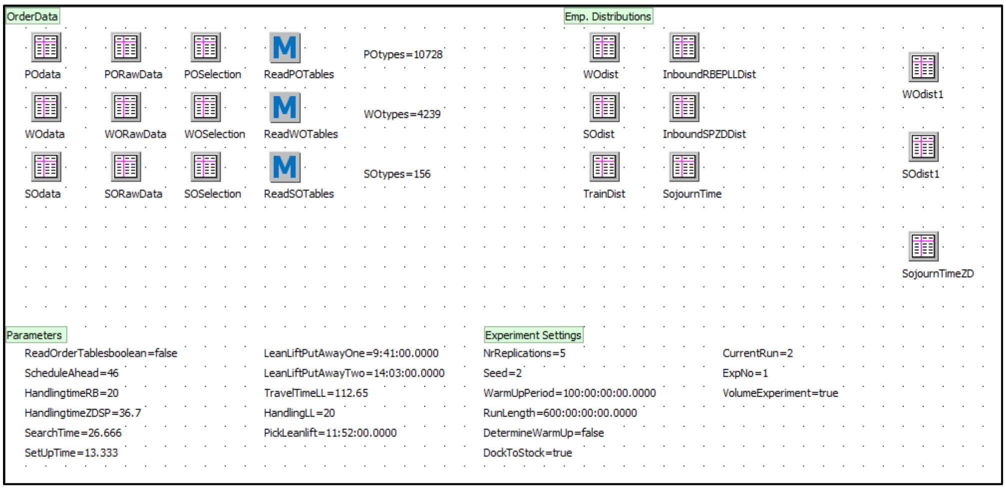


Figure D 20: The frame "DataandSettings".

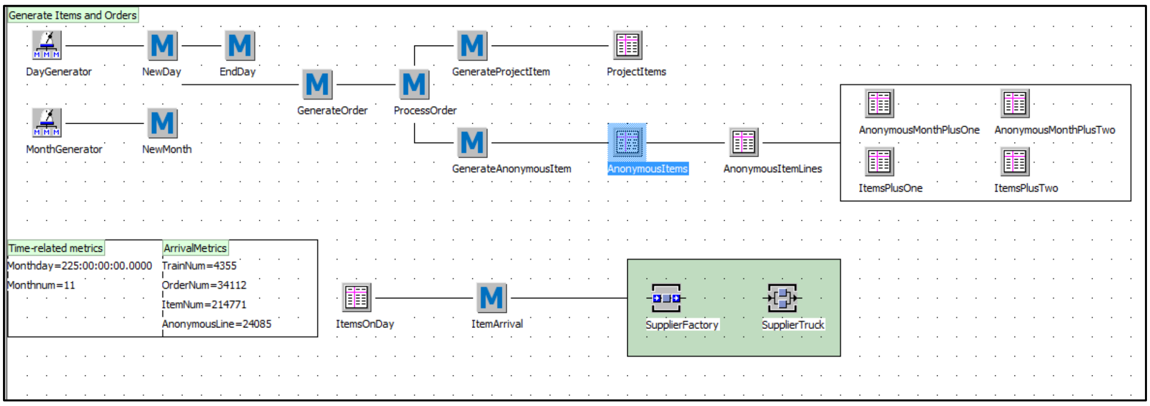


Figure D 21: The frame "ArrivalProcess".

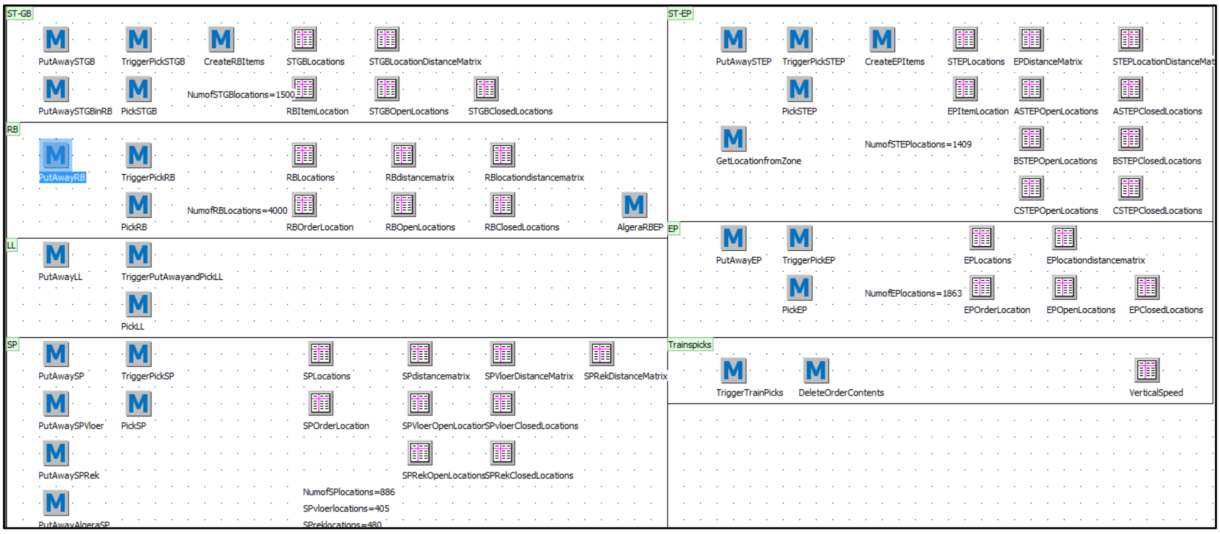


Figure D 22: A part of the frame "PickProcess".

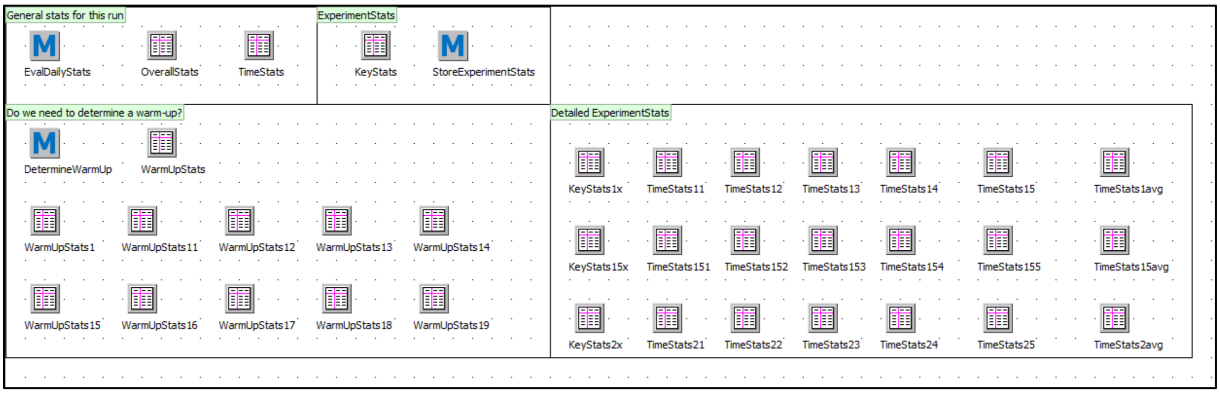


Figure D 23: The frame "Stats".

	string 0	string 1	table 2	real 3	boolean 4	integer 5	integer 6
string	Location code	Coordinate	Contents	Occupation	Full?	x coordinate	y coordinate
1	BA.01.01	(1,27)	Contents	0.67	false	1	27
2	BA.01.02	(1,27)	Contents	0.27	false	1	27
3	BA.01.03	(1,27)	Contents	0.78	false	1	27
4	BA.01.04	(1,27)	Contents	0.49	false	1	27
5	BA.01.05	(1,27)	Contents	0.08	false	1	27
6	BA.01.06	(1,27)	Contents	0.31	false	1	27
7	BA.01.07	(1,27)	Contents	0.41	false	1	27
8	BA.01.08	(1,27)	Contents	0.22	false	1	27
9	BA.01.09	(1,27)	Contents	0.99	true	1	27
10	BA.01.10	(1,27)	Contents	0.54	false	1	27
11	BA.02.01	(1,27)	Contents	0.49	false	1	27
12	BA.02.02	(1,27)	Contents	0.08	false	1	27
13	BA.02.03	(1,27)	Contents	0.80	false	1	27
14	BA.02.04	(1,27)	Contents	0.97	true	1	27
15	BA.02.05	(1,27)	Contents	0.75	false	1	27
16	BA.02.06	(1,27)	Contents	0.40	false	1	27
17	BA.02.07	(1,27)	Contents	0.70	false	1	27

