DESIGN OF A FRAMEWORK AND WAREHOUSE FACILITY AT ROSEN EUROPE

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Preface

In front of you is my thesis, written as part of the bachelor's in industrial engineering and Management at the University of Twente. This thesis explores the concept of warehouse design and applies it to the company I could conduct the research: ROSEN Europe in Oldenzaal. I am grateful for the opportunities I was given to learn, grow, and apply the theories I've learned in these real-world settings. Conducting this research at ROSEN has taught me a lot about how to put the theories I've studied in the bachelor IEM into practice. I also enjoyed learning so much about a new business and watching theories come to life. Additionally, learning how to conduct actual research and the workings of a research project was very valuable.

I would like to extend my heartfelt thanks to the people at ROSEN Group for welcoming me and giving me the chance to conduct my research. Special thanks go to my company supervisor, Stefan Tuiten.

I would also like to express my gratitude to my university supervisors, Peter Schuur and Patricia Rogetzer, for their patience, feedback, and support throughout my research process. The provided guidance was crucial to the completion of the research.

Finally, I want to acknowledge the support of my friends and family, who were there for me through every step of this journey.

Management Summary

Motivation

ROSEN Europe operates a facility in Oldenzaal where they process returned high-tech machinery and supporting equipment. These products are deployed in Europe, Africa, India and former Soviet countries to clean and inspect a wide variety of technical installations, with the focus being gas and oil pipelines. There, the machinery is sent through the lines for cleaning and investigating for possible damages. The products that come back to Oldenzaal are generally cleaned, inspected, stored and refurbished for new deployments. Due to space and storage limitations, ROSEN Europe is facing problems in handling their day-to-day workload in the inbound and outbound retrieval and storage processes. This is apparent in the times it takes to perform these relatively straight-forward actions, which can sometimes take up to several hours. Furthermore, a considerable amount of inventory does not fit in the indoor storage locations, leading to products staying outside for long times, with associated risks of deterioration and theft.

Research Question

The goal of this research is to gain insight in the current situation and to create the business case for a newly designed warehouse, that should fit expected operations measured against relevant performance indicators. Therefore, the main research question to be answered in this research is:

How can the storage facility of ROSEN be designed to better fit the needs and operations, based on current and forecasted data?

Methodology

The research was started by understanding how the ROSEN facility in Oldenzaal currently operates and what the faced problems are. This was done through the Managerial Problem-Solving Method, leading to a comprehensive view of the action problem and its core problem. With the analysis of the current situation completed, literature research was conducted into the area of warehouse design and planning. From this, a framework was derived to fit in the ROSEN context. The goal of this framework was to create a holistic approach to creating the alternative designs that solve the ROSEN problem. The framework consists of formulating design criteria, retrieving and profiling the required data, understanding the required processes and their relations, doing market research, and then creating alternatives that solve the problem. An optimal design is chosen according to performance criteria formulated in the start of the framework.

To demonstrate the effectiveness of the framework within the given time, scope and knowledge, a selection of the steps to complete was made. These focus areas were chosen, such that the end result is feasible and usable for ROSEN. Furthermore, the used data was generated manually and validated to achieve insightful results. The types of data created were decided such that activity profiling can be applied, while corresponding to actual-life data.

Results

The research demonstrates how ROSEN can use a systematic approach for the creation of a new warehouse. By following the selected steps from the framework, various layouts for the physical facility were created. These were subsequently measured against several performance criteria, leading to the final layout being chosen and evaluated in-depth. The result is a warehouse design that can fit the ROSEN operations better for the years to come. This consists of a newly built warehouse, built against the perimeter of the plant area, displayed in Figure 1. This specific location is chosen based on the process analysis and space-saving heuristics. The warehouse is designed to be able to house the required materials. The result accompanies the design criteria such that the core problem is solved.

Recommendations

As stated, the created framework has been selectively applied due to knowledge and scope limitations. However, the framework is described such that additional research can be done into the remaining steps. For example, the cost factor of certain machinery can be further investigated to achieve a more holistic warehouse design. The data that was used for the activity profiling has been validated with ROSEN and is similar to the factual data, but using the actual data would logically lead to a more situation-accurate design. With the described steps, it is recommended to follow the framework again with real-life data.

To further evaluate the achieved warehouse design, more thorough cost and implementation investigation is required. This would guide decisions in alternatives in later implementation steps, such that the actual realization of the warehouse fits the Oldenzaal context. This principle also applies for example to specific regulations in municipal building code.

With the proposed warehouse design come of course many changes to the overall processes and operations at the Oldenzaal facility. To best utilize the created result, it would be beneficial to reassess the facility operations, and especially those closely related to the warehouse.

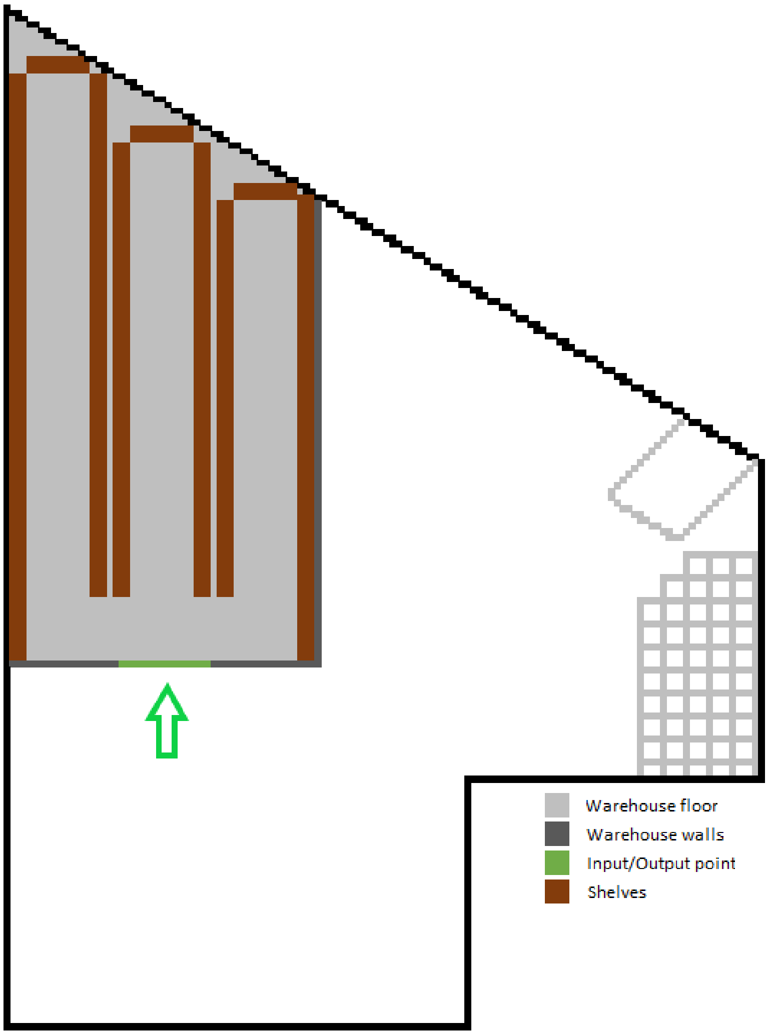

Figure 1: The proposed warehouse solution

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MPSM	Managerial Problem-Solving Method
BPMN	Business Process Model and Notation
SLP	Systematic Layout Planning
I/O point	Input/Output point

1 Introduction

In this chapter, an introduction to ROSEN Group in general, and the researched problem in particular is given. This sets the stage for the rest of the thesis and explains the context of the research.

1.1 Company introduction

ROSEN Group is the worldwide market leader in asset integrity management, operating globally to provide cleaning and inspections to a wide variety of installations, such as oil and gas pipelines, wind turbines and manufacturing. The company offers a wide variety of protection and diagnostics methods, but the core business consists of in-line inspection machines such as the one shown in Figure 2. In this sector, pipelines are first cleaned by sending cleaning apparatuses through, and then the high-technology machines are sent through to perform fully automatic diagnosing. This is done with their entirely self-manufactured inline inspection machines, from here on called 'tools'. These tools are designed and deployed to identify possible pipeline corrosion, cracks, and other deformations by scanning the pipeline as the tool is 'crawling' through it. The collected data is analysed and reported upon by ROSEN consultants and gives their customers insight in the integrity of their assets.

Figure 2: Work on an in-line inspection tool, with the holding frame and plastic accessories also visible (ROSEN Group, 2020)

ROSEN has facilities and offices throughout the world, stemming from the original location in Lingen, Germany, where they now have a Research and Development centre with over 2,000 employees. In Oldenzaal, The Netherlands, sales and support for the regions Europe, Africa, the Commonwealth of Independent States (former Soviet Union countries), and India takes place, along with the physical processes concerning receiving and preparing previously deployed tools for new deployments. This refurbishing takes place in the main mechanics hall ('workshop'), visible in Figure 3. The research described in this thesis leaves this refurbishing section of the facility out of scope and focuses on the logistical processes concerning the handling of tools at the Oldenzaal facility. This means we focus on the processes occuring outside of the workshop and inside the storage building called 'Fort Knox', labeled in the map in Figure 3. This is the warehouse in use for storing the tools. The other gray areas in the map are the workshop and office areas. A larger version of this map can be found in Appendix A.

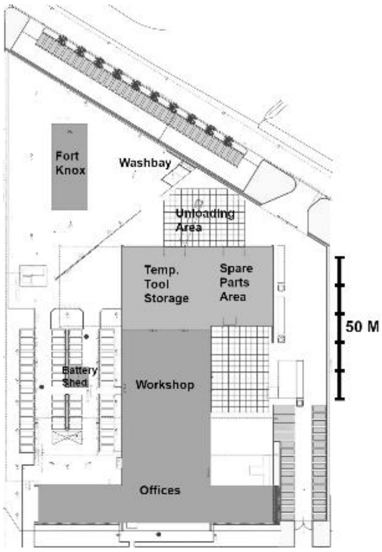


Figure 3: Map of the facility, with Fort Knox marked

1.2 Problem introduction

Due to space and storage limitations, ROSEN Europe is facing problems in handling their day-to-day workload in the inbound and outbound retrieval and storage processes. These processes consist of retrieving tools from Fort Knox and storing them until later use. This is apparent in the times it takes to perform these relatively straightforward actions, which can sometimes take up to several hours. Furthermore, a considerable amount of inventory does not fit in the indoor storage locations, leading to products staying outside for long times, with associated risks of deterioration and theft.

There are two scope-relevant main groups of products to be stored. Firstly, the high-tech tools which must be stored inside as they are especially valuable and contain proprietary information. The second group contains ancillary products, such as holding frames and (plastic) accessories, both of which can be seen in Figure 2. These are less critical to store inside, but the current situation of non-stop outside storages does lead to deterioration, such as rust and plastic weathering.

The disadvantages of the current warehouse and storage situation are not only deterioration and theft risk but are also apparent in the day-to-day operations of the facility. Because Fort Knox is too small and underutilized to fit all tools properly, much of the materials are stored on the floor area inside, instead of on the existing shelves. When the workshop department asks for a specific tool, the logistics team must first find the tool, and then ‘dig’ it out of other tools on the crowded floor space. This can involve a lot of redundant back and forth moving of unrequired tools, sometimes leading to hours of extra work. In a well-designed warehouse, this should be a matter of going up to the tool freely, retrieving and delivering it. The redundant movements and therefore slow retrieval and storage times are part of the core problem to be solved.

1.3 Outline

Now that the company context and problem have been introduced, the following chapters will explore these topics further and work towards a solution. This is done by first designing the research, through defining an approach, deliverables and related research questions in Chapter 2. Then, in Chapter 3, the current situation is explored further, through operation modelling and researching the current facility layout. Afterwards, in Chapter 4, a literature research is performed to create a theoretical framework that can help solve the problem. The following steps consist of solution generation and evaluation (Chapter 5), after which a discussion of the results and research are given in Chapter 6. Finally, the conclusion and recommendations are provided in Chapter 7.

2 Research design

Now that the broad context of the company and the problem have been introduced in Chapter 1, this chapter handles the design of the research of this thesis. Firstly, the problem-solving approach is chosen, and it is explained how it guides the rest of this thesis. Then, the end deliverables are stated, together with the research questions that guide the research to reach these deliverables. Finally, the methods used and the scope of the research are discussed.

2.1 Approach

For the problem-solving approach, the Managerial Problem Solving Method (MPSM) by Heerkens et al. (2017) is chosen and employed. The reason for choosing this method is that it fits well within a context like the logistics process the research is involved with. Furthermore, it is an approach that is familiar through previous use and has been used in similar settings before. The MPSM consists of seven phases, for which it is described below how they are concretely applied in this research.

Phase 1: Problem identification

The problem identification as laid out by Heerkens et al. (2017), can be found in the problem introduction in Chapter 1. The core problem to be tackled is as follows: the storage facilities of ROSEN are not well suited for the workload, leading to long retrieval times and outside product storage.

Phase 2: Solution planning

This phase is highlighted in this chapter. From phase 1, it has become clear what the core and part of the related problems are. The second phase, solution planning, is performed in this chapter. The required deliverables are discussed, and the research questions that lead to these deliverables are formulated. Furthermore, the applied research methods are determined and the scope of the thesis is set.

Phase 3: Problem analysis

After phase 2, it is clear how the problem is approached, and the in-depth analysis of the problem can begin in Chapter 3, Current situation. The current processes are examined and placed within the physical environment to get a full understanding of the as-is situation. From here, the core problem can be more precisely attributed to specific factors. This is supported by the activity profiling section of Chapter 3. In Chapter 4, the literature research, the goal is to create a broad understanding of other warehouse design problems and approaches in the scientific theory. A framework is derived for the following phases.

Phase 4 & 5: Solution generation and choice

From the derived framework of phase three and the work done in previous chapters, Chapter 5 consists of the application of the framework. Following the steps of the framework, several solutions are created that fit the ROSEN problem and context. By the formulated design criteria, an optimal solution can then be chosen.

Phase 6: Solution implementation

The selected solution and its implementation are further discussed in the last steps of the framework in Chapter 5. Discussion of these results can be found in Chapter 6, including how research can be furthered in the future.

Phase 7: Solution evaluation

The final phase is discussed in Chapter 7, Conclusion and recommendations. Here, we show and reflect upon the process to show what overall conclusions were reached. The recommendations handle how ROSEN can use the research.

2.2 Deliverables

Now that the research has been planned through the MPSM, the end deliverables are stated. They are each formulated to have individual worth to ROSEN and the thesis.

- A well-defined description of the current physical environment and existing handling and placing processes. The processes are modelled in Business Process Model and Notation (BPMN).
- A warehouse design framework formulated for the ROSEN context.
- A list of performance criteria and prioritizations (i.e., the objectives) which the solution must fulfil.
- Analysis of historical and forecasted data.
- Creation and evaluation of possible solutions and selection of solution.
- Bachelor thesis with report of the entire process and implementation recommendations, including relevant above deliverables as appendices.

2.3 Research questions

From the core problem 'The storage facilities of ROSEN are not well suited for the workload, leading to long retrieval times and outside product storage', a main research question can be derived: '*How can the storage facility of ROSEN be designed to better fit their needs and operations, based on current and forecasted data?'* This research question can be divided into the following sub-research questions. These sub-questions guide the research in answering the main research question.

1. What does the current facility of ROSEN look like, in terms of physical environment and processes?

The goal of this research questions is to get a complete overview of how the current facility is designed and how the processes occur in here. This can be found out through interviews, observations and analysing available data.

2. Where do the current problems occur and how is this supported by available data and used KPIs?

Here the goal is to identify possible bottlenecks and other concrete problems based on the mappings and information from question one. It provides the spearheads for solutions to focus and improve on. It is important to quantify the problems with the data from question one.

3. Which methods or theories exist in the scientific literature that guide the design of a new storage facility?

The literature research provides the concrete steps to go from found problems to an array of possible solutions, such that the process is insightful and trackable. A novel, ROSEN-adapted framework is constructed to create alternative solutions for the following questions.

4. What criteria and functions must an improved storage facility meet?

This question ensures that generated solutions can be measured against the desired effects in the problem context. It provides the performance criteria and operating needs that must be fulfilled.

5. What alternative solution best solves the problem based on the criteria and available data?

The framework from sub-question three is put in use in the ROSEN context to create several solutions that could meet the workload. These alternatives are modelled with the obtained data from steps questions one and two and weighed against the performance criteria coming from research four.

6. How can ROSEN implement and evaluate the chosen solution?

In this part, a business case is be created for ROSEN, such that the company can put the identified solution in action. Proper motivation and an insightful process are important to make the solution feasible in the eyes of the problem owner.

