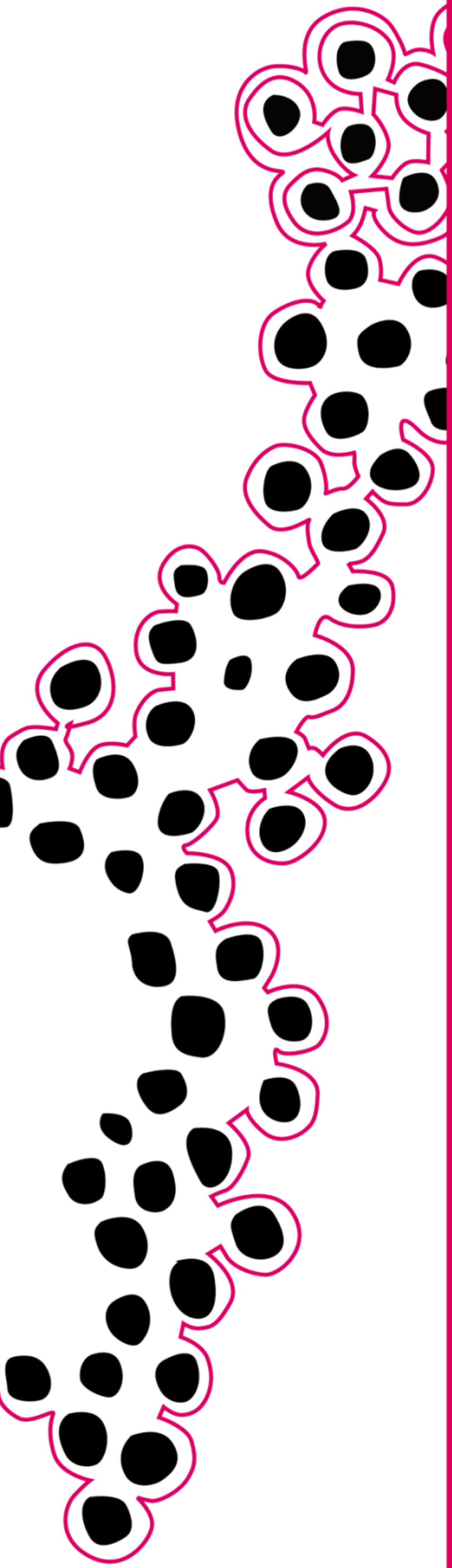

Warehouse Layout Design at NXP ICN8 Nijmegen

Industrial Engineering & Management

Master Thesis
Specialization Production & Logistics Management
Orientation Manufacturing Logistics

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MANAGEMENT SUMMARY

CONTEXT

This research focuses on the ICN8 plant of NXP in Nijmegen, one of Europe's largest chip manufacturing facilities. The plant faces challenges due to its aging infrastructure, specifically within its warehousing department. The scattered layout of multiple warehouses has led to inefficient operations, marked by long walking distances and inadequate space to cope with production growth and fluctuations. This has necessitated the design of a new, consolidated warehouse. The core problem addressed is the development of an adequate layout for this new facility that accommodates all current functionalities, while considering multi-level layout complexities and varying needs of different warehousing sections.

METHOD

The study's goal is to design a macro layout tailored to NXP's needs, beginning with a thorough analysis of the current warehousing situation and its strategic flaws. Key to this process is understanding the goals and requirements of the new warehouse and brainstorming layout options using a non-linear programming model. The research encompasses optimization of storage and handling sections, focusing on section sizing, operational flow, and strategic positioning of sections for efficiency. The study excludes areas needing specialized knowledge such as chemical storage and employee considerations.

RESULTS

The results show that combining the scattered warehouses to one centralized warehouse decreases the average walking distance by at least 50% (13 km per day). A centralized warehouse eliminates the movement of valuable SKUs outside and reduces the risk of damaged or contaminated SKUs. A centralized warehouse enables all office function to be combined, improving the communication and the flow of information.

The research yielded the flexible macro layout that is shown in Figure 1. The flexibility offers the problem owner to adapt the layout to their specific needs. Critical factors are considered, included the sizing of storage areas to meet current and future inventory needs, streamlining of operations to minimize handling time, and strategic placement of sections to optimize workflow.

The flexibility is offered in the green area on floor 1 and the yellow area on floor 1 and floor 2. The green area on floor 1 offers the flexibility to replace and dimension the sections to the needs of the problem owner as long as the sizes of the sections remain the same. As an example, the offices can be placed near the in and out point of the Dock (I/O Dock) for improved communications with deliverers, or the offices can be placed near the in and out of to the plant to make room for forwarding areas.

The yellow area on floor 1 and floor 2 designate the space that is available for the spare parts storage. It is advised to place rarely picked SKUs on floor 1 and frequently picked SKUs on floor 2. The spare parts section can be split in subsections, these subsections contain SKUs with specific characters or SKUs that have a divergent pick frequency. Subsections with specific characters are the Pumps, Quartz, Broken and Consignment. Subsections with frequently picked SKUs are Dry Etch SKUs and SKUs that get periodically cleaned. The subsection with SKUs that are rarely picked is the ‘Z02’-section that contains non-runners.

Splitting the spare parts section into subsections decreases the average walking distance and improves the clarity of the organization. However, splitting into subsections increases the required amount of storage space.

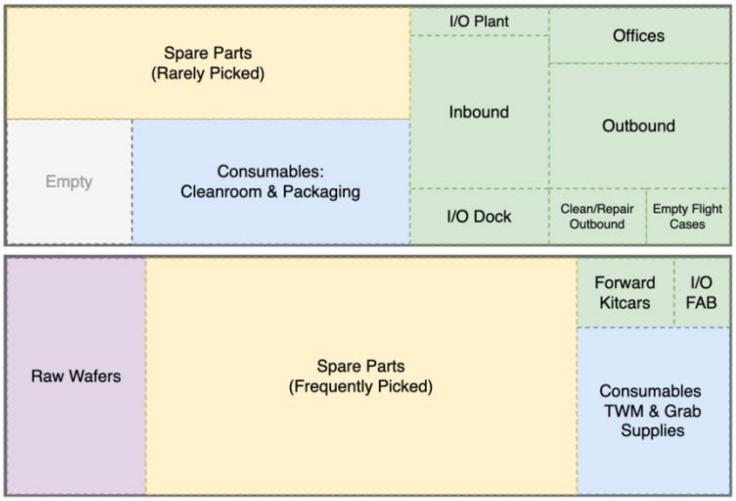

Figure 1 – Resulting warehouse macro-layout for floor 1 (top) and floor 2 (bottom)

CONCLUSION & RECOMMENDATIONS

The study identified potential layouts for NXP's new warehouse, addressing the core problem of minimizing walking distances while maintaining warehouse functionality. It demonstrated the complexity of multi-level warehouse design and the need to balance various operational and spatial considerations to achieve efficiency and adaptability. The thesis recommends selecting a warehouse layout that aligns best with the collective insights of all stakeholders. It suggests continued focus on strategic warehouse management, emphasizing efficient space utilization, streamlined operational flow, and careful placement of warehouse sections.

For future studies, the thesis recommends separate investigations into warehouse material movement, SKU classification, and the safety stocks. The material handling and material storage equipment is an important part of warehouse design but has gotten little attention in this thesis due to time constraints. SKU classification plays an important role in the layout and flow of the warehouse, but the classification seems to be update infrequently and unstructured. The number of SKUs that are stored in the warehouse is influenced by the safety stock. However, the safety stock is not used as intended at the ICN8 plant and thus requires further investigation.

PREFACE

I hereby present my master thesis 'Warehouse Layout Design at NXP ICN8 Nijmegen,' which concludes my master's degree in Industrial Engineering and Management. Completing this thesis marks the end of a long, enjoyable period at the University of Twente in Enschede. I look back with pleasure on my time as a student and am happy with everyone who has been a part of it. As a greenhorn, I started at the amazing house Avion and eventually graduated in my parental home. Where it went wrong, I don't know, but I wouldn't choose differently.