Figure D 24: A table showing locations in the RB zone. The locations contain one or multiple items, displayed in a sub-table "Contents". The occupation shows how full the location is. The coordinates determine the position in the warehouse.

	time 0	table 1	table 2	table 3	table 4	table 5
string	MonthDay	Items	Trains	AnonymousRB	AnonymousEP	AnonymousLL
1	226:00:00:00.0000	Item arrival	Trains	AnonymousRB	AnonymousEP	AnonymousLL
2	227:00:00:00.0000	Item arrival	Trains	AnonymousRB	AnonymousEP	AnonymousLL
3	228:00:00:00.0000	Item arrival	Trains	AnonymousRB	AnonymousEP	AnonymousLL
4	229:00:00:00.0000	Item arrival	Trains	AnonymousRB	AnonymousEP	AnonymousLL
5	230:00:00:00.0000	Item arrival	Trains	AnonymousRB	AnonymousEP	AnonymousLL
6	231:00:00:00.0000	Item arrival	Trains	AnonymousRB	AnonymousEP	AnonymousLL
7	232:00:00:00.0000	Item arrival	Trains	AnonymousRB	AnonymousEP	AnonymousLL
8	233:00:00:00.0000	Item arrival	Trains	AnonymousRB	AnonymousEP	AnonymousLL
9	234:00:00:00.0000	Item arrival	Trains	AnonymousRB	AnonymousEP	AnonymousLL
10	235:00:00:00.0000	Item arrival	Trains	AnonymousRB	AnonymousEP	AnonymousLL
11	236:00:00:00.0000	Item arrival	Trains	AnonymousRB	AnonymousEP	AnonymousLL
12	237:00:00:00.0000	Item arrival	Trains	AnonymousRB	AnonymousEP	AnonymousLL
13	238:00:00:00.0000	Item arrival	Trains	AnonymousRB	AnonymousEP	AnonymousLL
14	239:00:00:00.0000	Item arrival	Trains	AnonymousRB	AnonymousEP	AnonymousLL
15	240:00:00:00.0000	Item arrival	Trains	AnonymousRB	AnonymousEP	AnonymousLL
16	241:00:00:00.0000	Item arrival	Trains	AnonymousRB	AnonymousEP	AnonymousLL
17	242:00:00:00.0000	Item arrival	Trains	AnonymousRB	AnonymousEP	AnonymousLL
18	243:00:00:00.0000	Item arrival	Trains	AnonymousRB	AnonymousEP	AnonymousLL
19	244:00:00:00.0000	Item arrival	Trains	AnonymousRB	AnonymousEP	AnonymousLL

Figure D 25: This table shows all things that need to happen on a day: the items that need to arrive, the trains that need to be picked, and the anonymous items that need to be picked. Each of these things contains sub-tables providing information about which items exactly need to be picked or should arrive.

	string 0	table 1	table 2	table 3	table 4	table 5	table 6	table 7
string	Order	ST-GB	ST-EP	ST-LL	RB	EP	SP	ZD
4884	31895			Order-ST-LL-31895-Contents	Order-RB-31895-Contents		Order-SP-31895-Contents	
4885	31896	Order-ST-GB-31896-Contents	Order-ST-EP-31896-Contents	Order-ST-LL-31896-Contents	Order-RB-31896-Contents	Order-EP-31896-Contents		Order-ZD-31896-Contents
4886	31897		Order-ST-EP-31897-Contents					
4887	31898		Order-ST-EP-31898-Contents	Order-ST-LL-31898-Contents	Order-RB-31898-Contents	Order-EP-31898-Contents	Order-SP-31898-Contents	
4888	31899					Order-EP-31899-Contents		
4889	31900				Order-RB-31900-Contents			
4890	31901		Order-ST-EP-31901-Contents					
4891	31902				Order-RB-31902-Contents	Order-EP-31902-Contents		
4892	31903			Order-ST-LL-31903-Contents	Order-RB-31903-Contents	Order-EP-31903-Contents		
4893	31904				Order-RB-31904-Contents			
4894	31905			Order-ST-LL-31905-Contents	Order-RB-31905-Contents	Order-EP-31905-Contents		
4895	31906				Order-RB-31906-Contents			
4896	31907				Order-RB-31907-Contents			
4897	31908					Order-EP-31908-Contents		
4898	31909		Order-ST-EP-31909-Contents					
4899	31910	Order-ST-GB-31910-Contents	Order-ST-EP-31910-Contents	Order-ST-LL-31910-Contents	Order-RB-31910-Contents			
4900	31911			Order-ST-LL-31911-Contents		Order-EP-31911-Contents	Order-SP-31911-Contents	Order-ZD-31911-Contents
4901	31912		Order-ST-EP-31912-Contents	Order-ST-LL-31912-Contents	Order-RB-31912-Contents	Order-EP-31912-Contents	Order-SP-31912-Contents	
4902	31913					Order-EP-31913-Contents		
4903	31914	Order-ST-GB-31914-Contents	Order-ST-EP-31914-Contents	Order-ST-LL-31914-Contents	Order-RB-31914-Contents	Order-EP-31914-Contents	Order-SP-31914-Contents	Order-ZD-31914-Contents
4904	31915		Order-ST-EP-31915-Contents		Order-RB-31915-Contents			
4905	31916			Order-ST-LL-31916-Contents	Order-RB-31916-Contents			

Figure D 26: A table showing the contents of an order. The table shows exactly per order which items it contains, per zone.

	string 0	real 19	real 20	real 21	real 22	real 23	real 24	real 25
string	Coordinate	(0,18)	(0,19)	(0,20)	(0,21)	(0,22)	(0,23)	(0,24)
26	(0,25)	17.5	15	12.5	10	7.5	5	2.5
27	(0,26)	20	17.5	15	12.5	10	7.5	5
28	(0,27)	22.5	20	17.5	15	12.5	10	7.5
29	(1,11)	22.9375	25.4375	27.9375	30.4375	32.9375	35.4375	37.9375
30	(1,12)	20.4375	22.9375	25.4375	27.9375	30.4375	32.9375	35.4375
31	(1,13)	17.9375	20.4375	22.9375	25.4375	27.9375	30.4375	32.9375
32	(1,14)	15.4375	17.9375	20.4375	22.9375	25.4375	27.9375	30.4375
33	(1,15)	12.9375	15.4375	17.9375	20.4375	22.9375	25.4375	27.9375
34	(1,16)	10.4375	12.9375	15.4375	17.9375	20.4375	22.9375	25.4375
35	(1,17)	7.9375	10.4375	12.9375	15.4375	17.9375	20.4375	22.9375
36	(1,18)	5.4375	7.9375	10.4375	12.9375	15.4375	17.9375	20.4375
37	(1,19)	7.9375	5.4375	7.9375	10.4375	12.9375	15.4375	17.9375
38	(1,20)	10.4375	7.9375	5.4375	7.9375	10.4375	12.9375	15.4375
39	(1,21)	12.9375	10.4375	7.9375	5.4375	7.9375	10.4375	12.9375
40	(1,22)	15.4375	12.9375	10.4375	7.9375	5.4375	7.9375	10.4375
41	(1,23)	17.9375	15.4375	12.9375	10.4375	7.9375	5.4375	7.9375
42	(1,24)	20.4375	17.9375	15.4375	12.9375	10.4375	7.9375	5.4375
43	(1,25)	22.9375	20.4375	17.9375	15.4375	12.9375	10.4375	7.9375
44	(1,26)	25.4375	22.9375	20.4375	17.9375	15.4375	12.9375	10.4375
45	(1,27)	27.9375	25.4375	22.9375	20.4375	17.9375	15.4375	12.9375
46	(I point)	22.5	20	17.5	15	12.5	10	7.5

Figure D 27: Part of a distance matrix used in the RB zone. It shows the time needed to walk from the one coordinate to the other.