2.4 Methods

Each sub-question uses different methodologies, with the core of the research begin quantitative. To analyse the systems and methods at ROSEN, data is created and validated. This concerns for example the physical characteristics of the products, their relative importance (zoning) and information about the sizing of the facilities. This data is used to profile the activity and used as a base for the layout generation steps. Other inputs for these steps can be classified as qualitative research, namely the creation of the performance criteria and the literature research. These elements are found through research and reasoning. Information about the occurring processes is acquired through interview sessions with relevant ROSEN employees.

2.5 Scope

The scope of the research is set to contain the current Fort Knox situation. ROSEN requires a new storage facility that takes over the functions of this storage location. The current number of tools allocated to Fort Knox already causes storage problems and long retrieval times. Furthermore, extra capacity is required to store items that are currently stored outside because of space limitations. Left out of the scope are the processes and storage happening inside the main building.

Within the new design of the current outside warehouse, some factors that go into a complete design are left out of the scope due to knowledge and time limitations. An example is that for a full overview of costs, knowledge of and research into building construction itself is required. This is outside the scope of this design research, where the goal is to show how a solution can be created and would help improve warehouse operations.

2.6 Chapter conclusion

This chapter discussed the research design for the study, including the problem-solving approach, the end deliverables, the research questions that guide the research, the methods that are employed, and the scope of the research. The problem-solving approach chosen is the MPSM, which consists of seven phases and is well-suited to the logistics process being studied. The end deliverables of the research include a description of the current physical environment and existing processes at ROSEN, a warehouse design framework, a list of performance criteria, analysis of historical and forecasted data, and the creation and evaluation of solutions.

The research aims to answer the main research question '*How can the storage facility of ROSEN be designed to better fit their needs and operations, based on current and forecasted data?'*, and does so through six sub-research questions. The research is primarily quantitative, with some elements of qualitative research. The scope of the research is limited to the current outside warehouse Fort Knox and excludes processes and storage happening inside the main building, as well as supporting knowledge and research into factors such as building construction costs.

3 Current situation

This chapter further explains the current state of operations at ROSEN, with both the operational processes and the physical layout wherein these actions are performed being researched. The goal is to get a holistic overview of the current situation, which is backed up by the activity profiling performed in the third section of this chapter.

3.1 Operation modelling

The current operation has been modelled in Appendix B, with both the inbound and outbound processes being shown. The processes are modelled in a swim lane diagram, chronologically from left to right. The diagrams are derived from sessions that were held with ROSEN operators. In these sessions, the same but empty diagrams were drawn on a wall, and through questioning it was determined how both the inbound and outbound processes are designed. The results were filled in and later transferred to the digital diagrams of Appendix B and Appendix C.

Berg et al. (1999) and De Koster et al. (2007) mention that the activities in a warehouse can be subdivided into four categories: receiving, storage, order-picking and shipping. These stages can be applied to the ROSEN operations, albeit not always in the same arrangement or order.

From the detailed model in Appendix B, the two diagrams below are created for clarity. A broad description of the inbound process displayed in Figure 4 is as follows: A truck arrives and is unloaded, the contents get photographed and checked for large damages. The batteries are separated and discarded or reused, after which the top frame is taken off and inspected. The tool itself is checked for contamination with dangerous substances. The tool is then taken to the washbay and cleaned there. If the tool is not required in the workshop immediately, it is stored away, otherwise it is brought to the workshop and dismantled there. If more cleaning is then required, the parts go through the washbay again, to be further prepared afterwards. It becomes apparent that the mentioned stages of receiving, storage, order-picking and shipping can intertwine based on the specific requirements of the incoming tool.

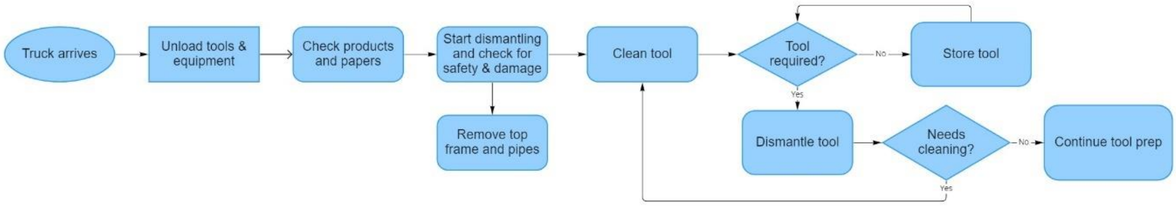


Figure 4: Inbound process of ROSEN Oldenzaal

The outbound process is displayed in Figure 5 and starts with the order-picking activities, based on the shipment list. When the required materials have been picked, the tool is set up and installed with further ancillary tools. If no truck is available after this preparation, the complete setup must be stored again until a truck does arrive. Once again, the process at ROSEN is not a straight-forward walk through the four standard steps.

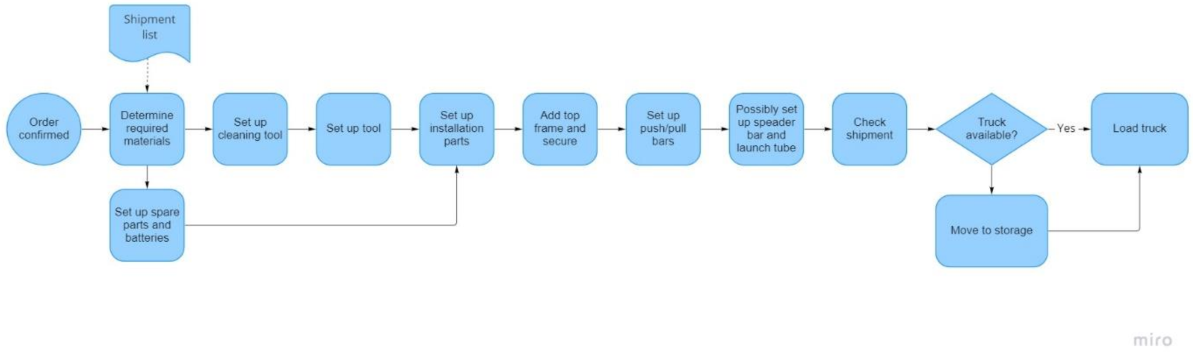


Figure 5: Outbound process of ROSEN Oldenzaal

3.2 Warehouse layout

In Figure 6, the map of the current Oldenzaal facility is shown, with added text to show functionalities. An enlarged version can be found in Appendix A, and the following descriptions are mapped in Appendix C. Trucks arrive at the bottom left corner of the figure and drive on through to the unloading area. The inbound process continues in this place up until the cleaning step, which takes place at the washbay. From here, the tool is placed in Fort Knox, or sent directly to the workshop. In Fort Knox, the forklift truck driver chooses where to place the tool. In practice, this happens mostly on the closest available spot.

A tool required for the workshop must be retrieved from Fort Knox, where often it has to be 'dug out' by moving the tools lying in front. This is the leading cause of long retrieval times, sometimes hours are lost. This problem is also known as the container retrieval problem in other contexts.

When work starts on a tool for a shipment, the outbound process flow is followed. Completed parts of the order list are placed in the temporary tool storage and spare parts area. After the handling processes, truck shipments are gathered at the grid below the spare parts area, where trucks then leave at the bottom right corner.

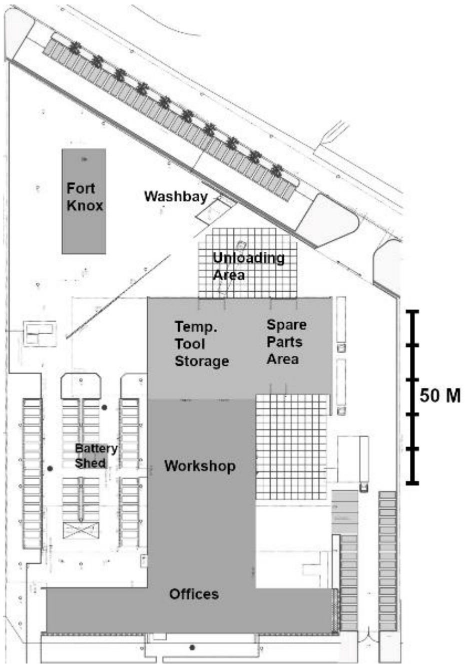


Figure 6: Map of the ROSEN Oldenzaal facility, with relevant areas named with text

3.3 Activity profiling

The textual and visual descriptions above must be qualified through historical data, such that the actual warehouse activity can be profiled. Firstly, this is done on the number of orders that happen throughout time, such that seasonality can be determined. In Appendix D, this is displayed by the number of orders per week for a 3-year period. The displayed information is actual ROSEN data, the source being equipment preparations sheets for the time period from 26-02-2020 through 11-07-2023.

3.4 Chapter conclusion

In this chapter, the current operations the Oldenzaal facility were modelled using swim lane diagrams derived from sessions with operators. The inbound process is described, including steps such as unloading, inspecting, and cleaning tools before storage or use in the workshop. The outbound process is also outlined, starting with order-picking and preparing tools for shipment. Furthermore, the layout of the warehouse was shown so the described processes can be mapped onto the map. These two sections together answer the first sub-research question: “What does the current facility of ROSEN look like, in terms of physical environment and processes?”. Furthermore, it was determined in collaboration with ROSEN that the problems to tackle occur at Fort Knox, and that this is the area to focus on, answering the second sub-question.

4 Literature review and theoretical framework

In the literature review of this thesis, various disciplines and frameworks for designing warehouses are examined. The goal is to get an overview of available methodologies, with their respective advantages and disadvantages for the ROSEN context. In the end, a properly fitting framework is distilled.

4.1 Systematic Layout Planning

Systematic Layout Planning (SLP) is a method that considers both flow and activity relationships while developing layouts. The SLP framework provides several tools for measuring and documenting material flows, as well as a classification of the relationships between activities. This classification is on a scale called AEIOUX, the letters standing for absolutely, essential, important, ordinary, unimportant, and undesirable relationships. The activities (or departments) with the strongest relationships are characterized as having an A relationship, meaning that closeness is *a*bsolutely required. Less important activity interactions are categorized in decreasing order as *e*ssential, *i*mportant, *o*rdinary closeness required, *u*nimportant, and *x* for undesirable in decreasing order of closeness importance (Muther, 1973). SLP combines this classification of activity relationships with data on material flows to build a relationship diagram. In this relationship diagram, the departments are drawn as equal-sized boxes, with the thickness of the connecting lines representing the relative importance of the relationship. An example can be seen in Figure 7. This diagram is then converted into a space relationship diagram by adding the space requirements of the departments, scaling the drawn department boxes (Malmborg, 2007). An example of this space requirements within ROSEN would be the battery-storage container, with a minimum required clearing for safety. By differing considerations and trying alternatives, several layouts are obtained, ready for systematic evaluation.

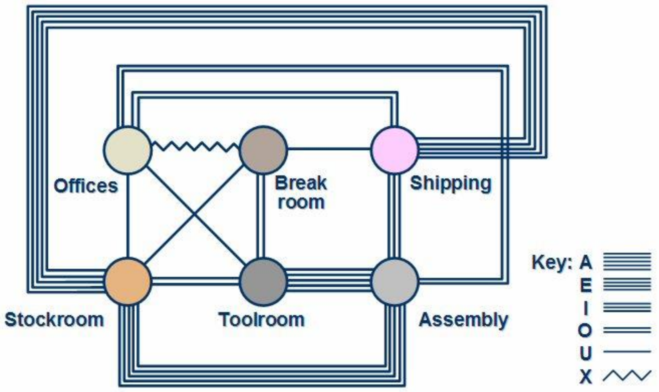


Figure 7: Example of SLP relationship diagram

4.1.1 Implementations of SLP framework in other literature:

Bai (2019) mentions factors to consider for the space requirements, such as storage capacity per square meter, what channels to account for, the type of forklift and its turning radius and shelf passage width. The physical location of the case is described and importantly, functional areas such as storage and packaging are divided. A workflow design shows the links between these areas, and with a correlation analysis the logistical relationship diagram between areas is set up. This is combined with the non-logistics relationship diagram (with for example personnel movement and handling) for a comprehensive relationship diagram. This was used as input for FlexSim to create a suitable layout.

Zakirah et al. (2018) provide an insightful graph of a modified SLP procedure for designing a new warehouse layout, displayed in Figure 8. The research is especially applicable because it handles a comparable case to the ROSEN group. The handled company (Pelindo Marine) is also a high-tech service provider with a lot of equipment, both in and outside, with reconditioning area needs. As in the above case, a workflow diagram is designed and from these departments the activity relation chart with the AEIOUX labelling applied between the departments. These are combined again for an activity relationship diagram.

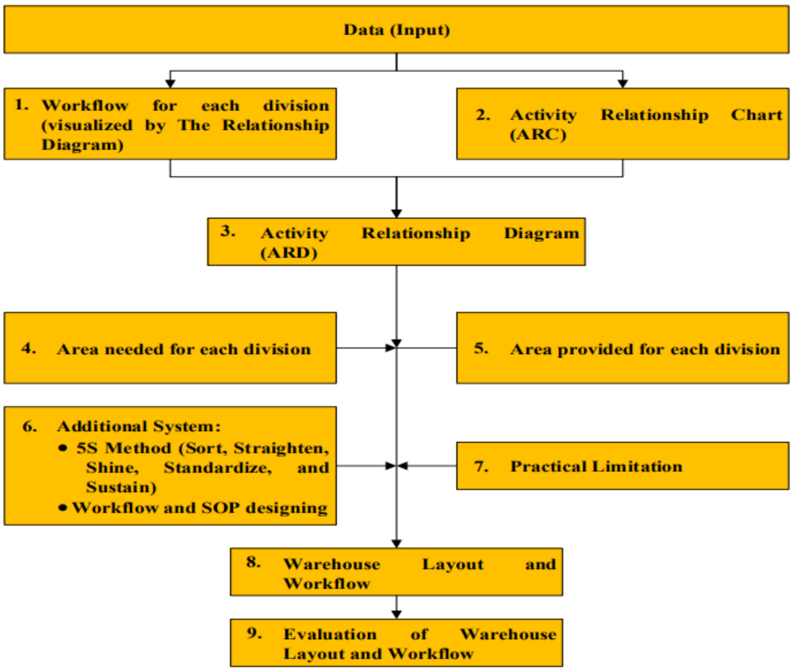


Figure 8: SLP procedure for new warehouse layout (Zakirah et al., 2018)

A same approach can be found in the literature of Hu et al. (2022) and Wen et al. (2015). Hu et al. make the translation to a solving model more concrete by stating "The closeness between functional areas is used as a parameter to optimize the warehouse layout." The logistics volume displacement is then graded and given the AEIO(UX) rating. These figures are then used in the objective function with constraints. Wen et al. go further in-depth to mathematically evaluate the established logistics layout.

To conclude this section, a frequently applied framework in (warehouse) layout problems is the SLP approach by Richard Muther. The framework demands an activity workflow, and the activity relationship chart of each activity. These are combined into an activity relationship diagram, which is further dimensioned by space requirements. There are several ways to take this into alternative layout solutions, for example with a computer simulation, but also by-hand evaluation is possible.
The SLP approach is tried and tested, but some more in-depth explanations of several steps are preferred. It can be used by experienced designers, but it might be difficult to make estimations and be inclusive of all components as a novel designer. Therefore, other more detailed literature was searched.

4.2 Warehouse design

This section handles several papers about the warehouse design process and decisions that must made throughout the procedure. We compare and contrast the papers in the field in the following section to get a holistic overview of the process of warehouse design. We start with the overall goal of a warehouse design. De Koster et al. (2007) quote multiple company missions that warehouses contribute to, relevant to this case being: supporting the customer service policies, meeting changing market conditions and uncertainties, supporting the just-in-time approach, providing temporary storage of material to be disposed or recycled, providing a buffer location for trans-shipments. Geraldes et al. (2011) add to this by stating more concrete reasons: consolidating products for less costs and better service, the advantage of economies of scale, deliver value-added processing and reducing response time.

Warehouse functions and flows

The flow of items through a warehouse can be divided in several distinct phases, or the warehouse processes De Koster et al. (2007). Firstly, there is the receiving stage, that comes with possible checking or transforming actions. From there, storage begins, which may consist of a reserve area with economical storage, and forward area with storage for easy retrieval. Moving from reserve to forward is called replenishment. When required, the order is then picked/retrieved from storage. After which it can then be transported to sorting and/or consolidation (grouping of items for the same customer). Finally, there is the shipping area, where orders are checked, packed, and loaded. Tompkins et al. (2003) give a more detailed diagram of the above functions, together with flows between them, in Figure 9.