For my guidance within NXP, I would like to thank Pieter Hofman and Andre Hoogeboom. I have learned a lot from you about NXP, the warehouse and project management, and with this thesis, I hope to contribute something in return. And Andre, I would gladly fetch a cup of coffee for you again. For my guidance at the UT, I would like to thank Breno Alves Beirigo for pushing my educational boundaries. During our meetings, the feedback sounded like theoretical grumbling, but now that the thesis is finished, I see its value.

NXP Nijmegen has provided me with many valuable and practical insights into its operations and processes, alongside the opportunity to adequately perform this intriguing thesis, for which I am grateful. Above all, I would like to thank all involved employees for their input, support, and sincere excitement while I performed this thesis as well as for answering any of my thesis-related questions.

I hope you enjoy reading this thesis!

Wytse Jansen
December 2023

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1. INTRODUCTION

This chapter introduces the manufacturing plant of NXP ICN8 in Nijmegen and motivates the research in Section 1.1. Section 1.2 provides the problem context to which the research framework is proposed in Section 1.3. Section 1.3 also provides the research questions and shows the structure of the report.

1.1 COMPANY INTRODUCTION

NXP, a name that is derived from ‘Next experience,’ is a Dutch multinational that joined the S&P500 (the 500 companies with the highest market capitalization on the American market) in 2021. The company has multiple plants located worldwide; the plant in Nijmegen is one of Europe's largest chip manufacturing plants. The production plant in Nijmegen has around 1,700 employees and includes manufacturing, R&D, testing, technology enablement, and support functions [1].

The manufacturing plant in Nijmegen, called ICN8, manufactures Integrated Circuits (ICs) that are primarily used in the automotive industry. The manufacturing process starts with an 8-inch wafer that is made of silicon. The wafer is inputted in the factory and can undergo more than 140 production steps that step by step ‘print’ multiple ICs on one wafer. After the process is completed, the wafers are shipped to internal and external assembly plants to create the final product, the computer chip. Figure 1.1 shows the raw wafer, the finished wafer, and the chips after assembly.

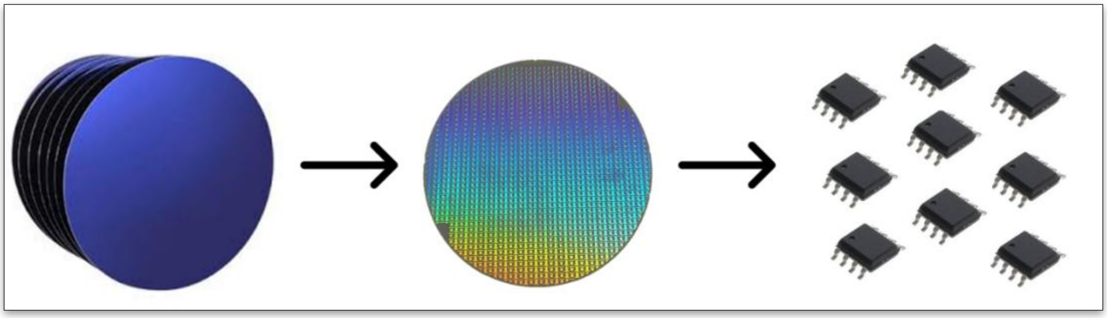

Figure 1.1 - From left to right the figure shows a raw wafer, a wafer after manufacturing and finished computer chips.

1.2 RESEARCH MOTIVATION

There are multiple divisions to support the production of the wafers, one of which is warehousing. At the ICN8 plant, the warehouses support the production process by providing raw materials needed for production, storing spare parts for production machines and by sending and receiving shipments on the ICN8 plant. The ICN8 plant was built in 1996, and the layout of the plant has changed a lot trough time. New production buildings were added, others were discarded, and buildings could get new functions.

The changes to the ICN8 plant have created problems for the warehousing department and subsequently created the motivation for this research. First, multiple warehouses are scattered around the plant, resulting long walking distances. Figure 1.2 shows a map of the ICN8 plant where the locations of the warehouses are highlighted in red and the movement between the warehouses in blue. Second, the size of the warehouses has become too small to keep up with the growth and fluctuation of production. The emergency warehouse they opened in building BQ exemplifies their struggle with their limited warehousing space. Third, future changes on the ICN8 plant require close parts of the current warehouses, emphasizing the need for a new warehouse.

Figure 1.2 – Map of ICN8 plant where the warehouses are in red and the paths between the warehouses in blue.

1.3 PROBLEM STATEMENT

In the research motivation in Section 1.2 we discussed how the spread of small warehouses on the ICN8 plant created long walking distances and space issues. This leads to the discission to relocate all warehousing functions to one new location. This new location is depicted in the blue area in Figure 1.2. This new warehouse should house all current warehouses' functions, and the new warehouse must be able to cope with future growth and fluctuations in production. The new warehouse leads to the problem of this research; how should the new warehouse be designed.

[2] said that designing a warehouse's layout is complex and that the topic has gotten much scientific attention throughout the years. Every company needs a warehouse, and these warehouses have different goals and requirements. The other goals and requirements of a warehouse mean that there is no easy ‘one-fits-all’ solution for designing the layout of the warehouse. Three problems that arise for designing a new warehouse in our research are securing that the warehouse functionalities are kept, designing a multi-level layout, and reorganizing and restructuring the sections.

Like every other warehouse, the new warehouse at the ICN8 plant has its requirements and goals. The new warehouse must inherit all functionalities of the current warehouses in the ICN8 plant. Chapter 3 analyses the organization and functions of the warehouses. The inherited functionalities include the standards such as receiving, storing, and shipping. Next to that, the new warehouse will have some non-standard functionalities. Examples of non-standard functionalities are building shipping boxes, an area with emergency goods for chemical complications, and a fault with limited access to high-valued goods.

The new warehouse requires multiple levels because of the designated location's surface and the inventory volume to store. Designing a new warehouse with various levels is also called the ‘multi-level layout design problem,’ which [2] states is one of the most complicated problems in warehousing literature.

The new warehouse has three storage sections with different needs. The biggest and most complex section is the spare parts section. This section takes up most space, has a wide variety of SKUs, and the flow from and to the section is the least plannable. The smallest and least complex section is the raw wafer storage. This section stores SKUs with the same dimensions and weight. The flow from and to this section is predictable. The third section is the consumables section, which stores packaging materials, support materials for the FAB, and office supplies. This section has a low variety of SKUs but has them in bulk. The flow of the consumable section is related to the flow of the raw wafer section but fluctuates more. The spare parts, raw wafer, and consumable storage have their own goals. For example, for the spare parts section, it is more important to have a low lead time; for the consumables, it is more important to store it efficiently; and for the raw wafers, it is more important to deliver the right SKU in the right amount on the right time.

Using the requirements and the goals for the new warehouse, we derive the core problem of the research. A core problem is derived from an action problem, and an action problem is the discrepancy between the norm and reality [3]. In the case of NXP, the norm is to have one warehouse that can fit all storable items in a way that minimizes walking distances. In reality, multiple warehouses are scattered around the ICN8 plant with high walking distances. Therefore, we define the core problem as follows:

‘Finding an adequate layout for the new warehouse at NXP that minimizes walking distances, considering the functionalities of the current warehouses, the multi-level layout problem, and the different warehousing sections.’

1.4 RESEARCH DESIGN

Solving the core problem described in Section 1.3 is done in multiple steps and aims to contribute to practice and science. In Section 1.4.1 we describe the goal of the research. Section 1.4.2 follows up by explaining the research questions that need to be answered to arrive at the research goal.