Appendix E Simulation results

This appendix shows the obtained simulation results.

Appendix E.1 Intervention 1: Doing anonymous picks simultaneously

Utilization levels

Number of orders x 1

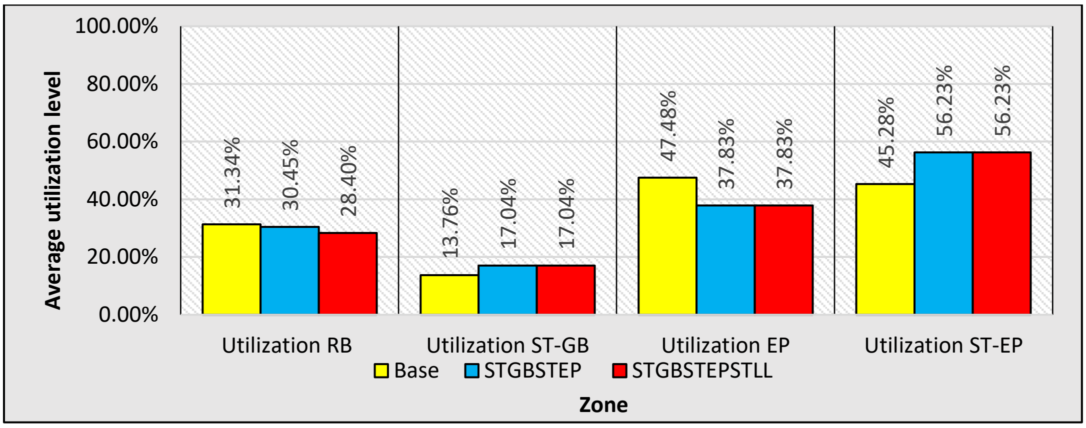


Figure E 1: Average utilization levels for the current situation and when anonymous items are picked simultaneously.

Table E 1: Average number of items not stored in this scenario.

	ST-GB Not Stored	ST-EP Not Stored	RB Not Stored	EP Not Stored
Base	0.00	0.00	0.00	0.00
STGBSTEP	0.00	0.00	0.00	0.00
STGBSTEPSTLL	0.00	0.00	0.00	0.00

Table E 2: Average and standard deviation of the utilization levels for the current situation and when anonymous items are picked simultaneously (1).

	Utilization RB		Utilization ST-GB		Utilization EP		Utilization ST-EP	
	Avg	Stdev	Avg	Stdev	Avg	Stdev	Avg	Stdev
Base	31.34%	0.64%	13.76%	0.26%	47.48%	0.69%	45.28%	0.64%
STGBSTEP	30.45%	0.63%	17.04%	0.31%	37.83%	0.60%	56.23%	0.72%
STGBSTEP STLL	28.40%	0.57%	17.04%	0.31%	37.83%	0.60%	56.23%	0.72%

Number of orders x 1.5

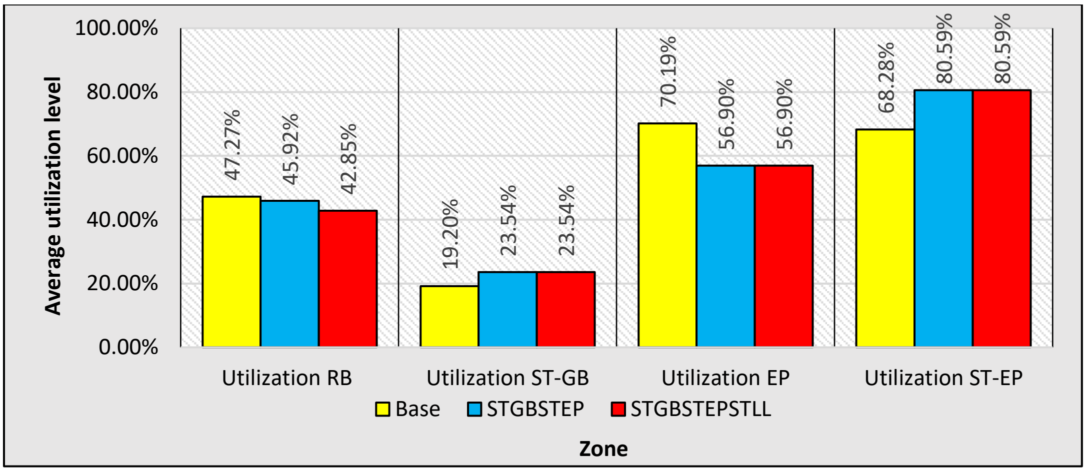


Figure E 2: Average utilization levels for the current situation and when anonymous items are picked simultaneously (1.5).

Table E 3: Average number of items not stored in this scenario (1.5).

	ST-GB Not Stored	ST-EP Not Stored	RB Not Stored	EP Not Stored
Base	0.00	0.00	0.00	26.00
STGBSTEP	0.00	657.40	0.00	0.00
STGBSTEPSTLL	0.00	657.40	0.00	0.00

Table E 4: Average and standard deviation of the utilization levels for the current situation and when anonymous items are picked simultaneously (1.5).

	Utilization RB		Utilization ST-GB		Utilization EP		Utilization ST-EP	
	Avg	Stdev	Avg	Stdev	Avg	Stdev	Avg	Stdev
Base	47.27%	0.84%	19.20%	0.29%	70.19%	1.29%	68.28%	1.27%
STGBSTEP	45.92%	0.81%	23.54%	0.34%	56.90%	1.21%	80.59%	1.09%
STGBSTEP STLL	42.85%	0.76%	23.54%	0.34%	56.90%	1.21%	80.59%	1.09%

Number of orders x 2

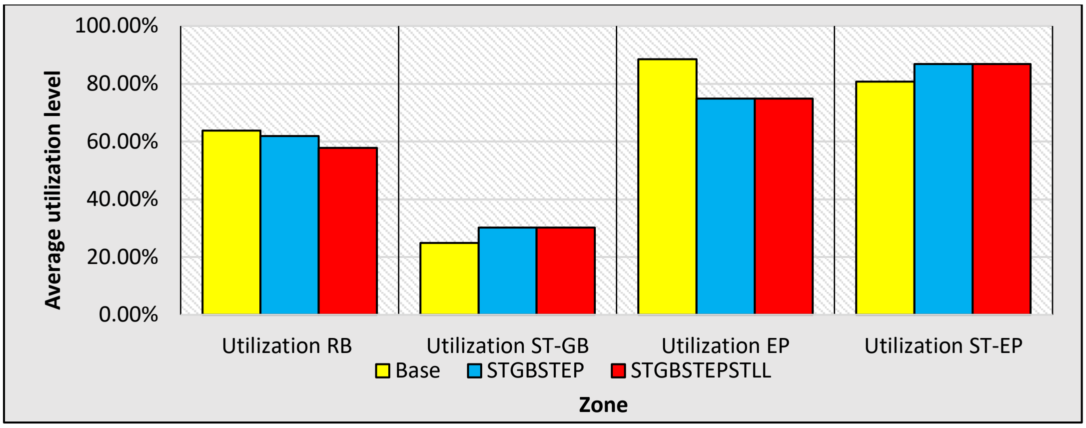


Figure E 3: Average utilization levels for the current situation and when anonymous items are picked simultaneously (2).

Table E 5: Average number of items not stored in this scenario (2).

	ST-GB Not Stored	ST-EP Not Stored	RB Not Stored	EP Not Stored
Base	0.00	4967.40	0.00	5857.40
STGBSTEP	0.00	14670.40	0.00	12.20
STGBSTEPSTLL	0.00	14670.40	0.00	12.20

Table E 6: Average and standard deviation of the utilization levels for the current situation and when anonymous items are picked simultaneously (2).

	Utilization RB		Utilization ST-GB		Utilization EP		Utilization ST-EP	
	Avg	Stdev	Avg	Stdev	Avg	Stdev	Avg	Stdev
Base	63.78%	1.47%	24.86%	0.60%	88.48%	1.18%	80.70%	0.40%
STGBSTEP	61.95%	1.42%	30.23%	0.66%	74.90%	1.49%	86.80%	0.26%
STGBSTEP STLL	57.77%	1.32%	30.23%	0.66%	74.90%	1.49%	86.80%	0.26%

Time

Table E 7: Averages and standard deviation of put away and pick times.