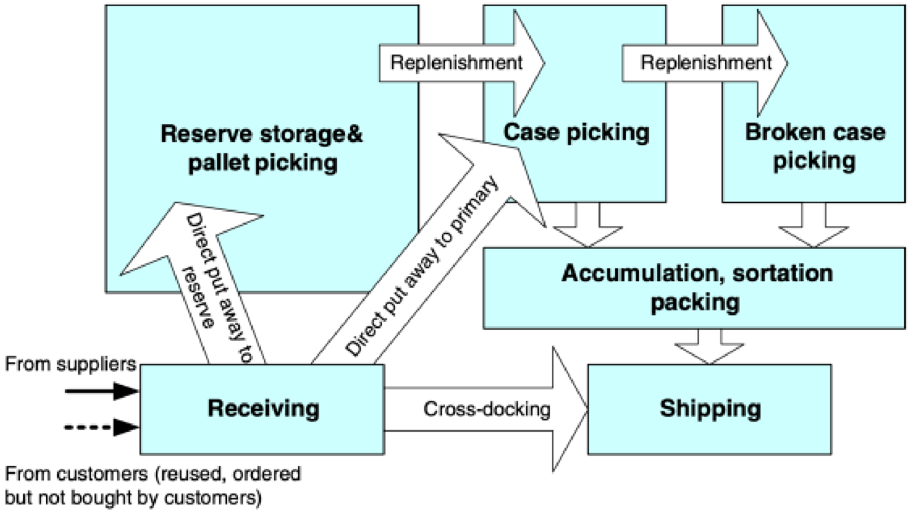


Figure 9: Typical warehouse functions and flows (Tompkins et al., 2003)

Points of interest for the ROSEN context are the 'possible checking or transforming', as it is visible in Figure 4 that the inbound process at ROSEN consists of many such steps before the storage stage. Furthermore, the ROSEN context is thus not always a direct following of these stages.

An important work in the field of warehouse design and control is the one by Rouwenhorst et al. (2000). They give an overview of the important factors in designing a novel warehouse, starting with characterizations, factors that play a part in warehouse design and then present a framework for warehouse design.

Organizational issues

The most important decision in warehouse design is definition of the process flow, with processes requiring specific policies. The organisation of these operations immediately impacts the supply chain's performance (De Koster et al., 2007). Rouwenhorst et al. (2000) also state that this is one of the first decision to make. There are many storage regulations. While a random storage policy gives the operator the option of where to place a product, a dedicated storage policy specifies a specific location for each product to be stored. De Koster et al. classify the policy where operators choose a location as closest open location storage, and dedicated storage as having the lowest space utilization among all policies. A class-based storage policy (ABC zoning) assigns zones to particular product groupings as a middle ground, frequently based on their turnover rate. Other storage rules, such as correlated storage or family grouping, are designed to keep products close together if they are frequently needed at the same time. A reserve area storage policy is also required if the storage system contains a separate reserve area. The forward/reserve and replenishment policies, respectively, determine which items are stored in the forward area and in what quantities, as well as when replenishments are made.

Rouwenhorst et al. (2000) and Sapry et al. (2020) describe the stages of the design process: concept, data acquisition, functional specification, technical specification, selection of means and equipment, layout, and selection of planning and control policies. These decisions are situated at the strategic, tactical and/or operation level. For example, designing the process flow is part of the functional and partly technical specification stages, while being of a strategic level. This can be compared to the diagram in Figure 10 by De Koster et al., where the main distinction is made on strategic versus policy levels.

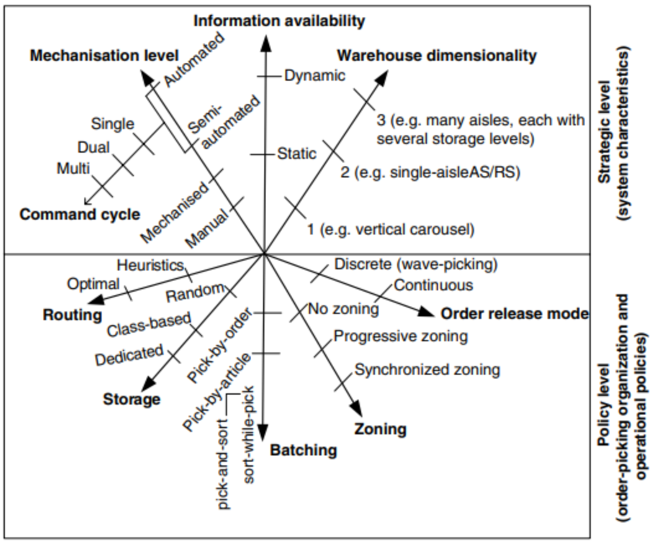


Figure 10: Complexity of order-picking systems (De Koster et al., 2007)

However, the hierarchical architecture described by Rouwenhorst et al. reflects the decision-making horizon (long term, medium term, short term), while solutions selected at a higher level serve as the constraints for lower-level design challenges. It goes without saying that most decisions are interrelated. A basic first design is outlined with limited detail, then at later stages, this design is improved. According to Geraldes et al. (2011), the process of warehouse design and planning starts with a functional description and moves on to a technical specification, equipment selection, and finally layout determination. Operating policies are seen as a separate section of the design process, instead of the final as by Rouwenhorst.

Of the two types of warehouses given by Sapry et al. (2020), distribution warehouse and production warehouse, the latter fits best to ROSEN. It is characterized by storing raw, work-in-process and finished products, sometimes for extended periods. For long duration storage, the prominent design criterion of this type of warehouse is the *storage capacity*, with the main design objectives being low investment costs and operational costs (Rouwenhorst et al., 2000). Work-in-process storage, a large part of ROSEN's storage, has the design constraint of *response time*, as demand can be unknown, and retrieval must be fast to prevent delays in the Workshop department.

4.2.1 Warehouse design problems on the strategic level

The two main groups of problems at the strategic level are the design of the process flow and the selections of types of warehouse systems. The process flow design defines the required processes, in its most basic form receiving, storing, picking and shipping. The decision concerning the types of warehouse systems at this level concern investments like the storage or sorting system. These are two-way related, because the processes dictate the required systems, while the possible processes can only be designed if there are available systems. The entire decision process at this level can be decomposed into two sequential decision problems: one based upon technical capabilities and the other one based on economic considerations. The technical problem concerns both the processes and system selections, with the input being the characteristics of the products and the orders. The output are combinations of systems that can technically handle the products while meeting the performance constraints (throughput, response times and storage capacity).

This is used for the second decision problems, where these possible system combinations are weighed economically, aiming at minimum investment and operational costs. Each decision made at the strategic level puts constraints and requirements on the lower levels.

Further classification of warehouse systems is given by De Koster et al. (2007) in Figure 11, with the focus being order-picking systems. The current situation at ROSEN can thus be derived as being human-employed, picker-to-parts, high-level, pick-by-order.

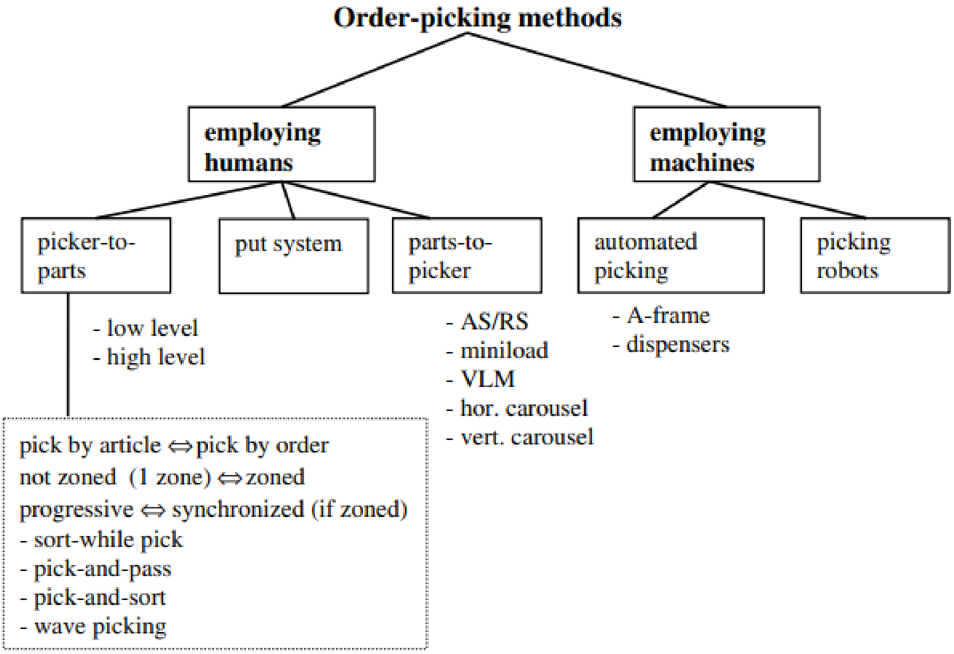


Figure 11: Classification of order-picking systems (based on De Koster, 2004)

Heragu et al. (2005) state that setting the size of each functional area is a strategic-level problem, but it is also a tactical-level problem because it depends on how the products will be distributed among the functional areas. The latter is called the product allocation problem. Therefore, they state that a combined solution to the problems of functional area size determination and product allocation is preferred. A mathematical model is presented to be used at the beginning of the warehouse design process, with the results being able to serve as a base for further detailed warehouse design. The paper assumes a set of four possible flows, and knowledge of several factors such as space, behaviour, rates and costs. These are combined into an extensive mathematical model that provides the ratio of fast pick area to bulk storage area. In case the situation is too extensive for the mathematical model, a heuristic algorithm is also given that can reach optimal solutions faster. Overall, the paper does not deal with types of storage systems and simplifies the storage to just the stages cross-docking, reserve and forward. It assumes the filling of these stages to be uniform, while in the ROSEN context, there are many different storage requirements. Therefore, the more extensive process of Rouwenhorst is further explored.

4.2.2 Warehouse design problems on the tactical level

Tactical decisions typically concern the dimensions of resources (storage system sizes but also number of employees), the determination of a layout and several organizational issues. Clusters of problems that arise at the tactical level and should be treated simultaneously include:

- organizational problems including the dimensioning of the picking zones and the ABC zones, the determination of replenishment policies and batch sizes, and the selection of a storage concept (random, dedicated, class-based),
- determining the dimensions of the storage systems, including the forward and reserve areas,
- determining the dimensions of the dock areas,
- determining the number of material handling equipment,
- establishing a layout of the overall system,
- determining the number of personnel.

4.2.3 Warehouse design problems on the operational level

The operational level has fewer process-interfaces than the strategic and tactical level, so the policies in this level can be analysed independently. The decisions are mainly about assignment and control problems of people and equipment. The storage decisions are assigning replenishment tasks and allocation incoming stock according to decisions made at the tactical level.
Order picking decisions are about creating batches, assigning these to order pickers and routing. Assigning personnel and equipment to inbound and outbound operations is furthermore a decision at this level.

To summarize, Rouwenhorst et al. (2000) create a broad framework with three levels of detail, strategic, tactical, and operational. Each stage has decisions that influence each other, with the biggest influence in the first stage, and so down. Other papers add background to these levels, with different focusses such as dimensioning and order-picking. The authors themselves notice that further literature in more detailed design is missing. More concrete, guided processes are required for the inexperienced warehouse designer.

4.3 Towards a structured approach

The literature review by Baker et al. (2009) looks at a vast number of papers that handle warehouse design frameworks. The goal is to create a comprehensive, detailed approach, as many researched papers state that a holistic framework is missing. All the methodologies share common themes: warehouse design is highly complex, step-by-step approaches are created to deal with this, these steps are interrelated and require reiteration, because of the vast amount of possible outcomes, it may not be possible to identify the optimum solution.

The steps differ from framework to framework because of grouping and scope, but a common pattern is found. To find out if and how these steps are used in real applications, seven companies were asked to set out their used steps. The used steps are not too different from the steps from literature. The literature provides useful tools for some of the found steps but does not cover all of them. Common tools are stated (such as spreadsheet models) and added to the framework summarizing the main tools used. The steps are as follows:

1. Define system requirement
2. Define and obtain data
3. Analyse data
4. Establish unit loads to be used
5. Determine operating procedures

6. Consider possible equipment types and characteristics
7. Calculate equipment capacities and quantities
8. Define services and ancillary operations
9. Prepare possible layouts
10. Evaluate and assess
11. Identify the preferred design

In the following chapter, this framework is explored further and applied to the context of ROSEN. While the framework is holistic, it is mentioned that useful tools are provided for some of the steps, but not all of them. Therefore, per given step, further context was found on the exact methods, combined with the knowledge gained from the broader warehouse design literature.

4.4 Chapter conclusion

To answer sub-question 3 – which methods or theories exist in the scientific literature that guide the design of a new storage facility – there is a lot of literature concerning warehousing and layout design. A standard work in this field is the Systematic Layout Planning (1973) and Systematic Handling Analysis (1975) by Muther, with a lot of researched papers dealing with the methods. Because the methods by Muther are not overly in-depth, extra papers were studied to provide more theory on the practical applications. Still, the methods and added frameworks are geared towards more experienced layout designers. Novel designers will look for more clarity in another often-cited work, by Rouwenhorst et al. (2000). This paper distinguishes three levels of design, strategical, tactical, and operational. A design is created by going through these stages consecutively, with the first being strategical. Decisions made at this level concern process flows and warehouse system types. These decisions affect the considerations at the following steps, and the same applies for tactical to operational. More papers that focussed on this central paper were researched, along with further warehouse design theories. In conclusion, a framework was derived based on work of Baker et al. (2009).

5 Application of framework

In this chapter, the previously found framework is adapted to the ROSEN context, and then performed stepwise. Each step consists of several issues to be answered with related deliverables. The goal is to continually use the deliverables of previous steps in the answering of the next steps issues.

As mentioned in the previous chapter, the framework of Baker et al. Baker et al. (2009) is employed, but for further information per step, other papers and literature can be consulted. Below is the framework, adapted to the ROSEN context through the second and third column.

Step	**Implication/questions at ROSEN**	**Deliverables**
1	What should the overall system be capable of handling? What KPIs need to be met? What is the future scope, what scenarios are imagined? What (primary) functions does the warehouse need to fulfil?	Description of warehouse type and functions. (Quantified/quantifiable) checklists of KPIs and design criteria.
2	What data needs to be retrieved from ROSEN? What aspects are important and in which (filetype) representation?	Checklist (=define) of product details, order profiles, goods arrival and dispatch patterns, inventory levels, cost data and site information. Retrieved data in workable and clean state, either spreadsheet or database.
3	What information needs to be extracted from the data, how can the above retrieved data be profiled to become insightful? How can this data give insights to the KPIs? How is this data expected to change in the planning horizon?	Activity profiling, for concepts as order, item, inventory, calendar-clock. Predictions of data changes.
4	What unit loads are in use, with what characteristics? Can this be changed, for example to become more uniform?	Quantified description
5	Aside from layout, how do the warehouse functions relate to each other? What operating methods fit with these functions? What zones could be determined (high-level and product level)? Which designs of processes can handle the work while meeting the performance constraints?	Mapped list of functions, their relations and groupings, used methods, and several overall process flows.
6	What is the scope of the equipment possibilities? What (physical) characteristics must equipment meet? What are the associated costs? How can combinations of equipment be made, so that they can handle the work while meeting the performance constraints?	Overview of market offerings, including costs. Checklist of physical requirements. Combinations of work-bearing equipment.
7	For the above combinations, how do they handle the work? How much of each is required? How would possible equipment perform under alternative scenarios?	Analysis of work-bearing performance, against differing constitutions of the equipment, with alternative scenarios.
8	What other operations must be supported by the design, aside from primary functions?	Checklist

9	What would possible layouts look like? What methodologies are applicable? What is a suitable approach and/or software? What objectives (besides overall design criteria) do generated layouts need to meet?	Description of generation process. Generated layouts in suitable format. Checklist of met objectives.
10	Validate the operational and technical feasibility of solutions, against overall design criteria and factors as flexibility and safety. What would capital and operational costs be? How can the results be simulated, and future resilience measured?	Mathematical analysis of the generated designs for design criteria. Added costs estimations. Future proofness statement.
11	Quantitative and qualitative analysis of the proposed design, as a business case for ROSEN.	Full implementation expectation of the chosen layout.

Table 1: Adapted framework

With the framework now created, the following part of this chapter uses it to create valid warehouse designs for ROSEN. It is important to take into account that due to stated scope, data and time restrictions, not every step as given in the framework is performed fully. Per step, the elements that were useful for subsequent steps and overall valid and usable designs were performed. The most important parts that were not executed of this framework concern forecasting, concrete data about products and equipment, and extensive costs calculations. Throughout the process, unknown or assumed information is indicated and subsequent steps are still insightful.

5.1 Define system requirement

In this step, the warehouse goals, type and required functions are explored so that a top-down approach is applied. Furthermore, the design criteria of a new facility are created and prioritized so that solutions can be assessed to the correct standards. Finally, the product portfolio is analysed together with future plans so that solutions are future resilient.