1.4.1 RESEARCH OBJECTIVE

The goal of the research is to tailor a macro layout for a completely new warehouse to the needs of NXP. To tailor a good macro layout, the current warehousing situation needs to be analyzed, and current design flaws must be addressed. Because the warehousing department gets a complete redesign, the analysis will focus primarily on strategic details. Based on the current situation and flaws on the strategic level, we select the goals and requirements for the new macro layout together with the stakeholders.

Once we have a clear understanding of our goals and requirements, we will brainstorm several options for the macro layout. These layout ideas will be generated using a non-linear programming model. Each layout has its own strengths and weaknesses, and we will dig into those details in Chapter 5 We will gather input and insights from all the stakeholders involved to make sure we choose the layout that works best for everyone.

1.4.2 RESEARCH SCOPE

The research is focused on the optimization of storage and handling sections within warehouse operations, aiming to enhance the efficiency and adaptability of these environments. The scope includes section sizing, which will explore the optimal dimensions of storage areas to meet both current and anticipated inventory requirements. Additionally, the flow of operations within these sections will be analyzed to identify opportunities to streamline processes and reduce material handling time. The placement of sections will also be investigated, with the aim of facilitating workflow through strategic positioning that considers access frequency and item interrelationships.

Secondary considerations within the scope of the research include the examination on the number of stairs and docks. Additional attention will be given to storage equipment in the context of these secondary scope to ascertain their contributions to overall warehousing efficiency.

Excluded from this research are areas that require specialized knowledge or are tangential to the core focus of the study. Chemical storage, employee-related considerations, the processing of order returns, forwarding area optimization, item classification, and financial cost analysis are beyond the purview of this investigation. This delimitation allows the research to maintain a concentrated approach on the physical layout and logistical strategies of warehouse section management without delving into the specialized domains that are better suited for separate, dedicated studies.

1.4.3 RESEARCH QUESTIONS

To solve the core problem given in Section 1.3 , we translate the problem into research questions. The main research question answers the core problem. The sub-research questions individually help to answer the main research question. Each sub-research question is answered in a different chapter in this research. Figure 1.3 shows the mapping of the chapters to the sub-research.

Main Research Question:

‘What are adequate layouts for the new warehouse at NXP that minimize walking distances, considering the functionalities of the current warehouses, the multi-level layout problem, and the different warehousing sections?’

Sub Research Questions:

1) *What is known on the new ICN8 warehouse?*
    a. What is fixed about the location and dimensions of the building that will house the new warehouse?
    b. What changes at the ICN8 plant that can influence the design of the new warehouse are to be expected?

We start our research by looking at the future situation at NXP ICN8. We analyze the new situation to have a more focused view when analyzing the current situation. To create a solution in the future, we need to know what will change and how this will change. Chapter 2 analyses the new warehouse sketches and discusses potential changes at the ICN8 plant that could impact the warehouse.

2) *What is the current situation of the warehouses?*
    a. How is the current warehouse organized?
    b. What are the sections of the warehouse?
    c. What are the characteristics of the storage sections?

Chapter 2 profiles the activity of the current warehouse. The warehouse's organization, sections, and characteristics are discussed in detail. The measurement of the performance of the warehouse is discussed to measure feature new solutions.

3) *What insights can be gathered from literature regarding the design of a new layout?*
    a. How can the problem of this research be classified?

    b. What framework for designing a macro layout fits this research best?
    c. What mathematical models can be used to create a macro layout?

Chapter 3 describes literature research of frameworks - or methodologies - for designing a macro layout and mathematical models to support creating a macro layout. The framework is used as a guide to solve the main research question. The mathematical model will create the macro layout.

4) *How do we translate the theoretical model to practice?*
    a. What should the input data for the model be?
    b. How do we translate real-world data to input data?
    c. How should the output of the model look like?

Chapter 4 prepares the experiments using the answers to sub-research questions 1, 2, and 3. This chapter clarifies what input data the model needs and how we can translate the practical information into usable data in the model. Chapter 4 also defines the output that the mathematical model gives.

5) *How do we execute and evaluate the model?*
    a. How does the current situation perform?
    b. How do the experiments compare to each other and the current situation?
    c. What conclusions give the experiments on how the layout should look like?

Chapter 5 first analyses the performance measurements of the current situation. These measurements are then compared to the results of the experiments. This chapter also evaluates the experiments to each other.

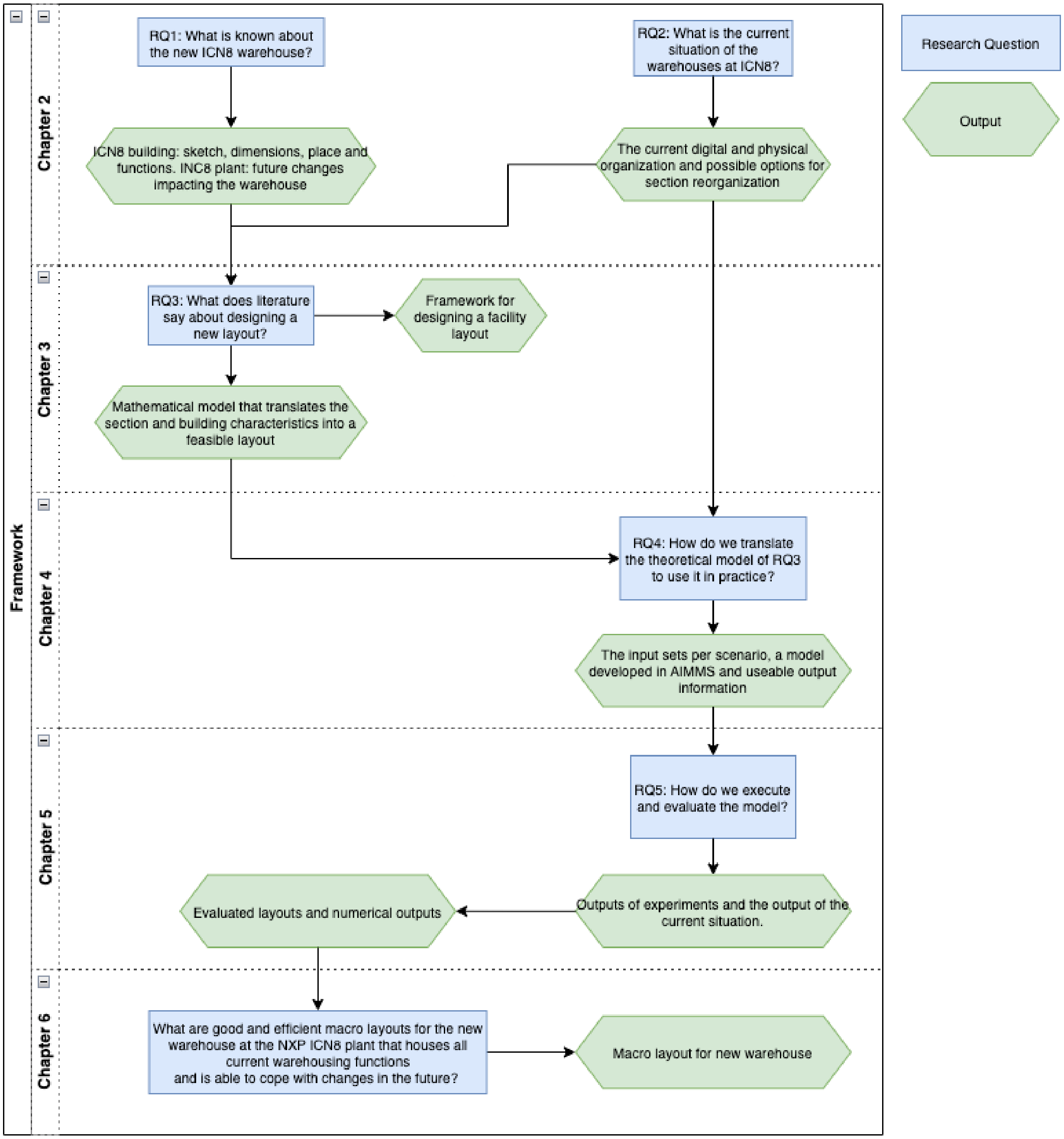

Figure 1.3 - Mapping of chapters to the research questions

2. CONTEXT ANALYSIS

The aim of this chapter is to provide insight to the current situation of the warehousing department of NXP ICN8, as well as to provide insight to the new warehouse that is planned to be built at NXP ICN8. As the context analysis of the new warehouse can influence the context analysis of the current warehouse, this chapter starts with the context analysis of the new warehouse in Section 2.1. Using the answers provided in Section 2.1, Section 2.2 of this chapter gives the context analysis of the current warehouse. Section 2.1 and Section 2.2 intend to give answer to research question 1 and research question 2, respectively.