Scenario	Total put-away time per day (h)		Total pick time per day (h)		FTE (0.7)		Time to pick one train (min)	
Volume x 1	**Avg**	**Stdev.**	**Avg**	**Stdev.**	**Avg**	**Stdev.**	**Avg**	**Stdev.**
BaseCase (A)	16.16	0.35	14.00	0.28	5.38	0.11	35.89	0.27
STGBSTEP (B)	14.46	0.32	15.07	0.32	5.27	0.11	46.82	0.37
STGBSTEPSTLL (C)	13.28	0.29	13.02	0.27	4.70	0.10	40.42	0.30
A-B	1.70		-1.07		0.11		-10.93	
A-C	2.87		0.98		0.69		-4.53	
Volume x 1.5								
BaseCase (A)	25.54	0.54	21.53	0.43	8.41	0.17	36.76	0.22
STGBSTEP (B)	22.44	0.426365	22.92	0.42	8.10	0.15	47.99	0.23
STGBSTEPSTLL (C)	20.60	0.40	19.81	0.36	7.22	0.14	41.47	0.20
A-B	3.10		-1.38		0.31		-11.23	
A-C	4.94		1.72		1.19		-4.71	
Volume x 2								
BaseCase (A)	35.95	0.92	30.47	0.80	11.86	0.31	38.13	0.49
STGBSTEP (B)	30.99	0.84	31.59	0.80	11.17	0.29	49.06	0.61
STGBSTEPSTLL (C)	28.43	0.78	27.39	0.70	9.97	0.26	42.52	0.53
A-B	4.96		-1.12		0.69		-10.93	
A-C	7.52		3.09		1.89		-4.39	

Appendix E.2 Intervention 2: Storing per SKU

Ratios

Table E 8: Ratios that could explain why utilization levels increase when storing per SKU.

Zone	SKUs / # Items	Average Size (location fraction)	SKUs / # locations
EP	0.32	0.25	2.22
RB	0.25	0.19	2.36
SP	0.26	0.70	0.85
ST-EP	0.10	0.24	0.49
ST-GB	0.18	0.17	0.39
ZD	0.35	0.36	4.93

Utilization levels for multiple volumes

Utilization levels

Table E 9: Average and standard deviations of utilization levels of the current scenario and when storing per SKU, for different volumes.

Volume x1	RB	ST-GB	EP	ST-EP	SP floor	ZD floor	SP rack	ZD rack
Base (avg.)	31.34%	13.76%	47.48%	45.28%	26.61%	52.50%	23.37%	20.07%
Base (st. dev.)	0.64%	0.26%	0.69%	0.64%	0.85%	1.03%	0.74%	1.32%
Per SKU (avg.)	53.34%	17.04%	47.93%	56.23%	27.03%	59.00%	23.84%	20.41%
Per SKU (st. dev.)	1.02%	0.31%	0.79%	0.72%	0.86%	1.19%	0.80%	1.23%
Volume x 1.5	**RB**	**ST-GB**	**EP**	**ST-EP**	**SP floor**	**ZD floor**	**SP rack**	**ZD rack**
Base (avg.)	47.27%	19.20%	70.19%	68.28%	39.79%	77.27%	35.30%	29.62%
Base (st. dev.)	0.84%	0.29%	1.29%	1.27%	0.93%	1.48%	0.38%	0.97%
Per SKU (avg.)	73.39%	23.54%	69.78%	80.59%	39.94%	82.70%	35.85%	29.65%
Per item (st. dev.)	1.00%	0.34%	1.45%	1.09%	0.86%	1.22%	0.37%	0.92%
Volume x 2	**RB**	**ST-GB**	**EP**	**ST-EP**	**SP floor**	**ZD floor**	**SP rack**	**ZD rack**
Base (avg.)	63.78%	24.86%	88.48%	80.70%	53.90%	92.30%	47.41%	40.48%
Base (st. dev.)	1.47%	0.60%	1.18%	0.40%	1.05%	0.97%	1.48%	0.43%
Per SKU (avg.)	90.11%	30.23%	88.75%	86.80%	53.69%	94.11%	47.87%	39.68%
Per item (st. dev.)	1.29%	0.66%	1.24%	0.26%	1.03%	0.78%	1.42%	0.44%

Items not stored per zone

Table E 10: Average and standard deviations of items not stored for the current scenario and when storing per SKU, for different volumes.

Zone	ST-GB	ST-EP	RB	EP	SP floor	ZD floor	SP rack	ZD rack	SP other	ZD other	ST-GB2	Total
Volume x1												
Base (avg.)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Base (st. dev.)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Per SKU (avg.)	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
Per SKU (st. dev.)	0.00	0.00	0.00	0.00	0.00	1.41	0.00	0.00	0.00	0.00	0.00	1.41
Volume x 1.5												
Base (avg.)	0.00	0.00	0.00	26.00	0.00	220.40	0.00	0.00	0.00	0.00	0.00	246.40
Base (st. dev.)	0.00	0.00	0.00	35.78	0.00	86.13	0.00	0.00	0.00	0.00	0.00	120.78
Per SKU (avg.)	0.00	657.40	37.20	74.20	0.00	524.00	0.00	0.00	0.00	0.00	0.00	1292.80
Per SKU (st. dev.)	0.00	254.98	51.11	29.30	0.00	86.67	0.00	0.00	0.00	0.00	0.00	333.74
Volume x 2												
Base (avg.)	0.00	4967.40	0.00	5857.40	0.00	2602.60	0.00	0.00	0.00	0.00	0.00	13427.40
Base (st. dev.)	0.00	1244.41	0.00	1621.38	0.00	449.35	0.00	0.00	0.00	0.00	0.00	3257.78
Per SKU (avg.)	0.00	14670.40	6493.80	4075.60	0.00	3407.00	0.00	0.00	0.00	0.00	0.00	28646.80
Per SKU (st. dev.)	0.00	1881.53	2397.71	1205.12	0.00	477.95	0.00	0.00	0.00	0.00	0.00	5910.94

Average locations needed

Table E 11: Average of locations needed for the current scenario and when storing per SKU, for different volumes (Item scenario – current scenario).

Per SKU - Base	RB	ST-GB	EP	ST-EP	SP floor	ZD floor	SP rack	ZD rack
100	879.90	49.24	8.33	154.20	1.73	10.91	2.26	0.25
150	1044.84	65.02	-7.64	173.38	0.62	9.13	2.63	0.02
200	1053.18	80.58	4.91	85.96	-0.85	3.04	2.24	-0.58

Time for multiple volumes

Table E 12: Average and standard deviations of several time measures for the current scenario and when storing per SKU, for different volumes.

Scenario	Total put-away time per day (h)		Total pick time per day (h)		FTE (0.7)		Time to pick one train (min)	
Volume x 1	**Avg**	**Stdev.**	**Avg**	**Stdev.**	**Avg**	**Stdev.**	**Avg**	**Stdev.**
Base (A)	16.16	0.35	14.00	0.28	5.38	0.11	35.89	0.27
Per SKU (B)	14.53	0.32	17.16	0.37	5.66	0.12	53.36	0.45
A-B	1.63		-3.17		-0.28		-17.47	
Volume x 1.5								
Base (A)	25.54	0.54	21.53	0.43	8.41	0.17	36.76	0.22
Per SKU (B)	22.62	0.44	26.14	0.47	8.71	0.16	54.77	0.23
A-B	2.92		-4.61		-0.30		-18.01	
Volume x 2								
Base (A)	35.95	0.92	30.47	0.80	11.86	0.31	38.13	0.49
Per SKU (B)	30.49	0.73	35.75	0.97	11.83	0.30	55.53	0.69
A-B	5.46		-5.28		0.03		-17.41	