Of the warehouse goals of De Koster et al. (2007), several apply to the ROSEN facility. These are supporting the customer service policies, meeting changing market conditions and uncertainties, supporting the just-in-time approach, providing temporary storage of material to be disposed or recycled and providing a buffer location for trans-shipments. Furthermore, in this specific case, it can be argued that the facility as a whole must provide value added services, such as the cleaning and refurbishing of the tools.

As stated before, the ROSEN facility is a production warehouse, storing semi-finished and finished tools together with ancillary products. Raw material storage does not play a role, as the initial production of the inventory in Oldenzaal takes place in Lingen, Germany. This classification differs from a distribution warehouse, where quantities of products from different suppliers are large, and distribution is instant after order-picking. Berg et al. (1999) and De Koster et al. (2007) mention that the activities in a warehouse can be subdivided into four categories: receiving, storage, order-picking and shipping. These are also visible in the ROSEN facility and have been further explained in Chapter 3.

De Koster et al. (2007) provide a classification of order-picking systems, which allows the situation at ROSEN to be described in literature terms. The ROSEN warehouse can be classified as a human-employed, picker-to-parts, high-level, pick-by-order. Picker to parts means that the employee moves to the stationary products to retrieve them. In the ROSEN case this is almost always with the use of fork-lift trucks. This allows for the process to be high-level, meaning tools and products can be retrieved from above regular reaching height, also called man-aboard order-picking. Lastly, pick-by-order is apparent from the figure above, where order-picking movements are based on the shipment list of a single order. This is also the case because the total amount of orders is not so high, with a relatively small number of products required, eliminating the need for pick by article or extensive order-picking strategies.

Design criteria

The primary goal of order-picking systems is to maximize service levels while taking into consideration resource limitations like labour, equipment, and capital (De Koster et al., 2007). These service levels relate to the customer in aspects like order delivery time, on-time shipping rate, cost per order and order completeness levels. To guide the execution of the framework, design criteria are created in this section, both general and ROSEN-specific. These are used after solutions have been created, so that they can be evaluated. The criteria are listed below in decreasing order of significance and are based on the literature research and findings at ROSEN.

Storage capacity

Because the ROSEN facility is a production warehouse, materials may be stored for long periods. Some of the tools and equipment is rarely needed, so the storage must be cost-efficient. The prominent design criterion is therefore storage capacity (Rouwenhorst et al., 2000). Furthermore, in the current situation, the warehouse is overfull, leading to tools being stored on the floor area and materials being stored outside. Therefore, created solutions must logically fit all the desired objects.

The literature further pointed out that, for a production warehouse, response time is an important design factor. This is captured by the following design criteria.

Accessibility

Solutions must provide proper access to the stored materials, such that they can be easily navigated to and easily retrieved. This implies a solution where all materials can be stored in their designated/zoned location, rather than being placed in other places where they block movement or are harder to retrieve. The design must make it intuitively clear where certain SKUs are to be found, so that tools are easy to find. Accessibility is provided by aisles, but they do not offer storage capacity. Therefore, as much aisle space is required for adequate accessibility, but no more (Bartholdi et al., 2019). The minimum for ‘adequate’ depends on the chosen material handling equipment.

Zoning

Solutions must allow for zoning to be applied in the slotting of the materials. Zoning, or class-based storage divides materials into classes based on some criteria and each class is assigned a block of storage locations (Önüt et al., 2008). Often the criteria for the classification are based on turnover rate (Rouwenhorst et al., 2000), but in the evaluation of a chosen solution, it is worthwhile to also consider profits generated by the respective turnovers. The goal is to allow more critical materials to be placed in more convenient locations.

Flow

Another aspect that must be considered in the created solutions is the way they allow a logical and efficient flow of all goods, personnel, and equipment throughout the facilities. Taking this criterion into account support the accessibility factor by reducing redundant movements. Furthermore, it reduces overall unnecessary movements and can help find bottlenecks (Yener et al., 2019).

5.2 Data retrieval

Now that the system requirements are defined, this step handles the data (retrieval) required for the subsequent steps. For this, several areas of the facility operations are segmented. Critical for a new system are of course the characteristics of the products it must store, also leading to the requirements for the storage systems. This flat product data must be dimensioned in quantities and through time to achieve an understanding of the requirements a new solution must meet. Thirdly, the possible day-to-day operations are analyzed such that solutions are not just capable of storing the products, but also support the daily workflows. The following table shows per subject the knowledge goals, the data area and properties.

Subject	Goals	Data area	Properties	Remarks
Product characteristics	Determine physical requirements of storage locations and systems	Tools	Length, width, height, weight, length-of-stays	Tool configurations differ through time, so there is not one dimension per tool, but the distribution is key
Inventory profiling	Determine required storage capacities	Tools	Order history	Tool configurations differ through time, so there is not one order history per tool, but the distribution is key
		Warehouse Management System	In-house tools, quantities through time	Also required for the seasonality analysis
Activity profiling	Analyze which activities a new warehouse must support (daily)	Tool Prep Sheets	List of required items to retrieve	Dependent on inside storage obligations

Table 2: Data retrieval characterization

Getting this data into a database requires certain tables, with relationships between the tables. These can be seen in the figure below.

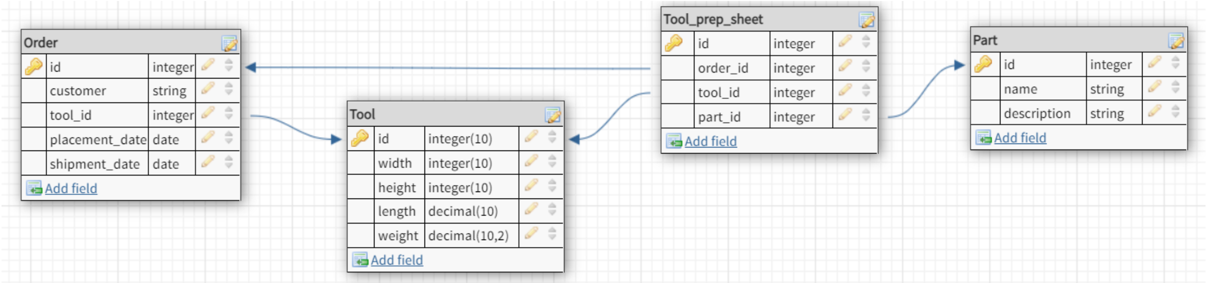


Figure 12: Data tables relationships

Below is an explanation of Table 3 and Table 4, which describe the tools and order tables. Furthermore, an explanation of the tool preparation sheet and part tables is given.

Tools table

Property	Unit and description	Minimum value	Maximum value	Distribution
Tool_ID	ID of tool	1	200	Ascending

Width	Width of the tool in cm. Width and height are equal due to the circularity of tools.	15 centimeters	142 centimeters	Normal distribution (μ = 78.5, σ = 25)
Height	Width of the tool in cm. Width and height are equal due to the circularity of tools.	15 centimeters	142 centimeters	Normal distribution (μ = 78.5, σ = 25)
Length	Length of the tool in cm. Length is measured in the same direction in which the tool passes through pipes.	40 centimeters	500 centimeters	Normal distribution (μ = 270, σ = 100)
Weight	Weight of the tool in kg.	14.3 kilograms (Theoretical minimum)	16,034.7 kilograms (Theoretical maximum)	Calculated as cylinder→π * 0.5 * Width * 0.5 * Height * length * density assumed based on aluminium

Table 3: Characteristics and properties for tools

Order table

Property	**Unit and description**	**Minimum value**	**Maximum value**	**Distribution**
Customer_ID	Customer ID	1	250	Random
Tool_ID	ID of the tool	1	200	Normal distribution (μ = 100, σ = 30)
Placement_date	Order placement date	23-02-2020	24-02-2023	Distribution in ROSEN data
Shipment_date	Date of dispatch of the order	24-02-2020	03-03-2023	Distribution in ROSEN data
Return_date	Date of order return	10-03-2020	17-04-2023	Distribution in ROSEN data

Table 4: Characteristics and properties for orders

There is also the auxiliary parts table, which contains 141 parts. This list is composed of lists of technical components found online. These are linked to the orders in the Tool Prep Sheet table, with a normal distribution for the parts used per order. This is used to create an estimate of the total workload per order.

Assumptions

The minimal and maximum values of width, height and lengths are set to 15-142 and 40-500 centimeters. These lengths are in whole centimeters. The maximum diameter of 142 cm comes from the 56-inch tool that is known to be the largest tool diameter in use.

Determining which dimensions apply specifically for each tool is done via a normal distribution. This leads to a graph like the one visible in Figure 13. It shows that tools with average dimensions are the most common, and tools with small or large dimensions occur less frequently.

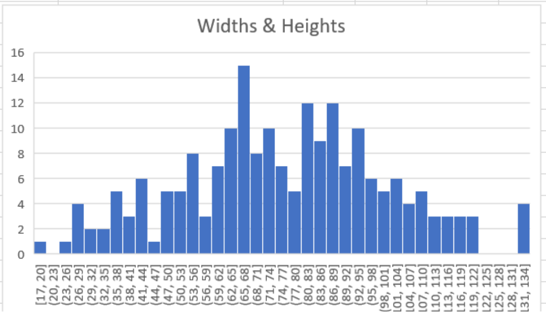


Figure 13: Generated widths and heights

The weight of a tool is logically dependent on its size, and can thus be calculated once the dimensions are given. The tool is seen as a cylinder with given dimensions. The calculated volume is multiplied by the average density of a tool to determine its weight. Aluminium is assumed to be the most determining factor for weight. A tool is of course not a solid cylinder of aluminum, so the density of alumium has been scaled with 0.75 (= 2.025 g/cm^3) to make an estimate of the real weight. A tool has many components, of which some are heaver and some lighter. Magnets are for example heavier than this density, but certain parts and air in the tool bring the average weight down again.

The order table contains a historical overview of ordered tools. For each order, a tool ID is generated in this data via a normal distribution. The tools with ID around 100 are therefore used more often than tools with a minimum or maximum ID, as visible in Figure 14. Sorted, it becomes clear that a relatively small part of the tools takes care of the most work, which is often the case in warehousing and other processes (pareto principle).

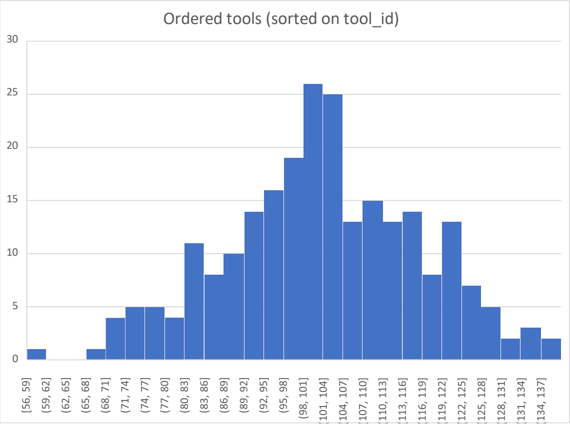


Figure 14: Generated ordered tools. Horizontal axis shows the times ordered in the 3-year timespan.

An often followed ratio is 80% of the work or profits come from 20% of the products. With 200 total products, this would mean 40 products leading to 80% of orders. To reach this principle in a normal distribution of μ = 100, the standard deviation σ would have to be 15

$$X \sim N(\mu, \sigma) \quad \mu = 100, \sigma = 15$$

$$\mathrm{P(X < 80) = \ P\ (X > 120) = \ 0.091\ and\ P(X < 81) = \ P(X > 119) = \ 0.103} \qquad (1)$$

Meaning that about 80% of orders come from tools 80 through 120. However, using this normal distribution, it can be calculated that over half of the products only make up 10% of orders in a given timeframe.

$$\mathrm{P(X < 50) = \ P\ (X > 150) = \ 0.00043\ and\ P(X < 51) = \ P(X > 149) = \ 0.00054} \qquad (2)$$

In discussion with ROSEN, this was deemed unrealistic, and a σ of 30 set for the distribution graphed in Figure 15:

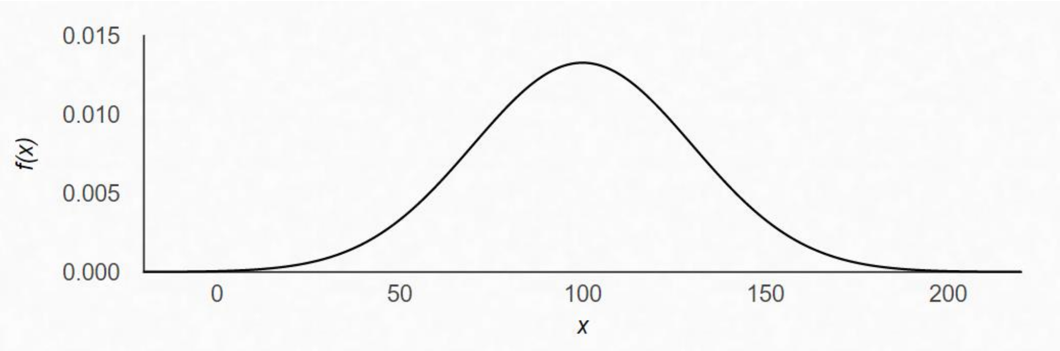


Figure 15: Normal distribution for ordered tools, μ=100, σ=30

The dates used in the order table come from data exported from ROSEN, called 'Preparations of equipment'. This file with 2134 rows was cleaned by only leaving unique projects, which makes it clear that in the period from 23-02-2020 to 24-02-2022 there have been 244 preparations/orders. This concrete and realistic data has been used for the column placement_date. The columns shipment_date and return_date are based on this, with the assumptions that an order is sent between one and seven days after placement and comes back between 15 and 45 days after shipment. These columns make it possible to analyze in the known time frame how often and when a tool is gone. This can be seen per completed tool number in the table to the right of the data and is expanded upon in the following section.

5.3 Data profiling

Inventory profiling

From the tools and order data above, an inventory master can be derived. This is first done by calculating how many tools are in shipment on any given day in the date range. It is visible in Figure 16 that, at most, around 20 of the 200 tools are shipped at a time. There are also moments where nearly every tool must be stored in the Oldenzaal facility. This means the tool storage facility must be capable of storing the total amount of materials throughout the year. This in contrast to a situation where a consistent amount of, for example, 40 tools are in shipment, which would reduce total storage requirements.

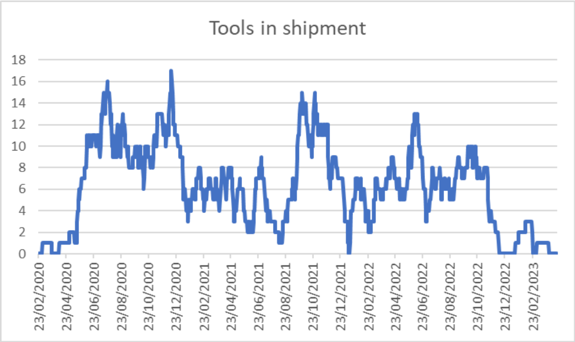
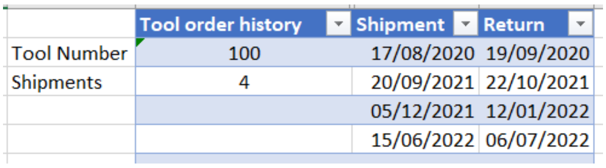


Figure 16: Shipped tools throughout time



	Tool order history	Shipment	Return
Tool Number	100	17/08/2020	19/09/2020
Shipments	4	20/09/2021	22/10/2021
		05/12/2021	12/01/2022
		15/06/2022	06/07/2022

Figure 17: Tool order history for selected tool

Furthermore, it can be calculated when and how long individual tools are in shipment. An example of this is shown in Figure 17, in this case for tool number 100. This calculation allows an overview of per tool analysis.

Zoning

Warehouse zoning classifications are used to organize the placement of items within a warehouse in order to maximize efficiency and reduce labour costs. One way to create warehouse zoning classifications is by using order history.

First, data from previous orders can be used to identify the types of items stored in the warehouse and the quantity of each item. This information can be used to create groups of products that are related to each other in terms of size, weight, and other characteristics. For example, items that are of similar size and weight can be placed in the same zone, while items that are of different sizes and weights can be placed in different zones.

Second, data from past orders can also be used to determine the frequency of orders for each item. This can be used to create zones for frequently ordered items, as well as zones for items that are ordered less often. For example, items that are ordered more often can be placed in a zone that is closer to the shipping dock, while items that are ordered less often can be placed in a zone that is further away.

Bartholdi et al. (2019) state three more specific views of how to analyse the order history for an ABC analysis. The given example considers a more classical warehouse, with cases that hold separate SKUs that can be picked more than one at a time. In fact, in the ROSEN context, these three views coincide to the following conclusion on useful turnover rate: “Most of the labour in a warehouse operations is devoted to order-picking and so it is useful to rank SKUs by the number of times they were picked during some recent interval” (Bartholdi et al., 2019).