2.1 NEW WAREHOUSE

The aim of this section is to provide a context analysis of the new warehouse and give answer to the first Research Question (RQ):

1. *What is known on the new ICN8 warehouse?*
    a. *What is fixed about the location and dimensions of the building that will house the new warehouse?*
    b. *What changes at the ICN8 plant that can influence the design of the new warehouse are to be expected?*

In the new situation, we know that a new building for the warehouse will be created and expect changes at the ICN8 plant that will affect the warehouse department. By looking at the new building and changes at the plant, we can focus the activity profiling of the current situation in Section 2.2. In Section 2.1.1 we intend to answer RQ 1.a and put together the information that we know about the new building for the warehouse. In Section 2.1.2 we intend to answer RQ 1.b and describes the changes to the ICN8 plant that we know of now, which influence the way of work at the warehouse.

2.1.1 NEW BUILDING

Using interviews with the managers and reviewing concept plans for the new warehouse during the interview [4] we received information for the new warehouse. The construction of the new building is planned on a fresh plot of land adjacent to the ICN8 plant. Figure 2.1 indicates the location in relation to the existing plant, and Figure 2.2 provides a rough layout of the new building. Figure 2.2 also highlights areas in yellow, allocated for the storage of this research, and the chemical storage in pink, blue, green, and bright yellow. This research will not cover the chemical storage area; we will concentrate on the rest of the storage. The building's width has been determined, but the depth and height can still be adjusted to increase the storage space.

The new building is set to have a minimum of two floors. This is due to the FAB's location on the adjacent building's second floor. Figure 2.1 illustrates the bridge connecting the warehouse to the FAB in blue. The production hall is a clean room, which means the air is virtually dust-free. This direct connection is beneficial for maintaining the cleanliness of the SKUs during transportation. Additionally, the proximity between the warehouse and FAB reduces walking distance, eliminating the need for an elevator.

The bridge to the FAB is one of three essential points where goods enter and exit the warehouse. These points are also called 'In & Out,' or I/O, points. The second mandatory I/O point is the warehouse's docking station, where trucks must load and unload goods. An additional I/O point can be established without a dock. The third mandatory I/O point is a location on the first level that allows transporting goods to and from the other buildings.

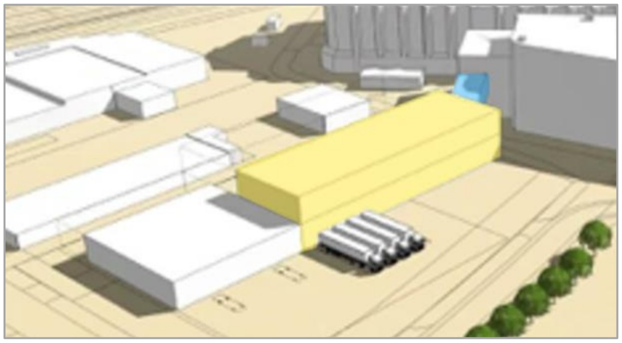

Figure 2.2 – Sketch of building

Figure 2.2 – Dimensions of new warehouse

2.1.2 CHANGES IMPACTING THE WAREHOUSE

Given that the new warehouse is projected to be in use for the next 10 to 20 years, it is crucial to design the building with this in mind. Changes within and outside the warehouse in the coming years could influence today's design decisions. Furthermore, the shift from multiple smaller warehouses to one large warehouse presents an opportunity to rethink the internal sections of the warehouse. We sought insights from various managers on-site to understand the potential changes at the ICN8 plant.

Externally, the warehouse is primarily influenced by the FAB, which requires raw materials, spare parts, and consumables. Other departments at the plant have less of an impact on the warehouse. Therefore, it is essential to consider the FAB's production increase and decrease. Managers indicated a slight increase in production capacity due to adding new machines. They also anticipate more fluctuations in production output, affecting the quantity of materials needed from the warehouse.

Internally, one significant change that will influence the warehouse design is NXP's commitment to sustainability [5]. This will lead to an increase in the number of reusable spare parts. Furthermore, these reusable parts will need to be stored in flight cases in the future. Currently, a few reusable parts are not stored in flight cases (boxes with cushions to prevent damage), occupying minimal space. However, the volume required to store parts in this section will grow in the future.

Finally, constructing a new warehouse allows us to reevaluate and redesign the sections and areas within the warehouse. Currently, sections are determined by available space and the evolution of the old warehouse. However, these sections aren't always logical or efficient. Therefore, we will closely examine the warehouse sections and explore options to enhance their efficiency.

2.1.3 CONCLUSIONS NEW WAREHOUSE

To answer RQ 1.a, we understand that the building's width is fixed, but adjustments can be made to its depth and the number of floors. Sections that are fixed to locations are the I/O points, the points where the goods flow in and out of the building. Regarding RQ 1.b, we need to consider three main factors. These are the slight increase and fluctuations in production output, the expansion of reusable spare parts and their new storage requirements, and the reconfiguration of the warehouse's internal sections.

2.2 CURRENT WAREHOUSE

This section aims to give a context analysis of the current situation of the warehouse at the ICN8 plant and answers to RQ 2.

2. *What is the current situation of the warehouses?*
    a. *How is the current warehouse organized?*
    b. *What are the sections of the warehouse?*
    c. *What are the characteristics of the storage sections?*

To understand the current situation, we first offer a broad overview of the physical and digital organization of the warehouse in Section 2.2.1. We then proceed to analyze and summarize the sections of the ICN8 warehouse, dividing the storage sections into spare parts storage, consumable storage, and raw wafers storage in Section 2.2.2. Finally, we carry out an analysis and characterization of these subdivided storage sections within the warehouse in Section 2.2.3.

2.2.1 ICN8 WAREHOUSE ORGANIZATION

The organization of the warehouse can be viewed from two perspectives: physical and digital. The physical layout of the warehouse has seen numerous changes over the years, often driven by production changes of the ICN8 plant. As required for locally optimized workflows, sections within the warehouse have been split and merged. However, each warehouse building generally serves a specific purpose. The digital organization is primarily optimized for the finance department, rather than the warehousing department and therefore cannot always be translated one to one to the physical organization. Because of the discrepancy between the physical and digital organization it is necessary to analyze the digital organization.

PHYSICAL ORGANIZATION

The ICN8 plant consists of four distinct warehouses, each housing a variety of items known as Stock Keeping Units (SKUs). These warehouses are spread across four buildings that are named: FD, BF, AO, and BQ. Figure 1.2 in Chapter 1 shows the locations of the buildings on the ICN8 plant.

FD: This building is the most used, facilitating the movement of inbound and outbound products through its loading dock. It provides a direct lift to the production floor and stores frequently used SKUs. **BF**: Located further from the production floor, BF serves as a storage facility for less frequently used materials, pallets, and packaging items. **AO**: This building is exclusively dedicated to storing raw wafers for production purposes. **BQ**: BQ serves as an emergency location, housing SKUs that were acquired in bulk during the COVID-19 pandemic. Appendix A overviews all the sections and their current surface area per building.