Per zone

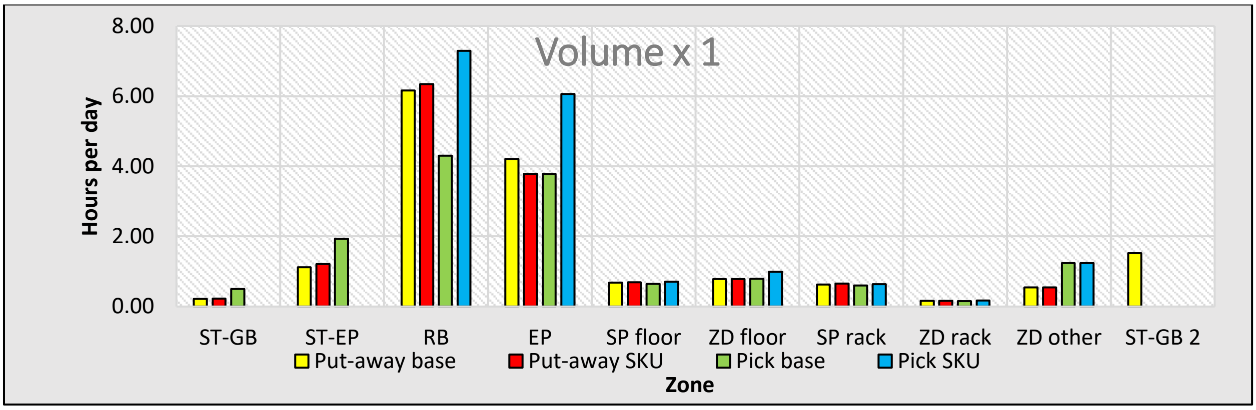


Figure E 4: Average hours to put away and pick items when storing per SKU and in the current scenario, per zone (volume = 100%).

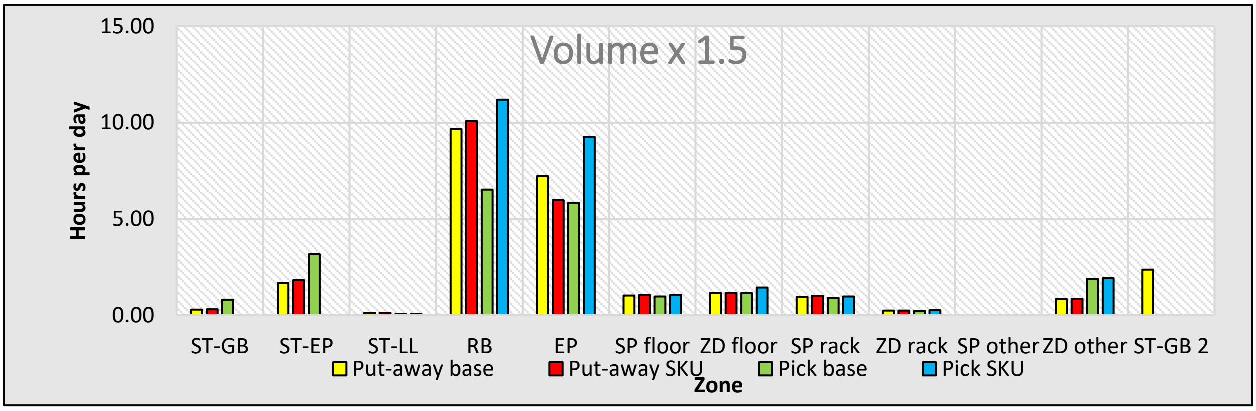


Figure E 5: Average hours to put away and pick items when storing per SKU and in the current scenario, per zone (volume = 150%).

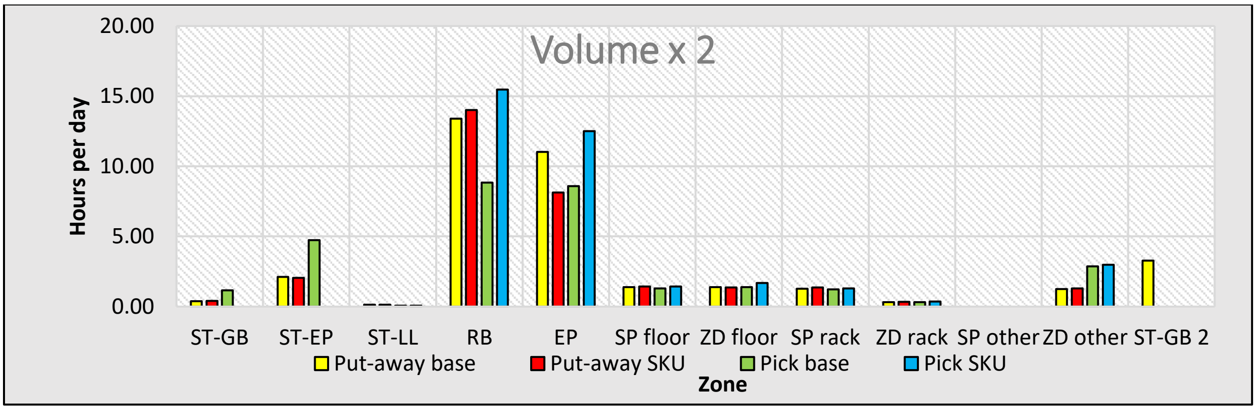


Figure E 6: Average hours to put away and pick items when storing per SKU and in the current scenario, per zone (volume = 200%).

More SKU types (volume x 1.5)

Note that in this scenario, different random number streams as before are used, resulting in slightly different values for different KPIs.

Average utilization levels base scenario

Table E 13: Average utilization levels when less/more SKU types come into the VMI warehouse (current scenario).

	Utilization RB	Utilization ST-GB	Utilization EP	Utilization ST-EP	Utilization SP floor	Utilization ZD floor	Utilization SP Rack	Utilization ZD rack
-0.1	47.19%	18.61%	70.10%	67.40%	39.61%	78.10%	35.33%	30.19%
-0.05	47.06%	18.85%	69.99%	67.67%	39.60%	77.95%	35.34%	30.18%
-0.03	47.01%	18.96%	69.94%	67.72%	39.63%	77.81%	35.35%	30.27%
0	46.95%	19.10%	69.85%	67.81%	39.64%	77.67%	35.31%	30.23%
0.03	46.95%	19.47%	69.86%	67.93%	39.64%	77.70%	35.33%	30.19%
0.05	46.95%	19.69%	69.86%	68.00%	39.65%	77.72%	35.34%	30.24%
0.1	46.94%	20.20%	69.84%	67.92%	39.64%	77.68%	35.35%	30.23%

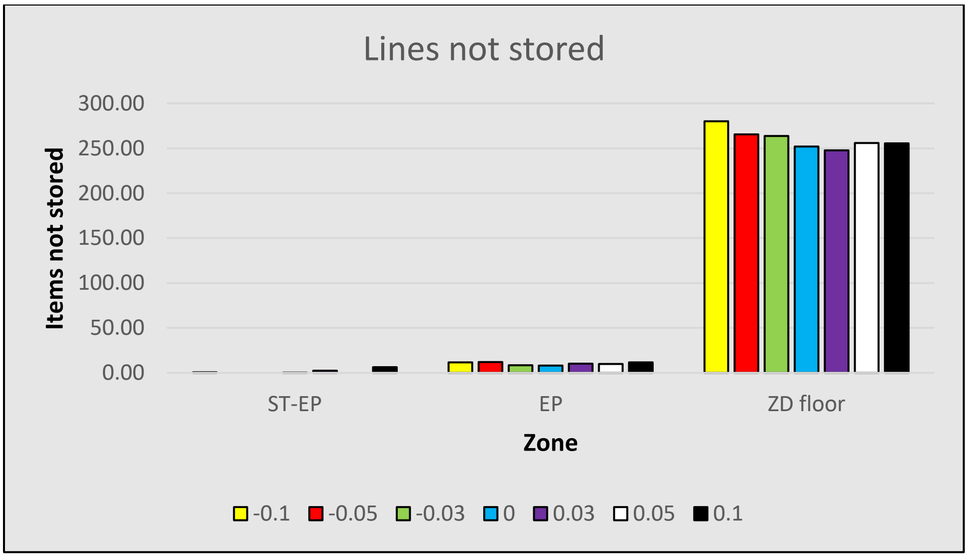


Figure E 7: Average items not stored when less/more SKU types come into the VMI warehouse (current scenario).