To apply this in the ROSEN context, with the generated data, it is apparent that tools with ‘average’ tool numbers are picked more often. To give insight to this, Figure 18 shows how often each tool is ordered in a generated data set.

A classical ABC analysis division is according to the pareto principle, where a large portion of the activity comes from a small portion of actors. As described in step 5.2, a normal distribution with μ = 100 and σ = 30 is used. To create insight on the relative importance of each tool, the tools are sorted on order frequency, with the cumulative order percentages calculated. This way, a distribution for the ROSEN situation becomes visible in Figure 19. To create the A zone tools, the first 20% of tools, that lead to 70% of orders is segmented.

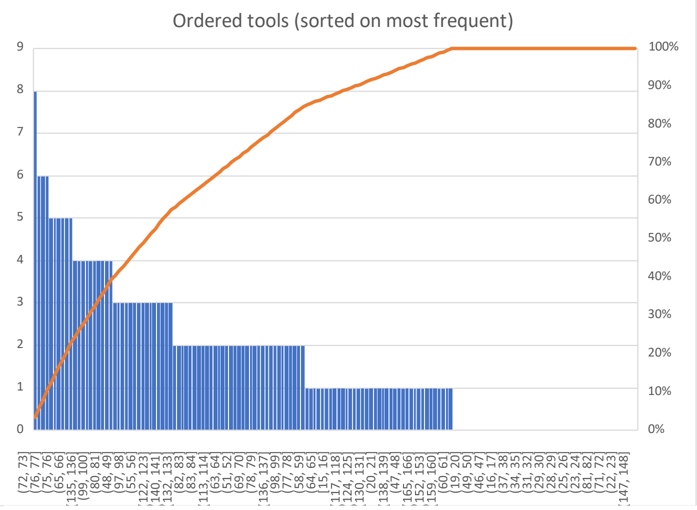


Figure 18: Generated ordered tools

For the B zone, it can be useful to determine the tools that lead to another 20% of orders, such that the remaining C zone tools make up 10% of orders. In order to determine which tools fall in this zone, the following statement is evaluated against the normal distribution with μ = 100 and σ = 30:

$$P(X < x) = P(X > y) = 0.01 \quad (3)$$

This leads to x and y being 30 and 170 respectively.

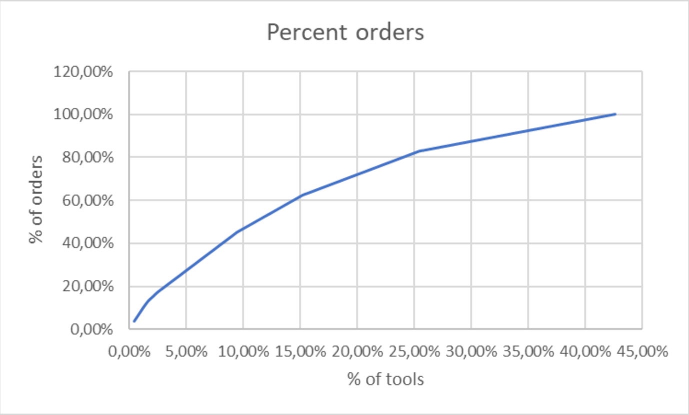


Figure 19: Ordered tools sorted with cumulative order percentages

Thus, the following ABC zoning is determined:
Zone A, with 70% of orders: tools 80 through 120
Zone B, with 20% of orders: tools 30 through 79, and 121 through 170
Zone C, with 10% of orders: tools 1 through 29, and 171 through 200.

5.4 Unit load description

Unit loads are a critical component to consider in the warehouse design process. Unit loads are the way items are packaged and stored in the warehouse. They are typically composed of multiple smaller items or components that are bundled together for efficient storage, transport, and handling.

In the case of the ROSEN tool context, the load to be moved is simply one tool. Whenever a tool is not in active deployment, it is stored on a frame, such as in Figure 20. The most used unit load is therefore a tool plus the underlying frame. As described in the process flows of Figure 4 and Figure 5, incoming tools also have an additional protective top frame, which is removed before further handling, and added before shipping.

Figure 20: Tool stored on frame

While this is the description of the unit load, in reality the specific unit loads vary greatly in terms of size and weight. This is because of the varying dimensions of the tools, although it is generalized all tools have the shape of a cylinder. To restate the minimum and maximum sizes and weights of the tools, please see section 5.2 and the table below:

	Width and height	**Length**	**Weight**
Minima	15 cm	40 cm	14,31 kg
Maxima	142	500	16.034,73 kg

Table 5: Unit loads

5.5 Function and process descriptions

In this section, a description of the functions and processes involved in the warehouse are provided. The warehouse objectives are known, and the specific functions and processes that are used to achieve these goals are described. The transportation methods that are used to move goods and materials within the warehouse are described.

Function mapping

Function mapping is a tool that can be used to analyse and improve the efficiency of a warehouse by identifying the specific functions and processes involved in storing, picking, packing, and shipping goods and materials. By creating a detailed map of the warehouse and the various functions and processes that take place within it, an overview of relevant focus points is created for the layout generation step. To create insight in the performed actions at ROSEN, Appendix B and Appendix C are combined. Namely, the process maps of Appendix B show the warehouse operations in a BPMN format. To create a proper mapping of these functions, the red texts in the notation are reflected in the maps of Appendix C. Thus, by comparing the process models to the process maps, it is visible how incoming and outgoing operations are constructed throughout the facility and time. Further explanation of the occurring processes at ROSEN can be found in Chapter 3.

Transportation methods

In this section, the transportation methods used in the facility are described. As stated in the previous step, the unit loads at ROSEN are single tools with frames, that are moved with forklifts. This transportation method is well equipped for the ROSEN facility for several reasons. First of course, it can handle the unit loads. No distinction has to be made in transportation method per transported tool. Secondly, the driving distances are not too large, so not too much time is wasted in manually driving equipment around. To add to that, the driven paths are not consistently the same but differ, as visible in Appendix C. Automated transportation methods or equipment like conveyor belts would lack the flexibility of forklifts. Tight spaces can be navigated, and materials moved to exact locations.

Another transportation method in use, which has not been discussed before, is the indoor overhead cranes used in the facility. These are used because tools must be moved throughout the dismantling, repairing and re-assembly process. It would be too inefficient to require a forklift to stay on stand-by indoor. Therefore, the main workshop hall has two large overhead cranes that allow the tools to be moved indoor.

Zone descriptions

From the function mapping section above and Appendix B and Appendix C, several warehouse zones can be described. This differs from the zoning described in step 5.3, as that section details storage policy within the general zone for storage in the facility. A derived list of zones present in the facility:

- Truck arrival dock, where the truck arrives, and papers are check before unloading
- Truck unloading area, place directly next to the main building where shipment is broken up
- Supporting equipment and inventory storage, room in main building for auxiliary tools
- Battery storage building, separate building to safely store batteries in accordance with regulations
- Top frame storage and repair section
- Washbay, designated place to clean incoming tools and tool components
- Fort Knox, storage warehouse for tools
- Workshop, dismantling, repairing and re-assembly of tools
- Electronics department, part of the workshop focussed on repairing fine electronics

- Preparation site, designated site where components of outgoing shipments are gathered

5.6 Material Handling Equipment

Besides the (transportation) equipment described above, another important aspect of equipment in the facility is the storage equipment. Bartholdi et al. (2019) give an extensive description of the types of storage equipment used for handling large products. Five types of pallet racking systems are explained, but in the ROSEN context, only single-deep racks are seen to make sense. The other systems all depend on a product SKU spanning two or more pallet spaces. As stated before, the ROSEN situation handles separate and non-duplicate SKUs. This makes the single-deep racking system the best fit for storing the tools in the context.

A balance must be made between the number of lanes and the depth of each lane to maximize efficiency and effectiveness. Too many lanes can make it difficult to access goods, while deeper lanes can make it harder to retrieve items at the back (Bartholdi et al., 2019).

5.7 Auxiliary operations

Solutions must support a variety of auxiliary operations in addition to the primary function of storing goods. Other operations besides this one can be derived from the process maps in Appendix C and have been stated in Section 5.5. As stated before, the scope of the redesign pertains to the Fort Knox section of the current warehouse. Nevertheless, solutions must act in accordance with the mentioned operations. The most important of these operations to be taken into account in the layout generation step are the washbay, workshop and preparation site. It is visible in the process maps that these zones are linked with direct activities to the current Fort Knox, meaning these are the auxiliary operations when looking at the scope of Fort Knox.

5.8 Layout generation

This step intends to generate several different layout solutions, based on the information gathered in previous steps. The previous steps had the function of properly defining the system and criteria, retrieving and profiling data, and describing the functions, processes and equipment used in the warehouse. This knowledge can now be used to generate several layouts that fit these descriptions. In the literature research, the systematic layout planning approach was examined, which focusses on zones in a facility and their relations. The scope of this thesis is a single zone that only relates directly to the washbay, workshop and preparation site. Therefore, and because the approach is more suited to experienced designers, this approach is too broad. It was therefore decided to take the lane versus lane depth consideration into account and start on a heuristics basis. Therefore, the work of Bartholdi et al. (2019) was examined and used. The results of this preliminary approach are afterwards further refined.

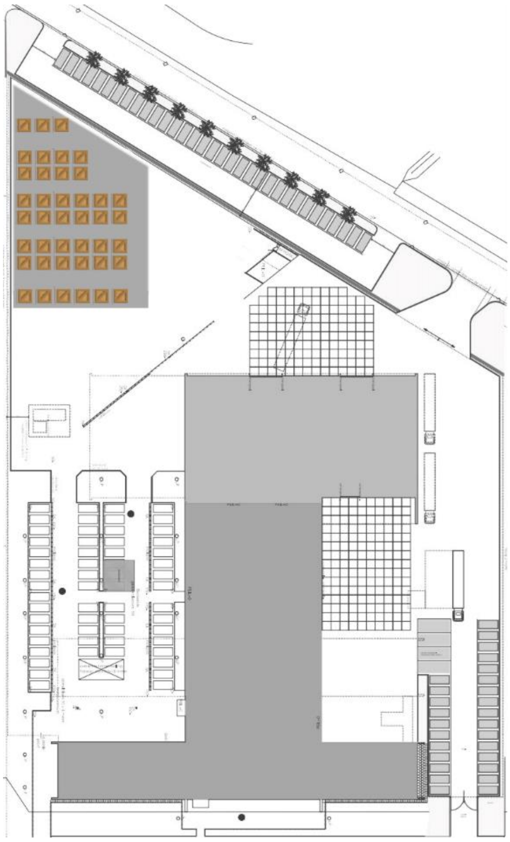


Figure 22: Novel layout

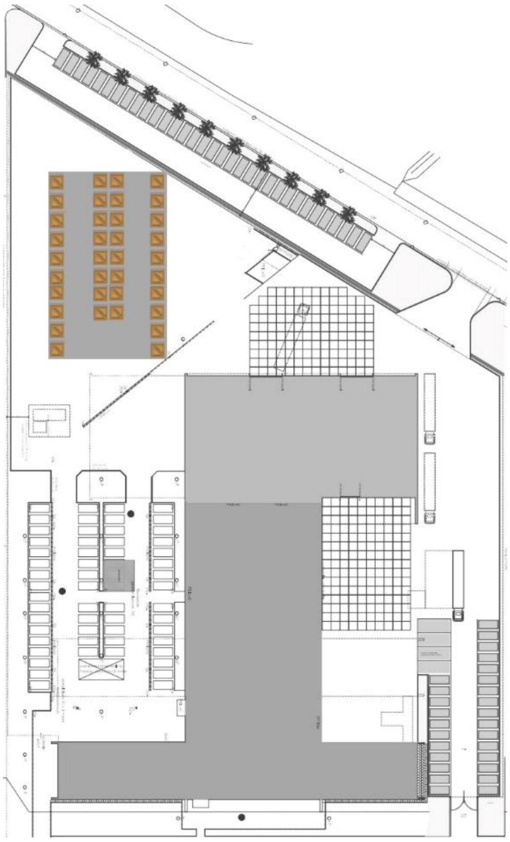


Figure 23: New warehouse on current location

Two layout directions are created, but after closer examination, it is apparent that practical considerations must be added to the layouts. From the previous framework steps, characteristics such as the equipment used, accessibility and flow, and tool dimensions must be taken into account when dimensioning the layouts. Therefore, the existing facility map was recreated in a grid, with each square representing 50 by 50 centimeters in real life. This scale allows for sufficiently detailed drawing so that the above characteristics can be implemented. Measurements were taken from Figure 21 and satellite images. The drawing focusses on the area that allows for redesign, meaning the outside area displayed in Figure 21 is mapped in Figure 24, shown with dimensions.

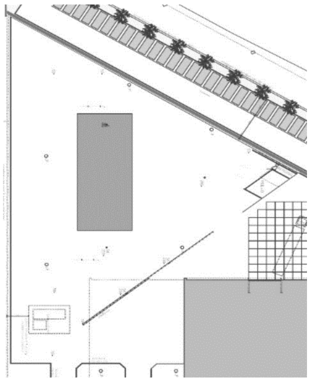


Figure 21: Usable area

Because of the large variety of tool sizes, it is to be expected that the aisle width is not 'one size fits all'. Minimum aisle width is impacted by the length of the tools, because of the way the forklift carries the tools. The smaller tools are not longer than the forklift's width, so will not require specific or smaller aisles. The widest tools are up to 500 centimeters long, meaning some of the aisles must allow for this transport.

Because of the heavy load weights at ROSEN, heavy-duty forklifts are used. Because the outside facility floor surfaces are not even, 3-wheel forklifts are not recommended due to risk of tipping over. However, 4-wheel forklifts have a larger turning radius than 3-wheel forklifts. The aisle width (W_a) needed for a 4-wheel forklift can be calculated through following formula (4) from Amon et al. (2022)

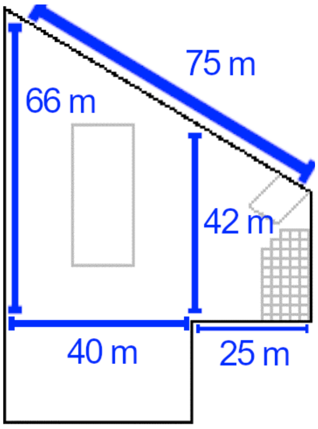


Figure 24: Mapped area

$$W_a = \sqrt{(y+\frac{c}{2})^2 + b^2} + \mathrm{x} + \mathrm{m} + 2\Delta \quad (4)$$

where

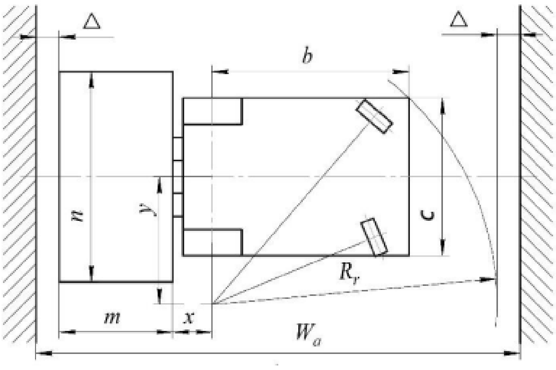


Figure 25: Scheme and dimensions of a four-wheel forklift (Amon et al. 2022)

y - the distance from the symmetrical axis of the forklift to the center of rotation in millimeter
c and *b* - constructive dimensions of the forklift in millimeters, with c being the width and b the distance from the rear to the front axle;
m – pallet width in millimeters;
x - the distance in millimeter from the front axle to the rear surface of the forklift;
Δ - the permissible distance between the aisle wall or the shelf and the forklift in millimeter, in practice this distance is taken as 100 mm (for a clearance of 200 mm).

Formula (4) is applied with ROSEN data and data from forklift (Toyota, 2022) that is similar to the ones in use at ROSEN.

$$W_a = \sqrt{(1500+\frac{2141}{2})^2 + 2780^2} + 715 + 780 + 2 * 100 = 5481\ \mathrm{mm} = 5.48\ \mathrm{meters} \quad (5)$$

We take the principles and dimensions from above to iterate on the previous designs. In the created designs Figure 26 and Figure 27, the shelves are 1.5 meters deep to accompany the tools, and a 5.5 meters clearance is held in aisle width and corners. To allow for more maneuverability and less hard-to-reach space outside, both of the created designs are placed in the corner of the facility. Layouts located similarly to the existing situation of Figure 21 were also created, but gave no advantages because when using a rectangular layout, they left much 'dead' space in the facility. They would create sharp corners that are unreachable by the equipment. Placing a warehouse parallel along the upper wall implies incorporating a lot of the diagonal wall. This leads to inefficient shelf placement due to the turning radius of the equipment. This is also visible in designs A and B, where the diagonal wall leads to unusable spaces. It was thus decided to create a design in the corner of the facility, with layouts parallel or perpendicular to the eastern wall.