DIGITAL ORGANIZATION

The digital organization of the warehouse is primarily influenced by financial factors, which means it does not always correspond directly with the physical layout. For example, from a digital perspective it might make sense to divide the warehouse into external and internal spare parts sections, but this division might not be practical physically. We need to understand the digital organization to profile the warehousing department. This section gives a brief description of the ‘digital warehouses’ and the ‘Material Resource Planner (MRP) controllers.’ This information is needed for profiling the warehouse in the remainder of this chapter.

The digital warehouse is divided into warehouses named ‘NL1’ and ‘NL2’ for administrative reasons. NL1 is home to all the raw wafers, while NL2 stores the rest of the inventory. Digitally the warehouse is also divided into three plant codes: NL42, NL47, and NL74, mainly used by the finance department. These codes also determine the first two digits of the four-digit digital storage location, providing information about the SKU and hinting about its physical location. While this information is helpful for extracting data from the Enterprise Resource Planning (ERP) system, it does not impact the physical warehouse design.

Digital information that could influence the warehouse design includes the MRP controller, a three-character number assigned to every SKU in the warehouse. The first character (0-9) provides information about the process, and the last two characters (01-17) indicate the section where the SKU is used.

2.2.2 ICN8 WAREHOUSE SECTIONS

Each section within the current warehouses serves a unique purpose and is crucial to the existing warehouse structure. However, some of these sections will become redundant in the new warehouse. Conversely, dividing certain sections, such as the storage section, might be beneficial.

Based on the information gathered during the problem identification phase and considering both physical and digital sections, we have defined a high-level overview of the situation. Initially, the warehouse is divided into 'storage sections' and 'other sections'. This division is chosen due to the storage section's complexity and the other sections' supportive role in facilitating movements to and from the sections.

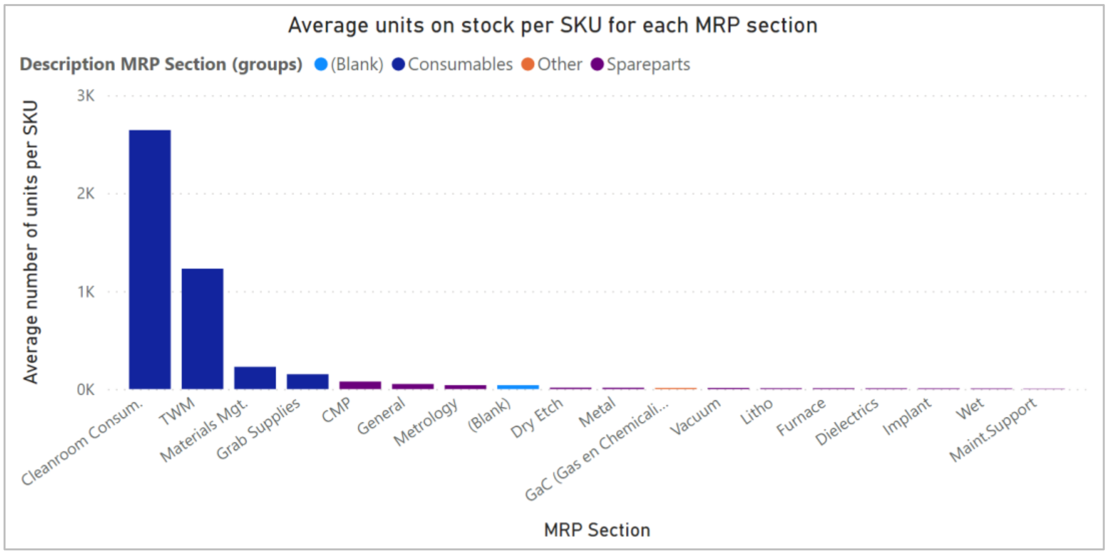

Figure 2.3 - Average units on stock per SKU per MRP section

Given the complexity of the storage section, we further divide it. Based on the analysis in Section 2.1.1 and conversations with employees, this can be done in several ways: by ownership, MRP logistic flow controller, MRP section controller, size, or fast and slow movers. Currently, the raw wafer storage is digitally and physically separated from the rest, making it an easy choice to keep it separate here. The remaining storage is divided into spare parts and consumables. When analyzing the storage by the MRP section controller, we find some MRP sections with low variation of SKU and high stock volume, and vice versa. MRP sections with low variation volume are spare parts. Figure 2.3 shows the average units in stock per SKU per MRP section. As a result, we divide the storage sections into 'Spare parts,' 'Consumables,' and 'Raw wafers.' The 'Spare parts' and 'Consumables' sections will be further divided into section groups.

STORAGE SECTIONS

This section characterizes the storage sections for spare parts, consumables, and raw wafers. Section 2.2.3 offers a more in-depth discussion of the storage sections for spare parts and consumables.

SPARE PARTS

Spare parts, ranging in size from a screw to a large pump, are essential for machine maintenance in the FAB. The warehouse ensures their correct storage and flow to prevent production disruptions, which could lead to significant costs. The parts undergo wrapping in plastic foils to ensure dust-free storage. Fragile parts, like quartz, require special care. On average, the stock holds 16.3 units per SKU.

CONSUMABLES

Consumables, such as office paper, shipping cartons, and cleanroom gloves and shoes, are constantly used. These items, delivered in bulk and picked in parts, occupy significant warehouse space. Therefore, the goal is high space utilization. Most consumables are stored in bulk, with pallet sizes being relatively uniform. On average, the shelf holds 856 units per SKU.

RAW WAFERS

Raw wafers, the production inputs, are delivered to the factory each morning. Any delay or error in delivery can disrupt production planning and incur significant costs. Therefore, the goal is the timely delivery of the correct type of raw wafer. All raw wafers have the same size and weight, are delivered in the same boxes, and have an expiration date. They are stored on slightly tilted shelves, accessible from both sides of the racks, and follow a first-in, first-out picking system.

OTHER SECTIONS

INBOUND

The inbound section handles the registration and processing of all incoming goods. It necessitates a large area for temporary storage of goods distributed throughout the plant after administrative tasks. Proximity to the dock is essential for this section.

OUTBOUND

The outbound section oversees packaging, temporary storage, and shipping all outgoing goods, including finished wafers, office packages, and transshipping packages from other companies. Due to the high value of the goods, packaging and temporary storage occur in a restricted area known as the 'yellow area.' The 'red area,' with even more restricted access, serves as a vault for temporarily storing finished wafers before packaging them in the yellow area.

FORWARDING AREA FAB

The FAB forwarding area stores cars with frequently used spare parts. Instead of ordering individual parts from the factory, a kit car is ordered to ensure immediate availability of all necessary maintenance parts.

FORWARDING AREA CLEAN PARTS

Dirty but reusable spare parts are sent to external companies for cleaning. Given the infrequent collection of these parts, a dedicated area is reserved for their temporary storage.

OFFICES

Offices facilitate administrative tasks in the warehouse. The inbound, outbound, the I/O to the FAB, and the warehouse manager require office space. These are noted as a separate section as they can be distinct from the areas they serve.

RESTROOMS, LOCKERS, AND BREAKROOM

These sections contribute to employee satisfaction. While restrooms are essential, lockers and breakrooms are optional, as warehouse employees can use those in the main building.

I/O POINTS

Although not strictly warehouse sections, I/O points are noted due to their requirement for a position in the new layout and their interactions with other warehouse sections. Section 2.1.1 mentions at least three I/O points: the dock, the I/O to the plant, and the I/O to the FAB.

BWT PRODUCTION

The shipping department packages the finished wafers in BWTs. The BWTs are made of pallets with a case of cartons that are fabricated on-site.

2.2.3 STORAGE GROUPS

Characterizing a storage section aims to facilitate its subdivision into distinct groups. This subdivision is crucial as it allows for the separate storage of certain groups and enhances the flexibility of macro layout design. However, this process also introduces a challenge: increasing the number of sections and groups adds complexity to the design process.