Average time measures base scenario

Table E 14: Average time measures when less/more SKU types come into the VMI warehouse (current scenario).

% SKUs	Total put away time per day (h)	Total pick time per day (h)	FTE (0.7)	Time to pick one train (min)
-0.1	25.35	21.36	8.34	36.87
-0.05	25.33	21.38	8.34	36.80
-0.03	25.32	21.41	8.34	36.77
0	25.31	21.41	8.34	36.72
0.03	25.38	21.44	8.36	36.73
0.05	25.43	21.46	8.37	36.73
0.1	25.50	21.50	8.39	36.73

Average utilization levels storing per SKU

Table E 15: Average utilization levels when less/more SKU types come into the VMI warehouse (storing per SKU).

	Utilization RB	Utilization ST-GB	Utilization EP	Utilization ST-EP	Utilization SP floor	Utilization ZD floor	Utilization SP Rack	Utilization ZD rack
-0.1	70.13%	22.85%	67.55%	80.03%	39.52%	82.20%	35.72%	29.91%
-0.05	71.50%	23.15%	68.44%	80.28%	39.66%	82.59%	35.81%	30.09%
-0.03	72.03%	23.26%	68.82%	80.35%	39.72%	82.84%	35.86%	30.25%
0	72.80%	23.41%	69.32%	80.42%	39.81%	83.04%	35.89%	30.26%
0.03	74.39%	24.08%	69.84%	81.05%	39.93%	83.36%	35.97%	30.34%
0.05	75.36%	24.45%	70.12%	81.33%	39.99%	83.50%	36.00%	30.45%
0.1	77.46%	25.20%	70.65%	81.72%	40.13%	83.97%	36.04%	30.60%

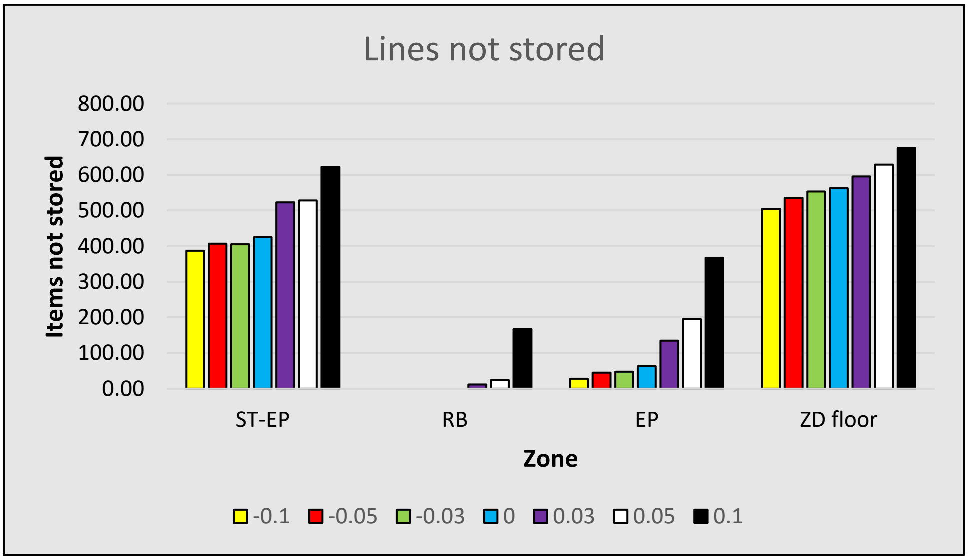


Figure E 8: Average items not stored when less/more SKU types come into the VMI warehouse (storing per SKU).

Average time measures storing per SKU scenario

Table E 16: Average time measures when less/more SKU types come into the VMI warehouse (storing per SKU).

% SKUs	Total put away time per day (h)	Total pick time per day (h)	FTE (0.7)	Time to pick one train (min)
-0.1	22.45	25.29	8.52	53.19
-0.05	22.45	25.63	8.59	53.92
-0.03	22.45	25.78	8.61	54.23
0	22.45	25.98	8.65	54.66
0.03	22.53	26.09	8.68	54.87
0.05	22.58	26.14	8.70	54.99
0.1	22.64	26.27	8.74	55.27

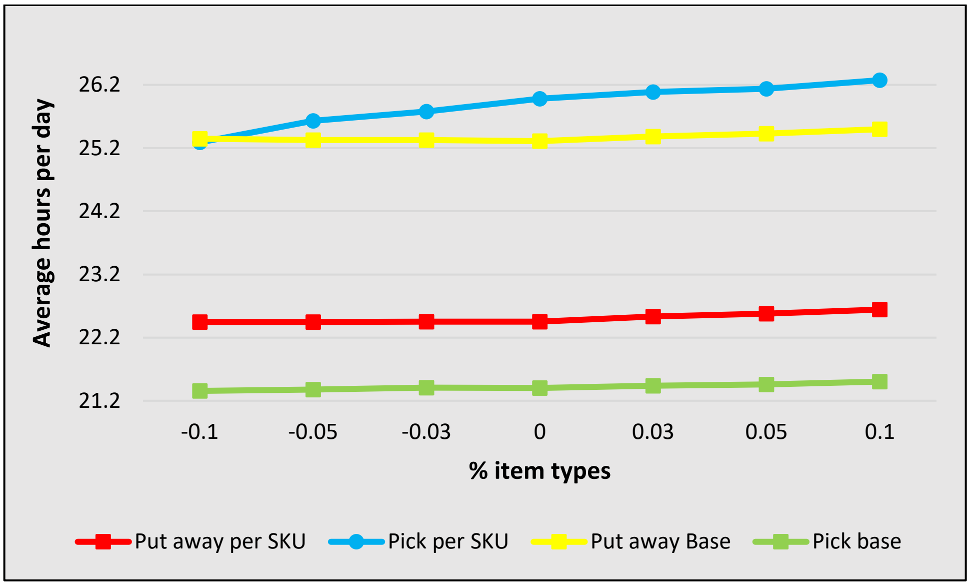


Figure E 9: Comparison of pick and put away times when more/less SKU types come into the VMI warehouse for both the current scenario and when storing per SKU.

Appendix E.3 Intervention 3: Storage per train

Utilization levels

Table E 17: Average and standard deviations of utilization levels of the current scenario, when storing per SKU, and storing per train, for different volumes.

Volume x1	**RB**	**ST-GB**	**EP**	**ST-EP**	**SP floor**	**ZD floor**	**SP rack**	**ZD rack**
Base (avg.)	31.34%	13.76%	47.48%	45.28%	26.61%	52.50%	23.37%	20.07%
Base (st. dev.)	0.64%	0.26%	0.69%	0.64%	0.85%	1.03%	0.74%	1.32%
Per SKU (avg.)	53.34%	17.04%	47.93%	56.23%	27.03%	59.00%	23.84%	20.41%
Per SKU (st. dev.)	1.02%	0.31%	0.79%	0.72%	0.86%	1.19%	0.80%	1.23%
Per train (avg.)	22.10%	13.76%	43.33%	45.28%	26.08%	50.45%	23.11%	20.01%
Per train (st. dev.)	0.47%	0.26%	0.65%	0.64%	0.87%	0.99%	0.75%	1.29%
Volume x 1.5	**RB**	**ST-GB**	**EP**	**ST-EP**	**SP floor**	**ZD floor**	**SP rack**	**ZD rack**
Base (avg.)	47.27%	19.20%	70.19%	68.28%	39.79%	77.27%	35.30%	29.62%
Base (st. dev.)	0.84%	0.29%	1.29%	1.27%	0.93%	1.48%	0.38%	0.97%
Per SKU (avg.)	73.39%	23.54%	69.78%	80.59%	39.94%	82.70%	35.85%	29.65%
Per SKU (st. dev.)	1.00%	0.34%	1.45%	1.09%	0.86%	1.22%	0.37%	0.92%
Per train (avg.)	33.27%	19.20%	64.06%	68.28%	39.02%	74.64%	34.90%	29.56%
Per train (st. dev.)	0.60%	0.29%	1.10%	1.27%	0.94%	1.46%	0.41%	1.00%
Volume x 2	**RB**	**ST-GB**	**EP**	**ST-EP**	**SP floor**	**ZD floor**	**SP rack**	**ZD rack**
Base (avg.)	63.78%	24.86%	88.48%	80.70%	53.90%	92.30%	47.41%	40.48%
Base (st. dev.)	1.47%	0.60%	1.18%	0.40%	1.05%	0.97%	1.48%	0.43%
Per SKU (avg.)	90.11%	30.23%	88.75%	86.80%	53.69%	94.11%	47.87%	39.68%
Per SKU (st. dev.)	1.29%	0.66%	1.24%	0.26%	1.03%	0.78%	1.42%	0.44%
Per train (avg.)	44.92%	24.86%	80.11%	80.70%	52.82%	91.08%	46.83%	40.33%
Per train (st. dev.)	1.09%	0.60%	1.31%	0.40%	1.08%	1.19%	1.43%	0.47%

Items not stored

Table E 18: Average and standard deviations of items not stored of the current scenario, when storing per SKU, and storing per train, for different volumes.