The designs take the calculated aisle width into account, and the building size is set such that it allows for an optimal number of aisles with this aisle width in both designs. This means we compare the two layout patterns on a rectangular warehouse area of 27 by 40 meters, with a triangular section of 28 by 17 meters.

Figure 26 and Figure 27 were created such that for the same floor dimensions, an optimal number of aisles could 'fit' in the area. If design B of Figure 27 was made smaller in the vertical (north-south) axis, it would linearly decrease the storage capacity, while design A of Figure 26 would have had a broken number of aisles or wasted space. Likewise, making the designs smaller in the horizontal (east-west) direction would negatively impact design B far more than design A. Therefore, the area in both designs is equal and set to a size where both designs come to their right. This way, both designs can later be judged fairly on their patterns. The dimensions are given in Figure 26, and are thus the same for Figure

27. Because of the orientation of the shelves, the input/output (I/O) point for the forklift is different in both designs. A single door is implemented because the order frequency is not high. Furthermore, constructing just one door is less costly and lastly, security is a concern, so it is preferred to have one door over two. In the construction and later use of the door, more attention can be paid to strength and safety protocols.

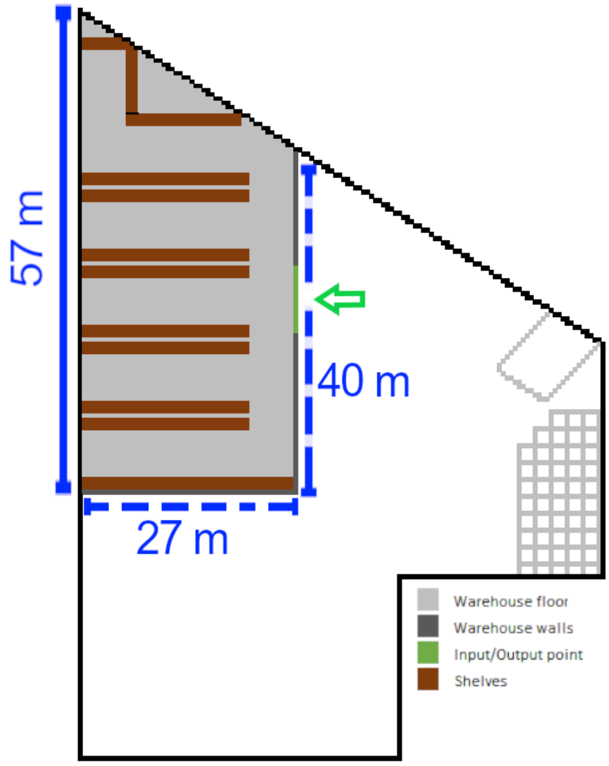


Figure 26: Design A

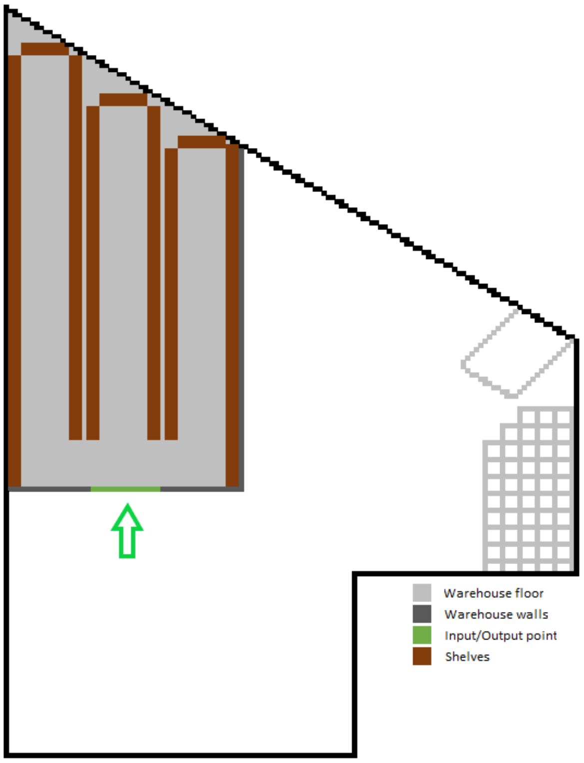


Figure 27: Design B

5.9 Layout validation and selection

This section of the framework validates the generated layouts based on the created design criteria. The created design criteria are storage capacity, accessibility, zoning, and flow. In short, the solution must ensure that the materials can be reached and retrieved efficiently, allow for zoning based on set classes, and fit well into the overall process flows at the facility. It goes without saying that solutions must also be able to store all of the required materials inside, so that the described problems of outside storage are eliminated.

Storage capacity

Because the designs are now created with measurements, and encompass the same floor area, it is possible to compare their relative storage capacities. To compare this for the designs, we can look at a single level of shelving, assuming every additional level has the same dimensions. Design A has 222 meters of shelf length at the ground level, and design B 258.5 meters. Both designs have shelves with a depth of 1.5 meter, meaning the designs have 333 m^2 and 387.75 m^2 storage area per floor respectively. This means that for the same floor area, design B has 16.44% more storage capacity.

Accessibility

As stated in the accessibility criterion, solutions must have as much aisle space as is required for adequate accessibility, but no more. Creating too many aisles can even hamper the accessibility. This can be seen in design A, where the upper section of the aisles is constructed in a manner that allows for maximum shelf space. It is apparent that the forklift operator must make up to four 90-degree turns to reach the shelf that is parallel to the left facility wall. In design B, operators pick one of the three aisles and can more easily turn into this aisle. They can then drive to the correct shelf location without further turns.

Zoning

For the zoning criterion, this section looks at how far the forklift operator has to drive within the warehouse to reach the class A tools. In the zoning section, class A was defined as containing 20% of tools, leading to 70% of picks. Here, we assume that storing this 20% of tools takes the same amount of shelving area in both designs, and that 20% of tools takes up 20% of a warehouse's storage. 222 is the total length of shelving in design A, which is thus also used for design B to keep the comparison fair. Therefore, we calculate how far the operator has to drive to reach the first (0.2 * 222 = 44.4 or) 45 meters of shelf. The required driven paths to reach this amount of storage are visible in Figure 28 and Figure 29 coloured in blue, together with the reached shelving. Here, design A requires a minimum driving distance of 19 meters to reach 45 meters of shelf space, and design B requires 17.5 meters to reach 47 meters of shelf space. Design B could thus be called more compact, although the difference is not significant. Changing the IO-point for design A did not improve its score over design B.

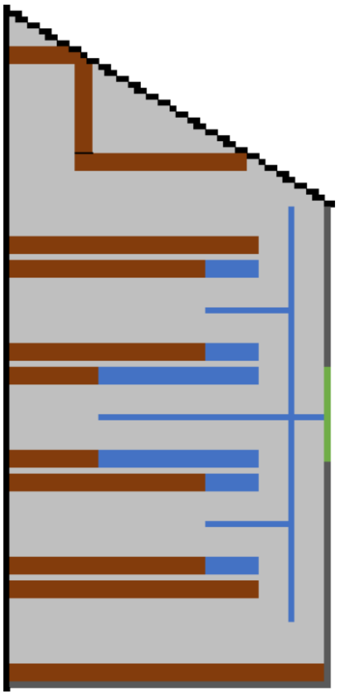


Figure 28: Paths to reach 20% of storage in design A

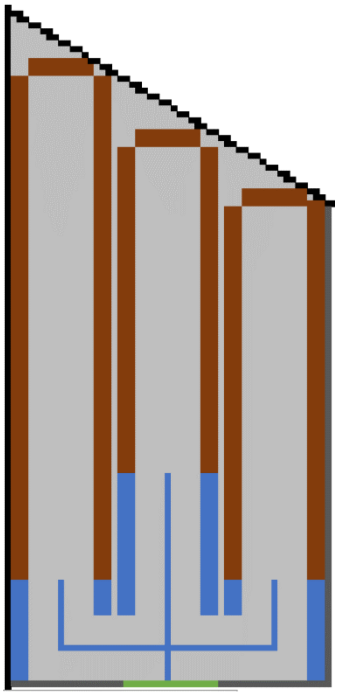


Figure 29: Paths to reach 20% of storage in design B

Flow

The third design criterion, flow, deals with the flow of goods and personnel throughout the whole facility, whereas the design drawings (Figure 26 and Figure 27) focus on a subsection of the facility. The grey lattice structure in the right corner of the plans is the unloading area, located above the workshop. The washbay is located above that, in the upper right corner. As stated in section 5.7, these areas are directly related to the designed warehouse. To better facilitate the flows stemming from this relationship, it is logical to have the I/O point near those areas, which is the case in design A. Design B would namely require the forklift operator to make detours in day-to-day operations.

Layout selection

To score the above results on the criteria, scores have been given to both designs based on the findings. The criteria are placed in order of importance, with the highest importance belonging to storage capacity. The scores are given based on the textual descriptions per criterion above. Design B scores better on three of the four criteria, with design A only being ranked better on overall facility flow. Therefore, design B is selected as the design to be analyzed in the next section. This design iteration has a width of 27 meters and minimum and maximum depth of 40 and 57 meters respectively.

	Design A	**Design B**	**Importance**
Storage capacity	+	++	1
Accessibility	-	++	2
Zoning	-	+	3
Flow	++	-	4

Table 6: Criteria ranking

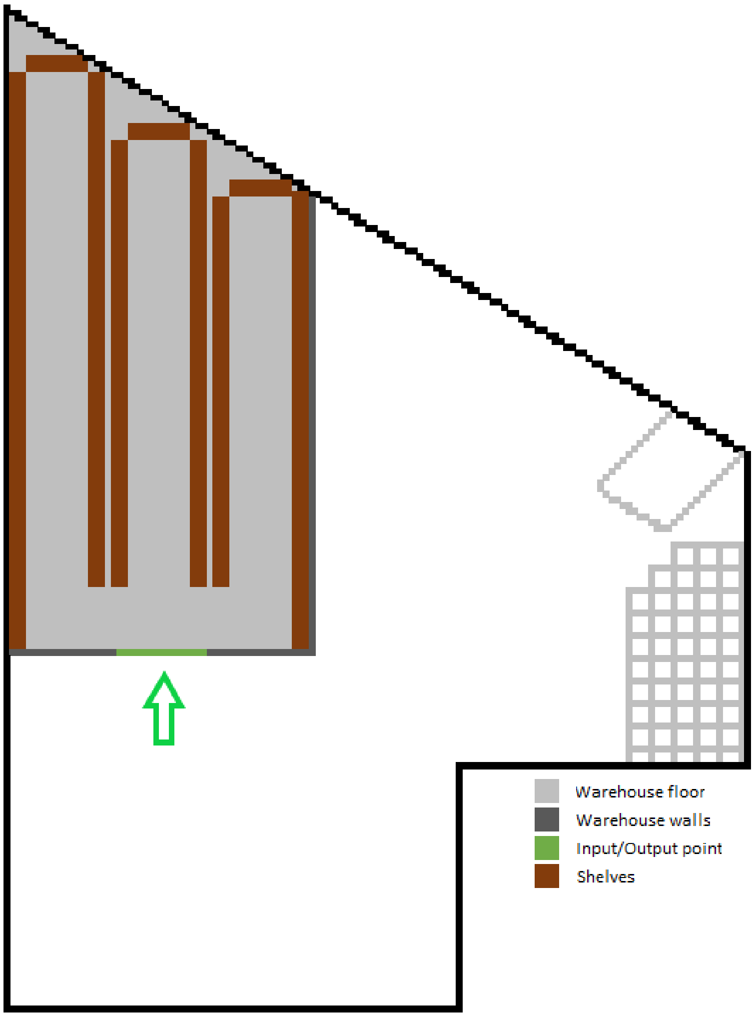


Figure 30: The selected warehouse design

5.10 Solution analysis

Now that a design has been selected, adjustments to the design iteration can be made to make a quantitative analysis.

Storage capacity

We take the situation with 200 generated tools with the following dimension distributions:

Property	**Minimum value**	**Maximum value**	**Distribution**
Width	15 cm	142 cm	$X \sim N(78.5\,, 25)$
Height	15 cm	142 cm	$X \sim N(78.5\,, 25)$
Length	40 cm	500 cm	$X \sim N(270\,, 100)$

Table 7: Tool dimensions

As stated in the above section, the currently selected warehouse design iteration of Figure 30 has 258.5 meters of shelf width or 387.75 m^2 of storage capacity per level. We first analyze how this iteration of the design stores the tools from Table 7. The distributions apply to 200 tools, so it is easily calculated that the expected total length of tools to store is 200 times the mean of the length distribution, $200 * 270 = 540$ meters.

As stated in section 5.6 every meter of shelving is only used for one tool, with no double-deep racking. Furthermore, there are moments in the year when every tool can be expected to be in the Oldenzaal facility (see Figure 16). It thus follows that at least 540 meters of shelf racking is required. With the 258.5 meters the current design iteration has, 3 levels of storage would be required.

An alternative for fitting the current generated tool stock into a two-level warehouse design is by extending the design of Figure 30 in the vertical (north-south) map direction. Because there are six shelves in parallel in this direction, extending the design by one meter increases the amount of shelf length by six meters per floor level. Extending the warehouse by two meters in a two-tier design would thus bring the total shelf length to $(258.5 + 12) * 2 = 541$ meters, which is strictly sufficient according to the expected total tool length from the distribution. The lengths are generated through a normal distribution, which means the expected total of 540 will sometimes be exceeded. However, it's shown that adding one meter to the depth of the warehouse increases the storage capacity significantly.

Extending in the horizontal (east-west) map direction is far less efficient because of the minimum aisle width of and the sloping direction of the northern-most wall. To fit an additional aisle on the right-hand side, a minimum of 1.5 meters for 1-sided shelving and 5.5 meters for minimum aisle width is required. Furthermore, the amount of shelving added by expansions in this direction shows diminishing returns because the diagonal back wall impedes aisle length. It is therefore recommended to use the designed three-aisle layout, with expansions in height or depth as required.

Now that a consideration of expansion directions has been made, the following section analyzes which dimensions would best fit the generated ROSEN situation, again considering the decision criteria, together with cost considerations.

	Adding depth	**Adding a level**
Storage capacity	6 meters per meter per floor	1-floor area extra per level
Accessibility	Little impact	Higher reaching (forklifts) required, harder work
Zoning	Little impact	Lighter or less used tools must be stored on extra level

Flow	Longer routes, extra-long detour from and to workshop	Little impact, storing and retrieving high can take longer but not significant
Cost	Scales linearly	One extra level costs considerably more

Table 8: Expansion options per design criterion

Based on above considerations, it is preferred to meet storage demands by scaling the warehouse dimensions via the depth factor. Every meter increase in depth gives 6 meters extra shelf length per floor, while little impact on the processes.

Of course, floor space is not unlimited. In the two-tier design, adding an additional level to the warehouse is equal to adding $258.5 \div 12 = 21.5\ \text{meters}$ of depth to the warehouse. If enough storage demands are apparent in the actual ROSEN situation and forecasts, making the warehouse higher is certainly a viable method of storing materials while saving floor space. This also depends on further processes taking place outside the warehouse building and is outside the scope of this research.

5.11 Chapter conclusion

In the beginning of this section, the fourth sub-question – what criteria and functions must an improved storage facility meet – was answered by defining the system requirements and design criteria. The warehouse was classified as a human-employed, picker-to-parts, high-level, pick-by-order warehouse, where employees use fork-lift trucks to retrieve products from above regular reaching height based on the shipment list of a single order. A new design must allow for the existing processes to continue, while removing the constraints of the current Fort Knox situation. To evaluate designs, design criteria were set up, based on literature research and ROSEN findings. Storage capacity is the primary design criterion, it must be cost-efficient and able to fit all the desired objects. The design objective of good retrieval times was illustrated according to the criteria accessibility, zoning, and flow.

The rest of the chapter followed the framework to answer the fifth sub-question: what alternative solution best solves the problem based on the criteria and available data? By generating and profiling data, and delving deeper into the used unit loads, functions and processes and equipment, borders were created for the generation of layouts. These were dimensioned and rated on the design criteria set at the beginning. After this layout validation, the design iteration of Figure 30 was selected. To quantitively analyze the dimensioning considerations, alternatives were again measured against the design criteria. This way, the process of final sizing determination has become insightful. This last consideration answers the final sub-question of how ROSEN can implement and evaluate the chosen solution.

6 Discussion

This chapter discusses the process of the research and highlight and review the decisions that were made to reach the final result. Limitations at these decisions are also described to put the research into context.