SPAREPARTS STORAGE

The spare parts section is an extensive section that contains a great variety of SKUs that can be divided into different groups. Some groups are, for example, NXP owned and consignment stock[1], fast-moving and slow-moving stock, and circular (reusable) and linear (not reusable) stock. The groups are not mutually exclusive, meaning that a SKU can fit in more than one group.

STORAGE TYPE

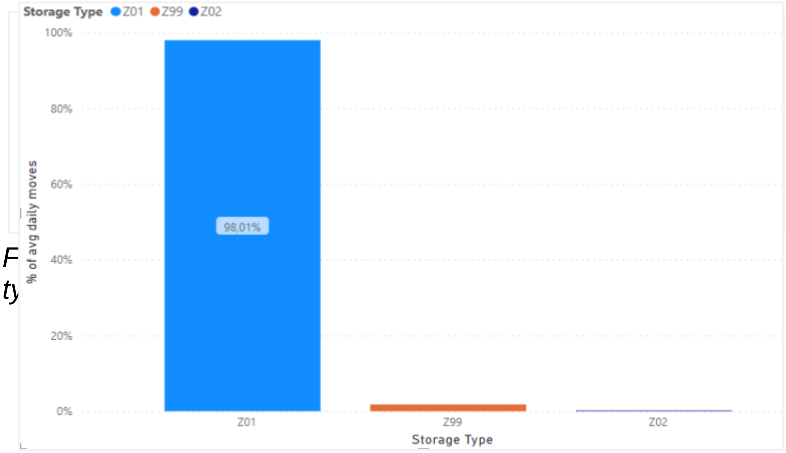

Figure 2.5 – Percentage of moves per storage type for all spare parts

The categorization of spare parts into 'Storage Type' is based on NXP's ERP system. Each spare part SKU is classified as either a 'Runner' (Z01), 'Non-Runner' (Z02), or

---

[1] Consignment stock are items that are stored at the ICN8 warehouse and are only paid for when a item is picked.

'Broken' (Z99), as illustrated in Figure 2.5. Runners are frequently picked SKUs, while Non-Runners are ones that have not been picked in recent years. The ERP system does not automatically reorder Non-Runners when they run out of stock.

Broken SKUs are reusable spare parts stored temporarily for repair. Repairs are only undertaken when the stock of functioning SKUs falls below the safety stock level. A broken SKU can remain in storage for months or even years. It is crucial to separate functioning and broken stock to avoid machine malfunctions physically.

Figure 2.5 and Figure 2.4 show the percentage of stock per SKU and the average daily moves, respectively. Storage type Z01 comprises 66.94% of the total stock but is responsible for 98% of the picks.

NXP-OWNED STOCK AND CONSIGNMENT STOCK

Spare parts in the warehouse may belong to NXP or an external vendor, as depicted in Figure 2.6. While it is not mandatory to physically separate NXP and consignment stock, doing so could enhance overview and efficiency. The separation is advantageous as NXP does not technically own the consignment stock, and preventing their loss is crucial. Conversely, merging the two sections simplifies the problem and allows for more efficient SKU placement. Figure 3.4 and Figure 3.5 show that consignment stock comprises only 6.26% of stock but is responsible for 21,28 of the daily picks.

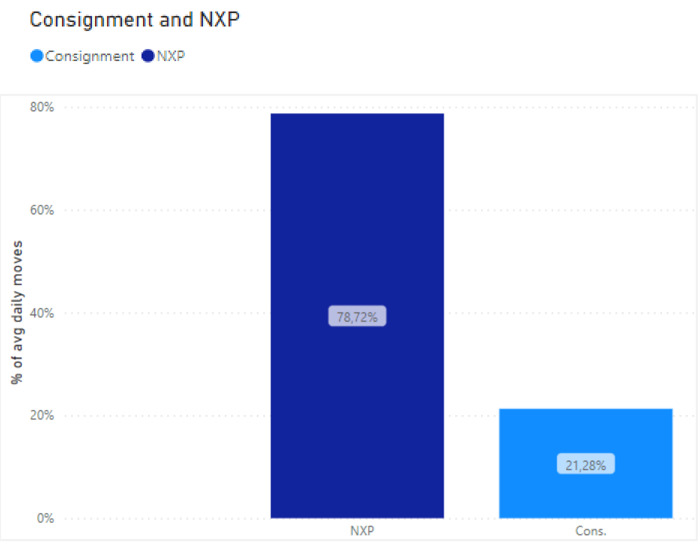

Figure 2.6 – Percentage of moves for NXP stock and consignment stock

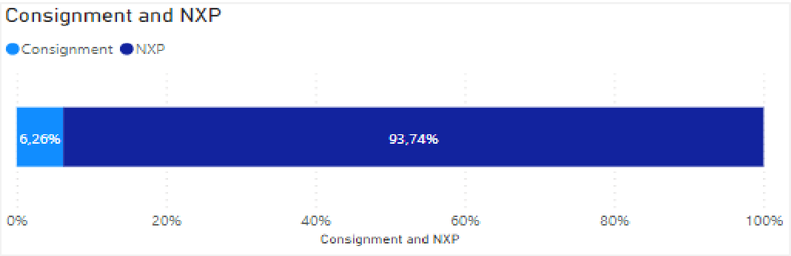

Figure 2.7 – Percentage of NXP owned stock and consignment stock

MRP SECTIONS

As outlined in Section 2.2.2, each SKU has an associated MRP section controller, indicating the MRP section of the FAB that typically uses it. It is worth noting that while an SKU is primarily used by its assigned MRP section, it is not exclusive to it. Figure 2.9 presents a bar chart detailing the number of distinct SKUs per MRP section, while Figure 2.8 displays a bar chart of the average daily orders per MRP section. Based on Figure 2.9 and Figure 2.8, it is evident that the dry etch section is the most utilized, leading with the highest variety of SKUs and accounting for 63% of daily picks.