Zone	ST-GB	ST-EP	RB	EP	SP floor	ZD floor	SP rack	ZD rack	SP other	ZD other	ST-GB2	Total
Volume x1												
Base (avg.)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Base (st. dev.)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Per SKU (avg.)	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	**1.0**
Per SKU (st. dev.)	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	0.0	**1.4**
Per train (avg.)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Per train (st. dev.)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Volume x 1.5												
Base (avg.)	0.0	0.0	0.0	26.0	0.0	220.4	0.0	0.0	0.0	0.0	0.0	**246.4**
Base (st. dev.)	0.0	0.0	0.0	35.8	0.0	86.1	0.0	0.0	0.0	0.0	0.0	**121.9**
Per SKU (avg.)	0.0	657.4	37.2	74.2	0.0	524.0	0.0	0.0	0.0	0.0	0.0	**1292.8**
Per SKU (st. dev.)	0.0	255.0	51.1	29.3	0.0	86.7	0.0	0.0	0.0	0.0	0.0	**422.1**
Per train (avg.)	0.0	0.0	0.0	0.0	0.0	134.4	0.0	0.0	0.0	0.0	0.0	**134.4**
Per train (st. dev.)	0.0	0.0	0.0	0.0	0.0	73.6	0.0	0.0	0.0	0.0	0.0	**73.6**
Volume x 2												
Base (avg.)	0.0	4967.4	0.0	5857.4	0.0	2602.6	0.0	0.0	0.0	0.0	0.0	**13427.4**
Base (st. dev.)	0.0	1244.4	0.0	1621.4	0.0	449.3	0.0	0.0	0.0	0.0	0.0	**3315.1**
Per SKU (avg.)	0.0	14670.4	6493.8	4075.6	0.0	3407.0	0.0	0.0	0.0	0.0	0.0	**28646.8**
Per SKU (st. dev.)	0.0	1881.5	2397.7	1205.1	0.0	477.9	0.0	0.0	0.0	0.0	0.0	**5962.3**
Per train (avg.)	0.0	4962.6	0.0	229.0	0.0	2114.0	0.0	0.0	0.0	0.0	0.0	**7305.6**
Per train (st. dev.)	0.0	1241.8	0.0	156.5	0.0	430.5	0.0	0.0	0.0	0.0	0.0	**1828.7**

Average locations needed

Table E 19: Average number of locations needed of the current scenario, when storing per SKU, and storing per train, for different volumes.

Volume x 1	**RB**	**ST-GB**	**EP**	**ST-EP**	**SP floor**	**ZD floor**	**SP rack**	**ZD rack**	**Total**
Base	1253.64	206.37	884.61	638.01	107.76	88.20	112.18	14.45	**3305.23**
Per SKU	2133.55	255.62	892.94	792.22	109.49	99.11	114.44	14.70	**4412.06**
Train	884.19	206.37	807.19	638.01	105.62	84.75	110.94	14.41	**2851.48**
Volume x 1.5	**RB**	**ST-GB**	**EP**	**ST-EP**	**SP floor**	**ZD floor**	**SP rack**	**ZD rack**	**Total**
Base	1890.77	288.07	1307.64	962.10	161.14	129.81	169.46	21.33	**4930.31**
Per SKU	2935.61	353.09	1300.01	1135.48	161.76	138.94	172.09	21.35	**6218.33**
Train	1330.79	288.07	1193.40	962.10	158.02	125.39	167.50	21.28	**4246.55**
Volume x 2	**RB**	**ST-GB**	**EP**	**ST-EP**	**SP floor**	**ZD floor**	**SP rack**	**ZD rack**	**Total**
Base	2551.37	372.92	1648.44	1137.08	218.30	155.06	227.55	29.14	**6339.88**
Per SKU	3604.55	453.51	1653.35	1223.04	217.45	158.10	229.79	28.57	**7568.37**
Train	1796.69	372.92	1492.52	1137.06	213.91	153.01	224.77	29.03	**5419.93**

Time measures

Table E 20: Average and standard deviations of time measures for the current scenario, when storing per SKU, and storing per train, for different volumes.

	Total put away time per day (h)		**Total pick time per day (h)**		**FTE (0.7)**		**Time to pick one train (min)**	
Volume x 1	**Avg.**	**Stdev.**	**Avg.**	**Stdev.**	**Avg.**	**Stdev.**	**Avg.**	**Stdev.**
Base (A)	16.16	0.35	14.00	0.28	5.38	0.11	35.89	0.27
Per SKU (B)	14.53	0.32	17.16	0.37	5.66	0.12	53.36	0.45
Per Train (C)	16.32	0.34	12.62	0.24	5.17	0.10	31.59	0.25
A-C	-0.16		1.38		0.22		4.30	
B-C	-1.79		4.55		0.49		21.77	
Volume x 1.5	**Avg.**	**Stdev.**	**Avg.**	**Stdev.**	**Avg.**	**Stdev.**	**Avg.**	**Stdev.**
Base (A)	25.54	0.54	21.53	0.43	8.41	0.17	36.76	0.22
Per SKU (B)	22.62	0.44	26.14	0.47	8.71	0.16	54.77	0.23
Per Train (C)	25.55	0.52	19.16	0.38	7.99	0.16	31.79	0.17
A-C	-0.01		2.37		0.42		4.98	
B-C	-2.94		6.98		0.72		22.98	
Volume x 2	**Avg.**	**Stdev.**	**Avg.**	**Stdev.**	**Avg.**	**Stdev.**	**Avg.**	**Stdev.**
Base (A)	35.95	0.92	30.47	0.80	11.86	0.31	38.13	0.49
Per SKU (B)	30.49	0.73	35.75	0.97	11.83	0.30	55.53	0.69
Per Train (C)	36.01	0.97	26.90	0.70	11.24	0.30	32.57	0.39
A-C	-0.06		3.57		0.63		5.55	
B-C	-5.52		8.84		0.59		22.96	

Table E 21: Put-away and pick hours per day, divided per storage zone.