The design question was a greenfield issue, meaning the warehouse was designed from scratch. The reasons for deciding on this approach were that the current Fort Knox was too small. This was gathered empirically through sessions with ROSEN operators. The utilization of the current warehouse was already exceedingly high, which is logically a limitation for a growing company. By seeing it as a greenfield problem, we opted for a redesign of the entire facility. Another option could have been expanding Fort Knox or adding a separate building besides it. This might be preferred because the construction of a replacing warehouse would disrupt operations for a longer time than adding to or modifying the existing situation. It was discussed with the company supervisor that the results would be most broadly useful if a full redesign was performed, so that more factors were explored in the process. From this, ROSEN can still use the results to modify the current facility without a full demolishment.

The same applies to others method of improving warehouses found in literature, the first being a warehouse management system. Currently, stock locations are not tracked, so operators have to find the required tools manually. Because the tools are visually identifiable, this is not a major factor in delays. A warehouse management system can help with the placing of tools in the optimal spot, but this is only useful if there is enough space to allow for dedicated storage policy. Literature namely points out that a dedicated storage policy has the lowest space utilization of all storage policies.

Another often used method in warehouse improvement is the implementation of an automated storage and retrieval system. This direction was not further looked into because of the relatively low order frequency, large unit loads and varying process flows. It became apparent that operator-manned forklifts are an essential part of ROSEN operations.

6.1 Methods

From the literature research, several methods for warehouse design were found. Eventually, the warehouse design framework of Baker et al. (2009) was modified to fit the ROSEN research context. Other methods such as the Systematic Layout Planning and Systematic Handling Analysis that were discussed required deep understanding of warehouse design, so that the user can use their experience to make proper assumptions in the design process. Furthermore, these methods were not described so in-depth that it was clear what factors to leave in or out during the design process. Also, they handled situations where a whole facility was being redesigned, with many operating areas and their relations. As described in this research, the ROSEN situation came to require a design of a singular warehouse, while taking a few related areas into account. Other methods researched dealt with mathematical modelling, and less on the construction of warehouses. Therefore, the adapted framework fits better to the scope of the research.

In the design process, we explored two warehouses placed along the eastern wall of the facility, as visible in Figure 26 and Figure 27. Another option would have been to assume a design along the northern, diagonal wall. For a rectangular building, this would make the shelf direction been either perpendicular to the processes, requiring operators to make detours every operations.

6.2 Data availability

A large limitation encountered during the research was not being able to access factual, real-world ROSEN data. To solve this limitation, assumptions were made about the data, which were validated with ROSEN. However, the generated data can be expected to be of smaller dimensions than what would be the actual case at ROSEN. For example, to create a workable dataset, the assumption of a total of 200 static tools was made. In reality, the situation consists of ordered tools being made up of specific components that are combined into unique combinations. However, because the data generation was validated beforehand, and the process of eventual layout generation documented, ROSEN can use the research with factual data to improve on the results.

This data limitation was also visible in other stages of the framework, such that forecasts and future plans were not taken into consideration. Furthermore, that generated data that was used for the design creation focused on the tools, as this is the most valuable part of ROSEN operations. However, the results are described in such a way that ROSEN can adapt them with more concrete data.

7 Conclusion and recommendations

The ROSEN Oldenzaal facility was facing challenges due to space and storage constraints leading to long retrieval times and outside product storage. The research question was: How can ROSEN design a new warehouse to better fit its needs and operations based on current and forecasted data?

A systematic approach was used to build a new warehouse, and the proposed solution is a brand-new facility located in the north-eastern corner of the plant that utilizes space without waste and allows an aisle pattern supporting accessibility and zoning. The proposed design criteria were used throughout the design process to better suit ROSEN operations in the future. To implement the design, ROSEN needs to compare the generated and used data to factual and projected data and consider different zoning policies to reduce overall storage and retrieval times. It is also important to train operators for the transition to achieve full effectiveness.

Further research is needed to achieve a more comprehensive warehouse design by evaluating the cost of machinery alternatives and assessing the achieved warehouse design to make the best use of the created result.

7.1 Conclusions

This thesis research focused on the warehouse operations of the ROSEN Oldenzaal facility. This facility handles tools returning from deployments, cleans and stores them, and prepares them for a following deployment. ROSEN is having trouble managing their daily workload in the inbound and outbound retrieval and storage processes due to space and storage constraints. This can be seen in the times it takes to complete these what should be straight-forward operations, which can occasionally take up to several hours. Additionally, a sizable portion of the inventory cannot fit in the indoor storage spaces, which results in products remaining outside for an extended period of time with associated risks of deterioration and theft. To solve this problem, the following research question was asked: How can the storage facility of ROSEN be designed to better fit the needs and operations, based on current and forecasted data?

This question is answered throughout the research by illustrating the systematic approach ROSEN can take when building a new warehouse. This approach consists of a framework that can be applied with readily available information consisting of both current and forecasted data. Numerous layouts for the actual facility were produced by implementing the chosen framework steps. The final layout was ultimately decided upon after being assessed on the formulated design criteria. As a result, the warehouse has been designed to better suit ROSEN operations in the future. This comprises of a brand-new warehouse that is situated against the plant's eastern wall, which is visible in Figure 31. This particular position was selected by following the process analysis and space-saving heuristics. The core problem of “the storage facilities of ROSEN are not well suited for the workload, leading to long retrieval times and outside product storage” is thus tackled. The design criteria were set so that the workload can be handled, and they were used throughout the design process.

The proposed solution is thus a new warehouse located in the north-eastern corner of the facility. This location was chosen because it utilizes the plant space without waste and allows an aisle pattern that supports the design criteria of accessibility and zoning. Because of the shape of the plant, a three-aisle design is proposed, and scaling the warehouse is most effective in the north-south direction.

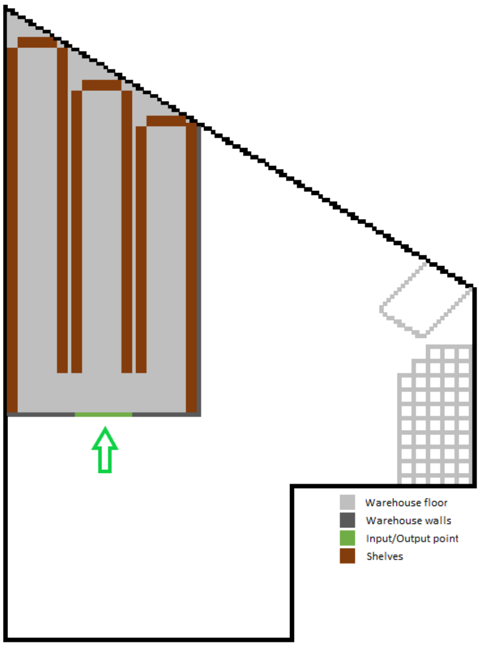


Figure 31: The proposed solution

7.2 Recommendations

The presented results can be put to use better when considering certain factors from the discussion. The main factor that must be taken into account when ROSEN analyses the results is the used data. Because this data was generated, the results are not applicable straight away. For implementation, ROSEN should compare the generated and used data to factual and projected data, so that the warehouse design can be scaled accordingly. This factual data can include information about the ancillary products, such as the frames and cleaning equipment. This different data can result in changes being made to the floor dimensioning, as well as to the height of the facility. However, for a holistic overview of possible solutions, it is recommended ROSEN refollows the framework. The performed research was done in such a way that it is clear from one step to the next how results are achieved, and so that ROSEN can replicate the process.

Within the proposed warehouse design, there are some further recommendations that can by made to further improve the implementation. To prevent the solution from being (under)utilized in the same way as the current Fort Knox, it is sensible to implement zoning. The research discussed ABC-zoning on order frequency, but in literature and reality, many different zoning strategies can be used. In the end, the zoning policy that reduces overall storage and retrieval times is dependent on the overall processes. Within any zoning policy, it is recommended to make the zones clear by using proper signing. Lastly, within any change to the facility, it is important to train the operators for the transition, so that full effectiveness can be reached.

7.3 Further research

Due to knowledge and scope constraints, the created framework was not entirely followed, as stated. However, the framework is laid out so that further study into the remaining steps can be done. For instance, a more comprehensive warehouse design can be achieved by looking further into the cost of machinery alternatives. Using actual data would logically result in a more situation-accurate design because the data used for activity profiling has been validated with ROSEN and is similar to the factual data. It is advised to use the described steps in conjunction with actual data to reevaluate the framework.

It is necessary to conduct a more in-depth cost and implementation investigation in order to assess the achieved warehouse design further. This would serve as a guide for choosing between alternatives in later stages of implementation so that the warehouse's actual realization fits the Oldenzaal context.

There will undoubtedly be significant changes to the overall procedures and operations at the Oldenzaal facility as a result of the proposed warehouse design. It would be beneficial to reevaluate facility operations, particularly those closely related to the warehouse, in order to make the best use of the created result.