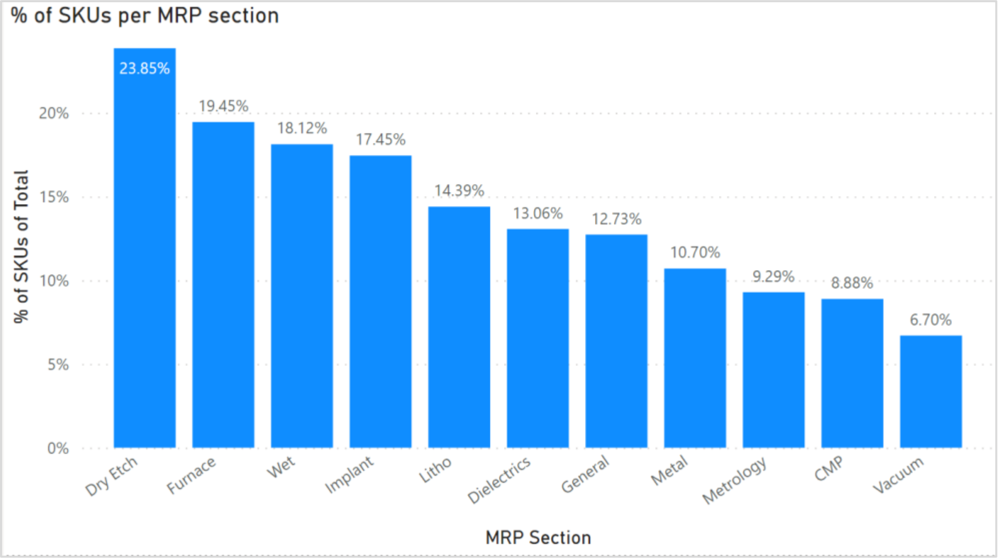

Figure 2.9 – Percentage of SKU per MRP section

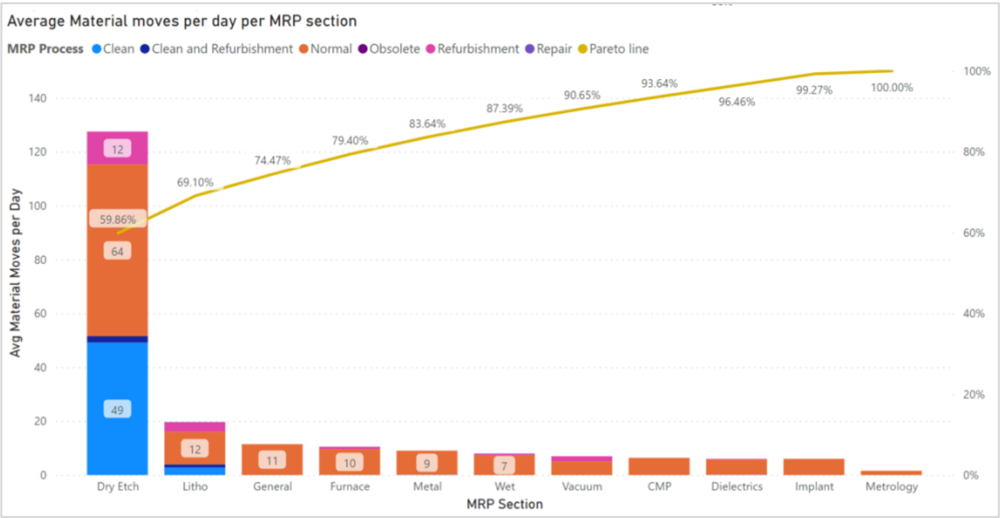

Figure 2.8 – Average material moves per MRP Section

MRP PROCESSES

As detailed in Section 2.2.2, each SKU has an associated MRP process controller, which indicates the process flow of the SKU. Figure 2.11 presents the number of distinct SKUs per MRP process, while Figure 2.10 displays the average daily orders per MRP process.

Based on Figure 2.10, it is clear that 97% of the SKUs fall under the normal and obsolete processes (86% + 11%). This implies that a SKU is typically used once and then discarded. Only 2% of SKUs undergo the refurbishment process, and a mere 1% enter the clean process.

Figure 2.10 reveals that most daily picks come from the normal process, averaging 92 picks per day, or 66% of the picks. The clean process follows with an average of 36 daily picks, accounting for 29%. This indicates that parts in the clean MRP process are utilized significantly more relative to their quantity. Figure 2.10 further shows that the dry etch MRP section utilizes a substantial portion of the average moves of the clean parts.

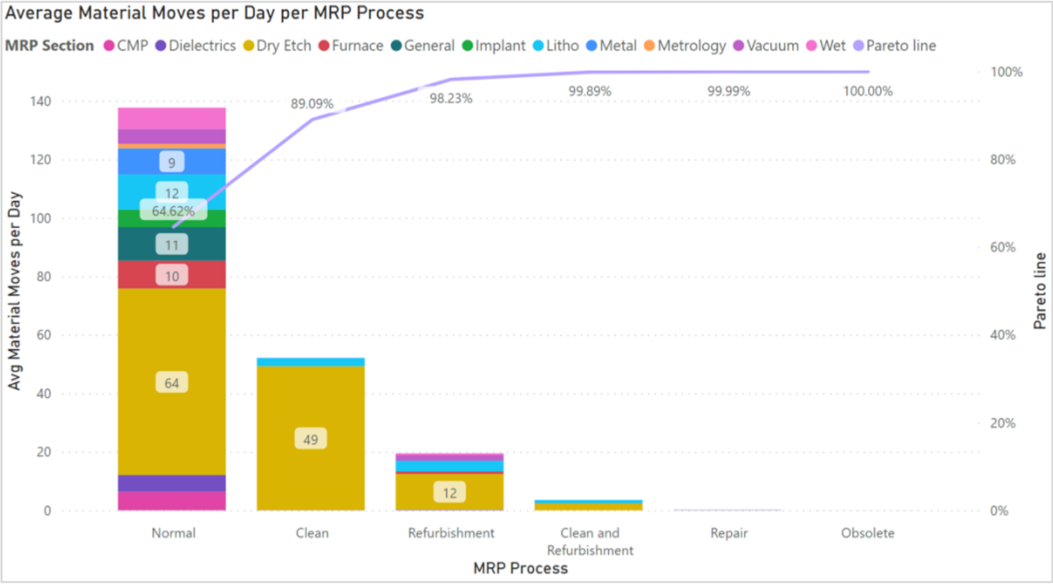

Figure 2.11 –Average material moves per MRP Process

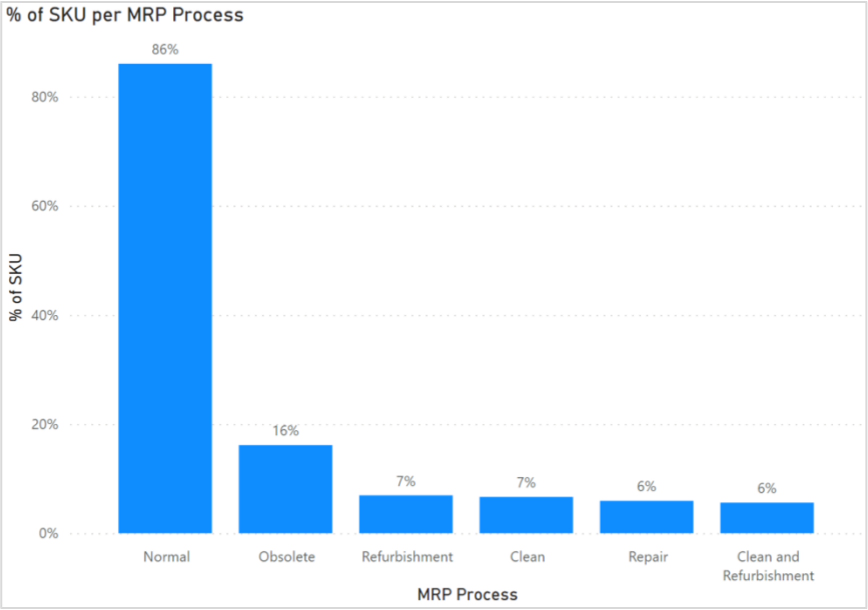

Figure 2.10 – Percentage of SKU per MRP Process

OTHER

Two types of SKUs necessitate separate storage. Firstly, quartz, a highly fragile and costly material [6], requires careful handling. Its separate storage helps maintain product quality. Secondly, due to their significant weight and storage challenges, pumps must also be stored separately. They require a specific type of lifting device for handling.

CONSUMABLES STORAGE

Consumable SKUs are found across four MRP sections: Cleanroom Consumables, Grab Supplies, Materials Management, and TWM, all of which are part of the standard MRP process. The SKU distribution is illustrated in Figure 2.12, while Figure 2.13 presents the average picks per section.

Cleanroom Consumables, including items such as gloves, shoes, coveralls, and cleanroom paper, are supplied to the FAB via the first level I/O point. Grab Supplies, comprising smaller items like screws, nuts, connectors, and O-rings, are picked by the box, not individually, and exit the warehouse at the second level I/O point.

The Materials Management section houses packaging materials such as cartons, bubble plastic, and tape, primarily utilized by the warehouse's shipping department. The TWM section stocks products for the FAB's TWM section, with SKUs leaving the warehouse internally at the second level.