Volume x 1	ST-GB	ST-EP	ST-LL	RB	EP	SP floor	ZD floor	SP rack	ZD rack	SP other	ZD other	ST-GB (2)
Put away base	0.22	1.12	0.13	6.16	4.21	0.68	0.79	0.63	0.16	0.00	0.55	1.52
Put away per SKU	0.23	1.21	0.13	6.35	3.78	0.69	0.79	0.65	0.17	0.00	0.55	0.00
Put away per train	0.22	1.12	0.13	6.30	4.48	0.69	0.80	0.65	0.16	0.00	0.55	1.21
Pick base	0.50	1.93	0.06	4.30	3.78	0.64	0.79	0.60	0.15	0.00	1.24	0.00
Pick per SKU	0.00	0.00	0.06	7.29	6.06	0.71	0.99	0.64	0.17	0.00	1.24	0.00
Pick per train	0.50	1.93	0.06	3.22	3.53	0.63	0.76	0.60	0.15	0.00	1.24	0.00
Volume x 1.5	**ST-GB**	**ST-EP**	**ST-LL**	**RB**	**EP**	**SP floor**	**ZD floor**	**SP rack**	**ZD rack**	**SP other**	**ZD other**	**ST-GB (2)**
Put away base	0.30	1.67	0.13	9.67	7.21	1.02	1.16	0.96	0.24	0.00	0.83	2.36
Put away per SKU	0.31	1.82	0.13	10.08	5.97	1.05	1.15	1.01	0.25	0.00	0.85	0.00
Put away per train	0.30	1.67	0.13	9.86	7.45	1.04	1.19	0.98	0.24	0.00	0.83	1.87
Pick base	0.80	3.16	0.06	6.52	5.85	0.96	1.16	0.91	0.23	0.00	1.88	0.00
Pick per SKU	0.00	0.00	0.06	11.18	9.25	1.06	1.44	0.97	0.26	0.00	1.92	0.00
Pick per train	0.80	3.16	0.06	4.84	5.23	0.94	1.13	0.90	0.23	0.00	1.87	0.00
Volume x 2	**ST-GB**	**ST-EP**	**ST-LL**	**RB**	**EP**	**SP floor**	**ZD floor**	**SP rack**	**ZD rack**	**SP other**	**ZD other**	**ST-GB (2)**
Put away base	0.38	2.12	0.13	13.40	11.03	1.37	1.40	1.28	0.32	0.00	1.25	3.28
Put away per SKU	0.40	2.04	0.13	14.00	8.14	1.43	1.36	1.36	0.34	0.00	1.30	0.00
Put away per train	0.38	2.12	0.13	13.64	11.44	1.41	1.46	1.32	0.32	0.00	1.22	2.58
Pick base	1.16	4.75	0.06	8.84	8.59	1.30	1.38	1.22	0.31	0.00	2.86	0.00
Pick per SKU	0.00	0.00	0.06	15.46	12.50	1.43	1.68	1.29	0.35	0.00	2.98	0.00
Pick per train	1.16	4.75	0.06	6.51	7.47	1.27	1.37	1.21	0.31	0.00	2.79	0.00

Appendix E.4 Intervention 4: Procuring more SKUs anonymously

Number of locations needed

Table E 22: Average and standard deviations of locations needed for the current scenario, when storing per SKU, and when doing anonymous pick simultaneously, when more SKUs are procured anonymously.

Scenario		Avg/Stdev	UtilizationRB	UtilizationSTGB	UtilizationEP	UtilizationSTEP	SPVloer	ZDVloer	SPrek	ZDrek
Base		Avg	1873.33	286.93	1298.63	946.97	160.30	129.83	168.93	21.54
Base		Stdev	20.15	2.39	10.11	12.82	2.23	1.21	1.98	0.52
Base	**RB**	Avg	1035.65	3536.99	1313.82	998.75	160.23	129.27	168.20	21.67
Base	**RB**	Stdev	11.11	21.72	10.95	12.52	1.53	0.64	1.61	0.77
Base	**RBEP**	Avg	1035.66	3538.46	973.33	2310.04	159.77	128.98	168.19	21.57
Base	**RBEP**	Stdev	10.88	24.08	8.33	23.66	1.89	0.89	1.85	0.78
AnonyIn1x		Avg	1697.74	351.91	1053.52	1124.23	160.30	129.83	168.93	21.54
AnonyIn1x		Stdev	17.14	2.54	8.16	14.21	2.23	1.21	1.98	0.52
AnonyIn1x	**RB**	Avg	254.27	4398.20	1054.34	1162.04	160.23	129.27	168.20	21.67
AnonyIn1x	**RB**	Stdev	2.07	27.45	8.10	11.79	1.53	0.64	1.61	0.77
AnonyIn1x	**RBEP**	Avg	254.49	4398.74	341.08	2852.10	159.77	128.98	168.19	21.57
AnonyIn1x	**RBEP**	Stdev	1.54	28.60	2.12	26.83	1.89	0.89	1.85	0.78
SKU		Avg	2915.07	351.91	1292.80	1124.23	161.20	138.78	171.91	21.33
SKU		Stdev	21.76	2.54	7.29	14.21	2.29	1.26	2.16	0.35
SKU	**RB**	Avg	248.84	4398.20	1291.81	1162.04	160.70	138.25	171.26	21.47
SKU	**RB**	Stdev	2.70	27.45	7.27	11.79	1.69	0.91	1.98	0.75
SKU	**RBEP**	Avg	249.38	4398.74	400.51	2852.10	160.37	138.16	171.07	21.41
SKU	**RBEP**	Stdev	2.76	28.60	3.56	26.83	1.92	1.11	2.21	0.77

Table E 23: Average and standard deviations of time measures for the current scenario, when storing per SKU, and when doing anonymous pick simultaneously, when more SKUs are procured anonymously.

Intervention	Scenario	Avg/Stdev	Total put away time per day (h)	Total pick time per day (h)	FTE (0.7)	Time to pick one train (min)
Base		Avg	25.24	21.37	8.32	36.73
Base		Stdev	0.22	0.21	0.08	0.26
Base	RB	Avg	23.02	30.48	9.55	36.79
Base	RB	Stdev	0.20	0.31	0.09	0.27
Base	RBEP	Avg	23.85	34.13	10.35	36.32
Base	RBEP	Stdev	0.18	0.32	0.09	0.26
AnonyIn1		Avg	20.38	19.67	7.15	41.37
AnonyIn1		Stdev	0.15	0.16	0.06	0.28
AnonyIn1	RB	Avg	15.68	23.12	6.93	48.65
AnonyIn1	RB	Stdev	0.08	0.18	0.05	0.30
AnonyIn1	RBEP	Avg	15.07	24.29	7.03	51.12
AnonyIn1	RBEP	Stdev	0.08	0.19	0.05	0.32
SKU		Avg	22.38	25.95	8.63	54.61
SKU		Stdev	0.17	0.20	0.07	0.36
SKU	RB	Avg	16.16	25.30	7.40	53.24
SKU	RB	Stdev	0.10	0.37	0.08	0.64
SKU	RBEP	Avg	15.66	25.57	7.36	53.81
SKU	RBEP	Stdev	0.09	0.20	0.05	0.35

Appendix E.5 Parameters for calculating the costs and savings per €

Costs per location

Table E 24: Parameters for storage costs per m^2 per zone.

RB rack	
m^2	20.3
Number of locations per rack	320
Costs per location per year	€ A
Costs per rack per year	€ B
EP rack	
m^2	10.9415
Number of locations per rack	27
Costs per location per year	€ A
Costs per rack per year	€ B
ST-EP rack	
m^2	10.9415
Number of locations per rack	36
Costs per location per year	€ A
Costs per rack per year	€ B
SP rack	
m^2	16.2045
Number of locations per rack	40
Costs per location per year	€ A
Costs per rack per year	€ B
SP floor	
m^2	4.635
Number of locations per rack	3
Costs per location per year	€ A
Costs per rack per year	€ B
ZD rack	
m^2	16.2045
Number of locations per rack	6
Costs per location per year	€ A
Costs per rack per year	€ B
ZD floor	
m^2	11.375
Number of locations per rack	3.5
Costs per location per year	€ A
Costs per rack per year	€ B

Costs per item not stored

Table E 25: Parameters for calculating the € per item not stored per zone.

Zone	Location m²	Average item size in this zone (relative to its location)	€ per item not stored
RB	0.06	0.185	€ A
EP	0.41	0.246	€ B
SP floor	1.55	0.632	€ C
ZD floor	3.25	0.475	€ D
SP rack	0.41	0.771	€ E
ZD rack	2.70	0.729	€ F
ST-EP	0.30	0.238	€ G
ST-GB	0.06	0.166	€ H

Values of costs per year for the number of FTE needed, locations needed, and items not stored

Table E 26: Costs per year for the number of FTE needed, locations needed, and items not stored.

Vol-ume	Inter-vention	Costs for FTE (per year)	Costs for items not stored (per year)	Costs for locations used (per year)	Total costs per year
1x	Base	A	A	A	A
1x	SKU	B	B	B	B
1x	Anonyin1x	C	C	C	C
1x	Per train	D	D	D	D
1.5x	Base	E	E	E	E
1.5x	SKU	F	F	F	F
1.5x	Anonyin1x	G	G	G	G
1.5x	Per train	H	H	H	H
2x	Base	I	I	I	I
2x	SKU	J	J	J	J
2x	Anonyin1x	K	K	K	K
2x	Per train	L	L	L	L

End of report