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Appendices

Appendix A Facility map

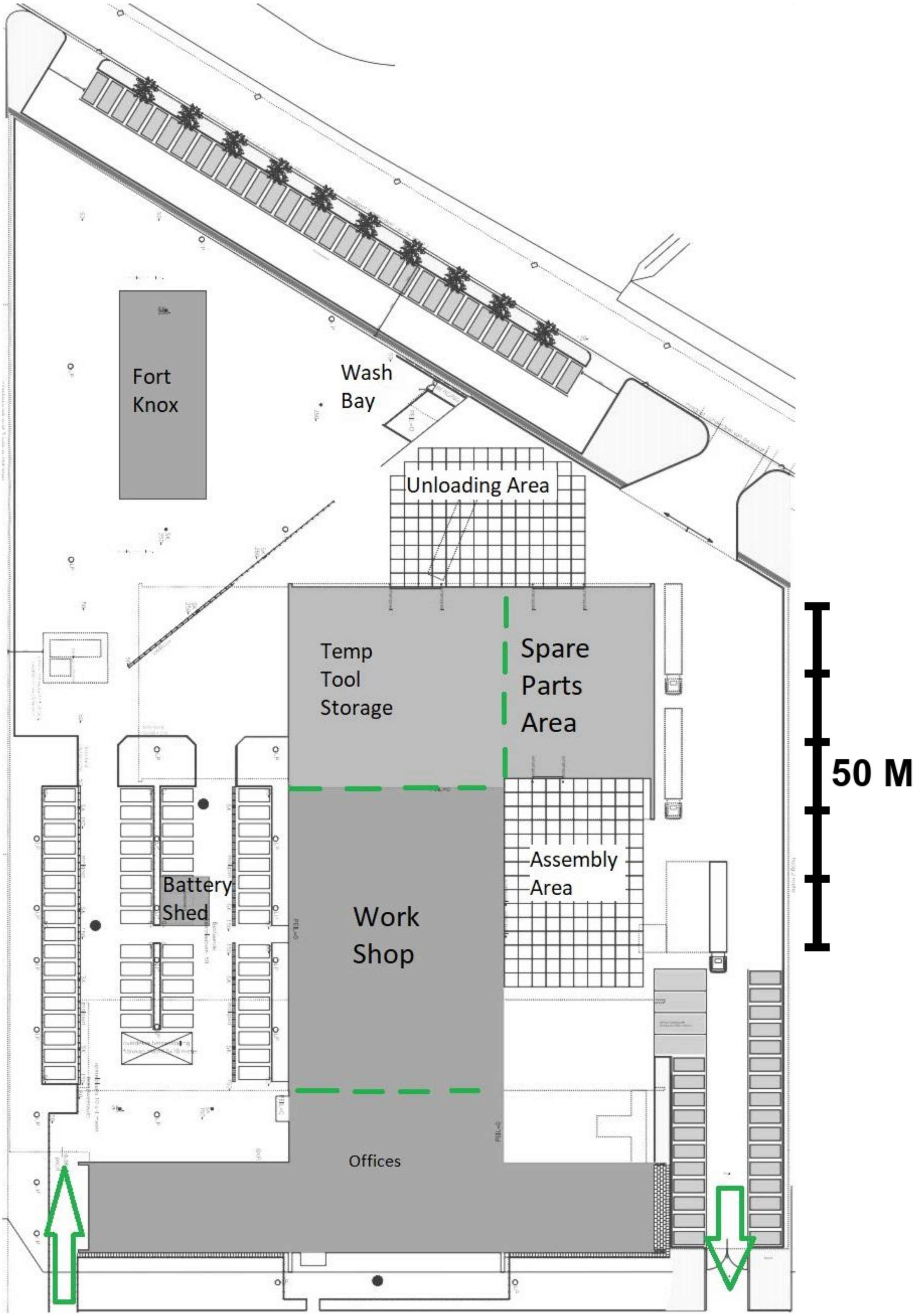

Figure 32: Annotated facility map

Appendix B Operations modelling

Appendix B.1 Inbound process

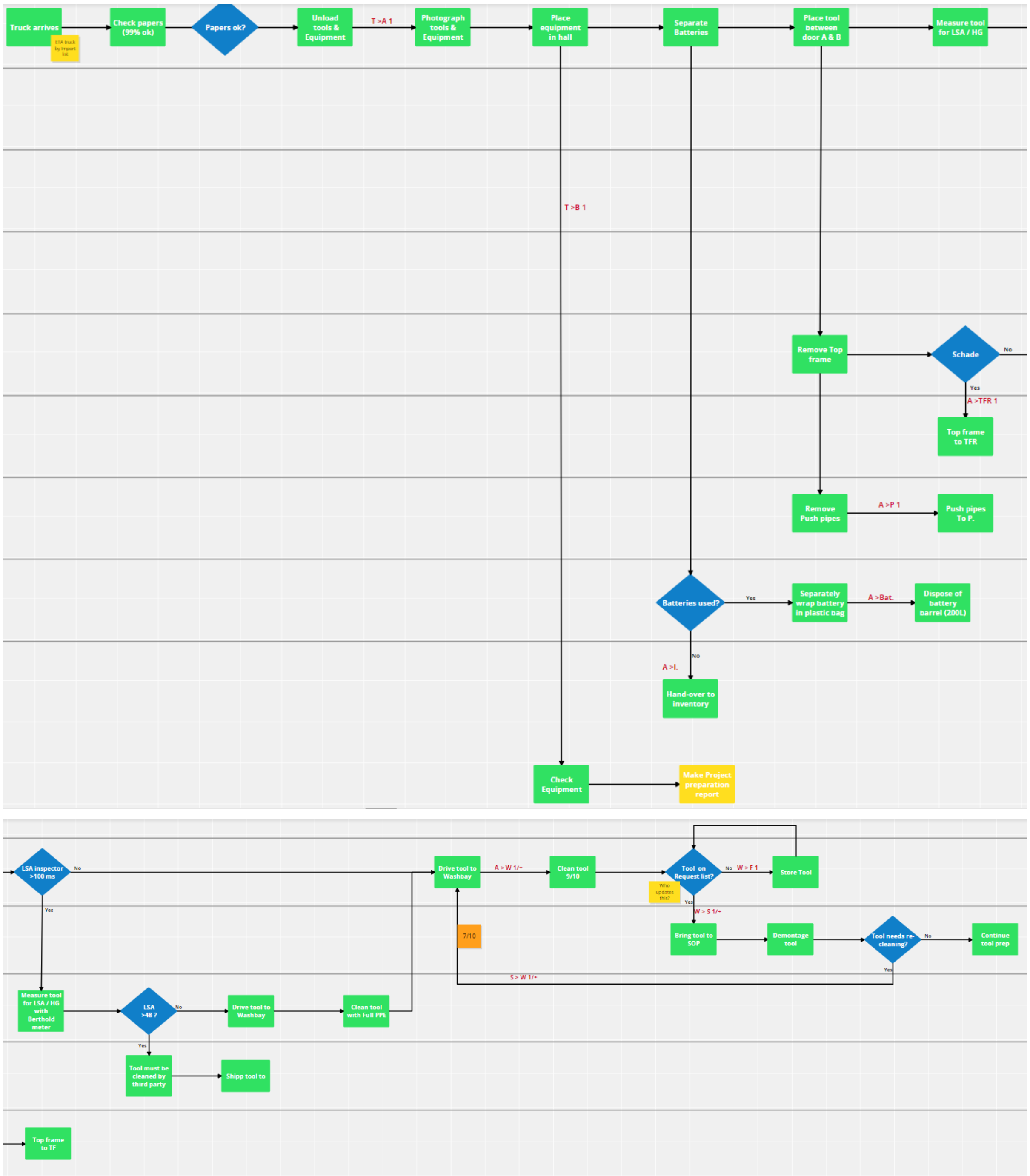

Figure 33: Inbound process model

Appendix B.2 Outbound process

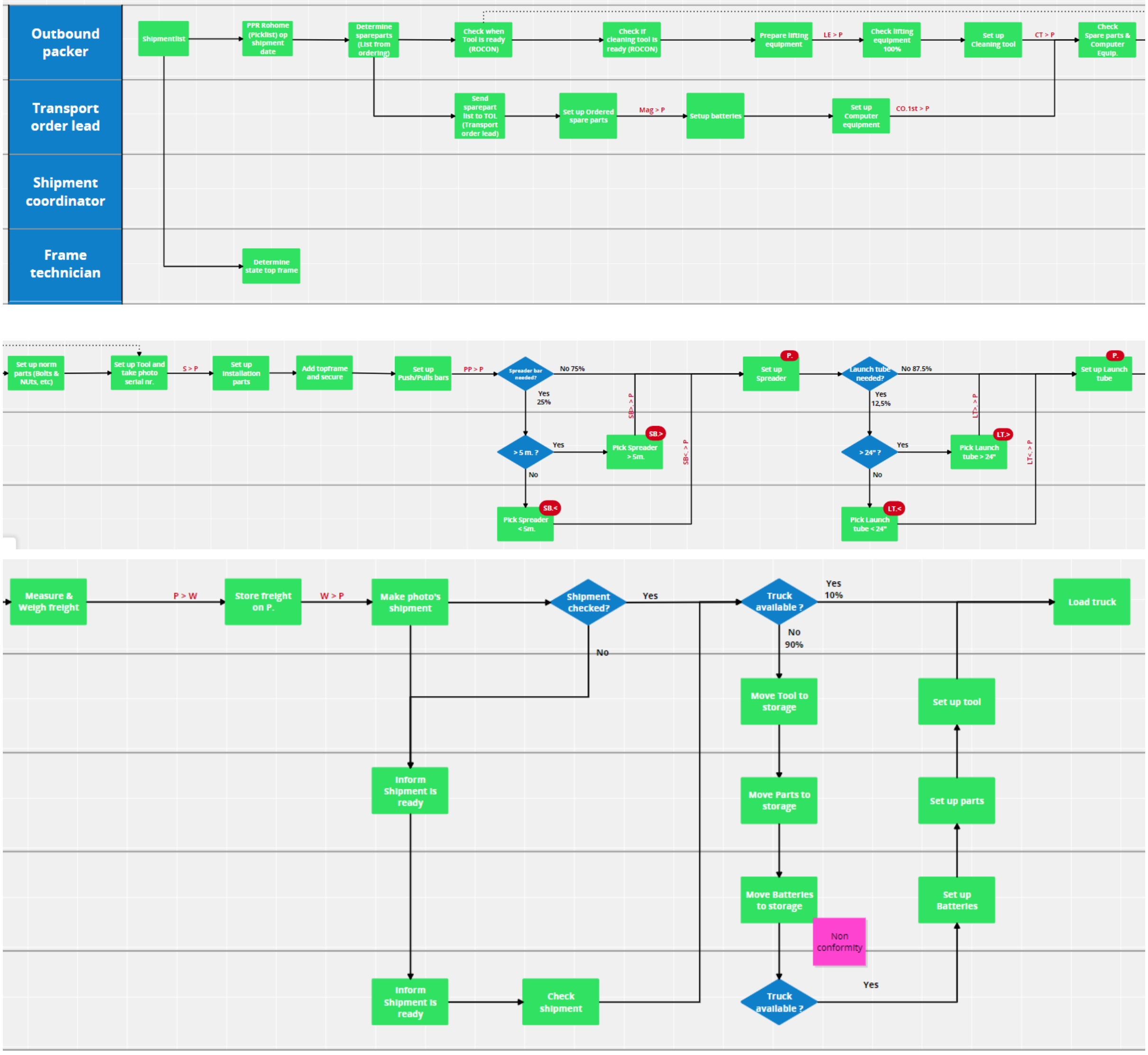

Figure 34: Outbound process model

Appendix C Process maps

Appendix C.1 Inbound process map

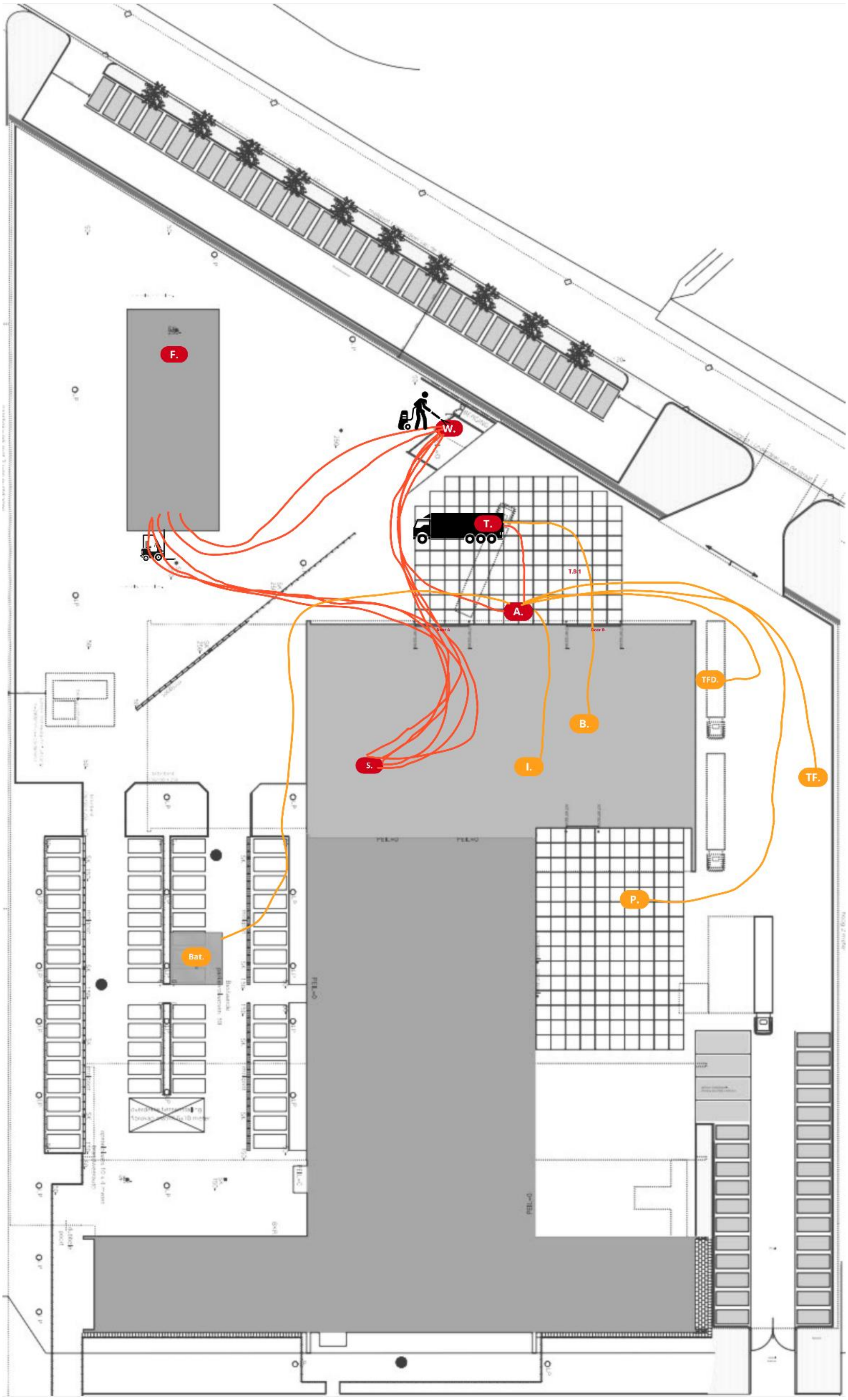

Figure 35: Inbound process map

Appendix C.2 Outbound process map

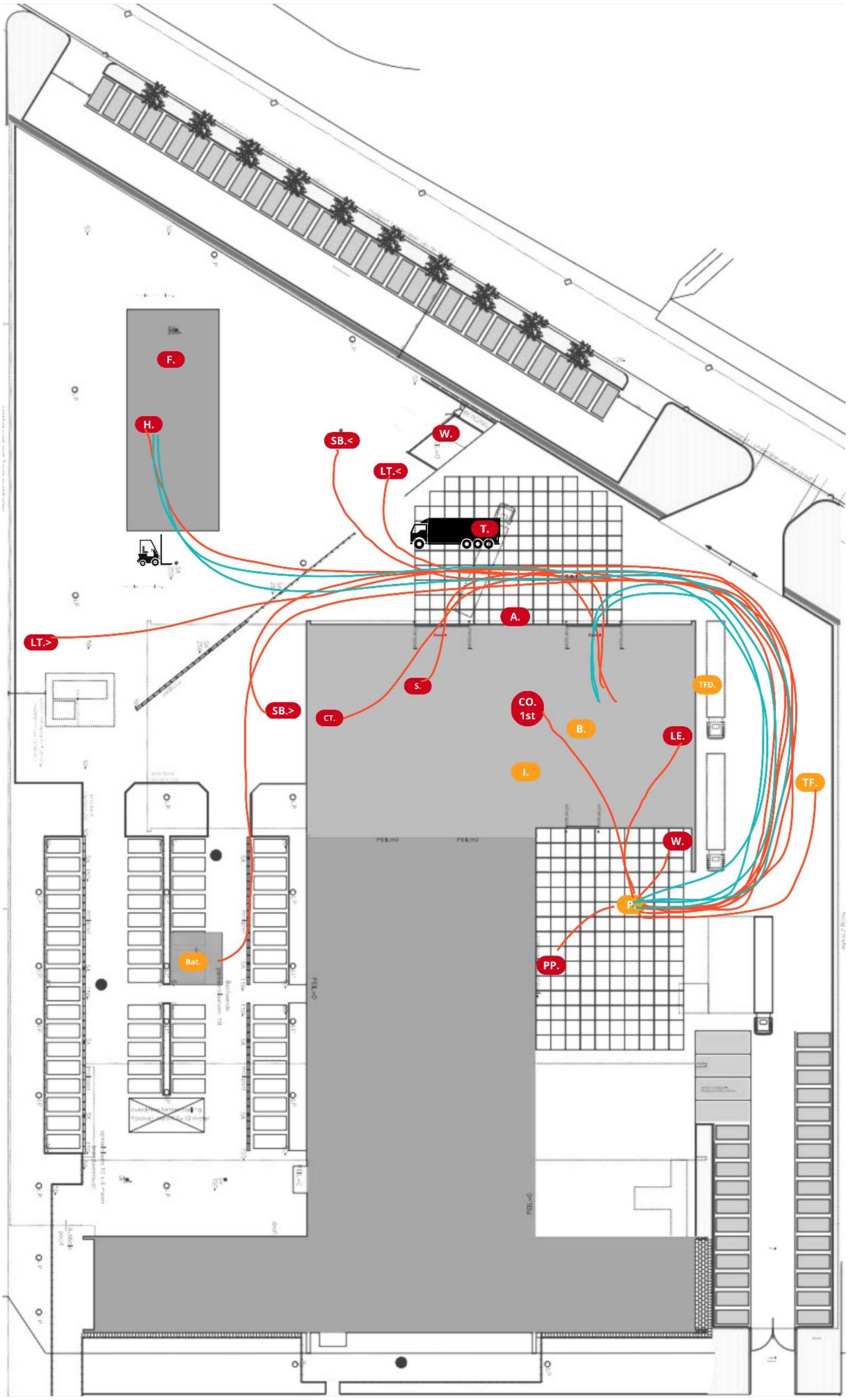

Figure 36: Outbound process map

Appendix D Weekly order numbers

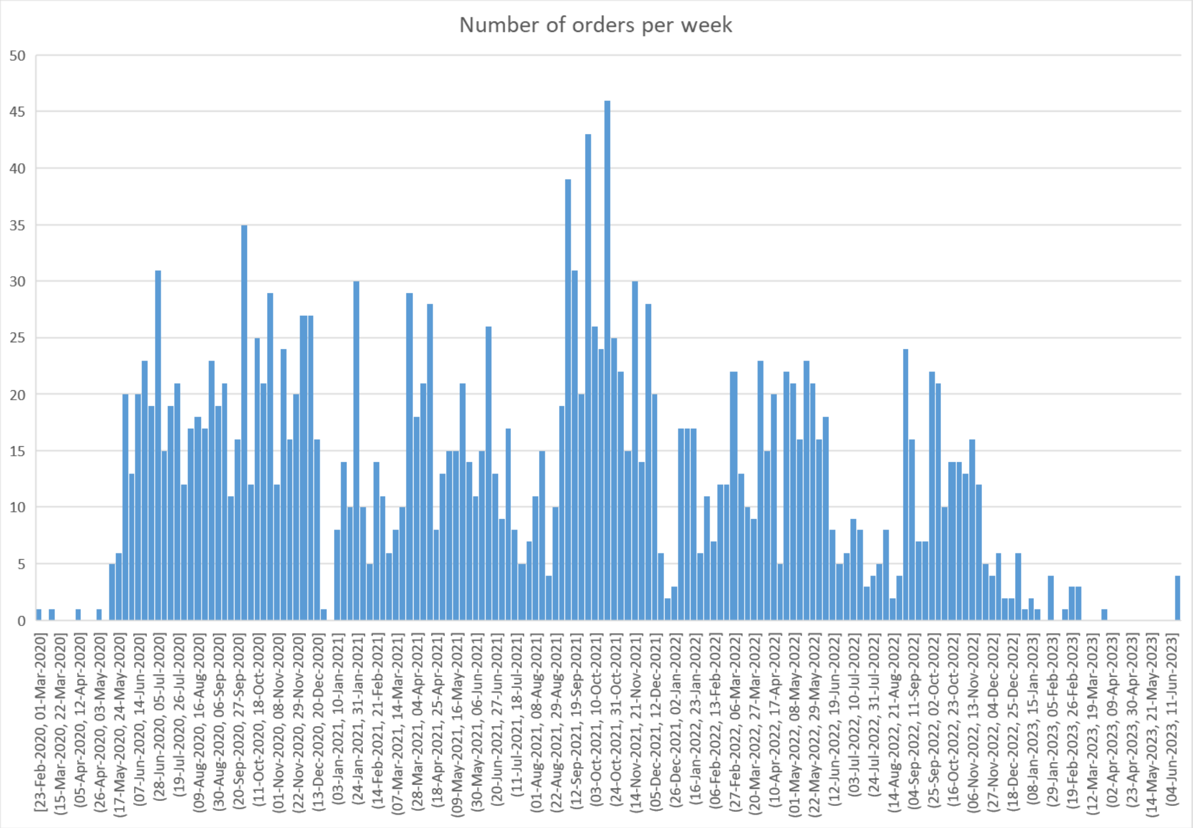

Figure 37: Weekly order numbers at ROSEN

Appendix E ROSEN-adapted warehouse design framework

Step	**Implication/questions at ROSEN**	**Deliverables**
1	What should the overall system be capable of handling? What KPIs need to be met? What is the future scope, what scenarios are imagined? What (primary) functions does the warehouse need to fulfil?	Description of warehouse type and functions. (Quantified/quantifiable) checklists of KPIs and design criteria.
2	What data needs to be retrieved from ROSEN? What aspects are important and in which (filetype) representation?	Checklist (=define) of product details, order profiles, goods arrival and dispatch patterns, inventory levels, cost data and site information. Retrieved data in workable and clean state, either spreadsheet or database.
3	What information needs to be extracted from the data, how can the above retrieved data be profiled to become insightful? How can this data give insights to the KPIs? How is this data expected to change in the planning horizon?	Activity profiling, for concepts as order, item, inventory, calendar-clock. Predictions of data changes.
4	What unit loads are in use, with what characteristics? Can this be changed, for example to become more uniform?	Quantified description
5	Aside from layout, how do the warehouse functions relate to each other? What operating methods fit with these functions? What zones could be determined (high-level and product level)? Which designs of processes can handle the work while meeting the performance constraints?	Mapped list of functions, their relations and groupings, used methods, and several overall process flows.
6	What is the scope of the equipment possibilities? What (physical) characteristics must equipment meet? What are the associated costs? How can combinations of equipment be made, so that they can handle the work while meeting the performance constraints?	Overview of market offerings, including costs. Checklist of physical requirements. Combinations of work-bearing equipment.
7	For the above combinations, how do they handle the work? How much of each is required? How would possible equipment perform under alternative scenarios?	Analysis of work-bearing performance, against differing constitutions of the equipment, with alternative scenarios.
8	What other operations must be supported by the design, aside from primary functions?	Checklist
9	What would possible layouts look like? What methodologies are applicable? What is a suitable approach and/or software? What objectives (besides overall design criteria) do generated layouts need to meet?	Description of generation process. Generated layouts in suitable format. Checklist of met objectives.
10	Validate the operational and technical feasibility of solutions, against overall design criteria and factors as flexibility and safety. What would capital and operational costs be? How can the results be simulated, and future resilience measured?	Mathematical analysis of the generated designs for design criteria. Added costs estimations. Future proofness statement.

11	Quantitative and qualitative analysis of the proposed design, as a business case for ROSEN.	Full implementation expectation of the chosen layout.

Table 9: Adapted warehouse design framework