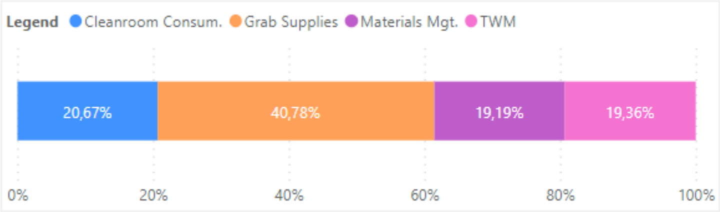

Figure 2.12 – % of SKU per MRP section

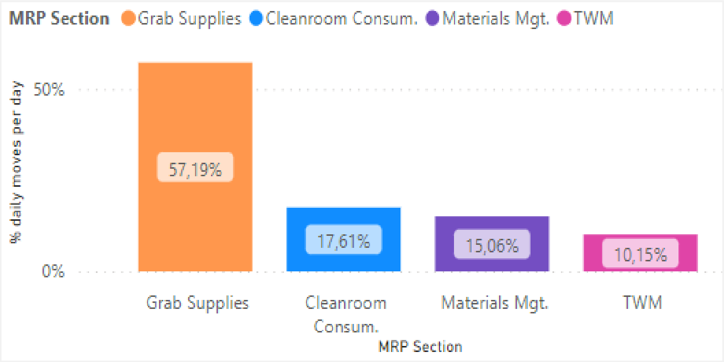

Figure 2.13 – Average moves per day per MRP section

2.2.4 CONCLUSIONS CURRENT WAREHOUSE

This section answers RQ 2:

2. *What is the current situation of the warehouses?*
    a. *How is the current warehouse organized?*
    b. *What are the sections of the warehouse?*
    c. *What are the characteristics of the storage sections?*

Section 2.2.1 analyzed the current functionality and organization of the warehouse, giving answer to RQ 2.a. We analyzed the physical warehouses and summed all the sections and functions they contain. We conclude that the digital and physical organization are not synchronized. The digital organization is influenced by the financial aspects and can have the result that digitally, two SKUs are in different warehouses, but physically, they are only a shelf apart. The digital organization, however, is useful for the research as it assigns each SKU a MRP controller that contains information about the section where the SKU is used and the process that the SKU is in.

Section 2.2.2 continues by globally profiling the sections at the ICN8 warehouse, giving answer to RQ 2.b. All storage sections and supporting sections are identified and characterized. As storage sections, we define the raw wafer section, spare parts section, and consumables section

Section 2.2.3 profiles the activity of the storage sections, answering RQ2.c. We conclude that the spare parts section has a high variety of SKUs and can be divided into storage type, NXP owned and consignment, MRP section, MRP process. The consumables section has a low variety of SKUs and can be divided into grab supplies, cleanroom consumables, materials management, and TWM.

3. LITERATURE STUDY

This chapter addresses the literature study of the Facility Layout Problem (FLP) within the warehouse context and answers Research Questions 3:

3. *What insights can be gathered from literature regarding the design of a new warehouse layout?*
    a. *How can the problem of this research be classified?*
    b. *What framework for designing a macro layout fits this research best?*
    c. *What mathematical models can be used to create a macro layout for a warehouse?*

Section 3.1 provides a theoretical framework and describes the literature to find answers to the research questions. Section 3.1 starts with a broad explanation of the FLP. Section 3.1.1 provides literature on the classification of an FLP and directly classifies the FLP of this research, answering RQ3.a. Section 3.1.2 and Section 3.1.3 provide the theoretical framework for the FLP design frameworks and resolution approaches to create a macro layout, respectively.

Section **Error! Reference source not found.** uses the theoretical framework to create the literature model. Section 3.2.1 selects and describes a design framework that will be used in this research, answering RQ3.b. Section 3.2.2 selects and describes a resolution approach to mathematically create a macro layout, answering RQ 3.c.

3.1 THEORETICAL FRAMEWORK – FACILITY LAYOUT PROBLEM

A warehouse is a facility and plays a crucial role in the efficient functioning of supply chains and logistics operations. [7] It involves storing, managing, and distributing goods and materials in a controlled environment. [7] Warehouses serve as centralized hubs where products are stored, sorted, and prepared for onward transportation to retailers, wholesalers, or directly to end consumers. [7] The reason that we hold stock in warehouses is that our society and our markets are not predictable. [7] This can be caused by uncertain and erratic demand patterns, the trade-off between transport and shipping costs, discount via bulk buying, the distance between the manufacturer and the end consumer, cover for shutdowns, ability to increase production runs, high seasonality, spare parts storage, work-in-progress storage, investment stocks, document storage, and third sector storage. [7]

In literature, a facility is defined as a building on a plant where people utilize materials, machines, and other resources to make a tangible product or provide a service [8]. The placement of the facilities in the plant area, often referred to as a 'facility layout problem' (FLP), is known to significantly impact manufacturing costs, work in process, lead times, and productivity. Simulation studies often measure the benefits and performance of given layouts. Unfortunately, layout problems are known to be complex and are generally NP-Hard. [9] This research defines the warehouse as the plant and the sections as the facilities. We place the sections inside the warehouse considering the restrictions.

Designing the layout of a warehouse is a complex task, and many researchers have looked at the topic [10] [11] [12] [13]. Layout design is a complex task because a lot of decisions are interdependent. Figure 3.1 shows the five decisions that influence the design [13]. Choices on the department layout, operation strategy, equipment selection, sizing and dimensioning, and overall structure are highly interrelated, making the problem very complex.

In Section 3.1.1 we introduce the FLP classification and directly conclude on the classification of this research. In Section 3.1.2 we dive into the frameworks that are available for designing a facility and in Section 3.1.3 we search through literature to find applicable resolution approaches to solve the FLP.

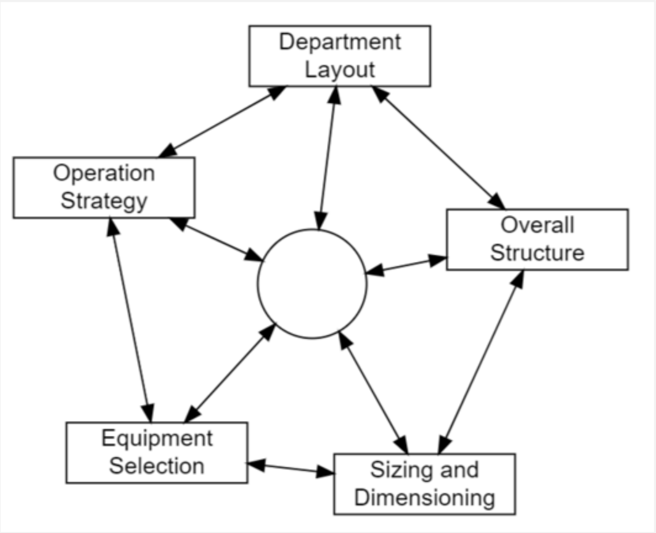

Figure 3.1 – Decisions influencing the layout design [12]

3.1.1 FLP CLASSIFICATION

FLPs can be classified in different ways. Ensuring that our literature review is focused on the right classification of the FLP we use this section to both explain the types of classification for the FLP, as well as to classify the FLP of this research. To classify the FLP of our research, we use the classification tree created by [14]. Figure 3.2 shows the classification three where the blue boxes indicate the classification of this research's FLP.

Figure 3.2 shows that the FLP can be classified in layout evolution, workshop characteristics (characteristics of the warehouse), problem formulation, and resolution approaches. The layout evolution can either be static or dynamic. Most articles dealing with layout problems are implicitly considered static; in other words, they assume that the key data about the workshop and what it is intended to produce will remain constant over time. Recently, the idea of dynamic layout problems has been introduced by several researchers. Dynamic layout problems consider possible changes in the material handling flow over multiple periods [14]. In this research, we deal with a static layout problem because we do not consider changes in multiple periods.

Under the workshop characteristics (or the warehouse characteristics in this research) we find 'shape and dimension,' 'manufacturing systems,' 'material handling,' and 'flow movement.' For the shape and dimension in the workshop characteristics, our research classifies as regular/irregular shapes. This is because the sections we place in this research are not fixed to an area of to an aspect. The manufacturing systems classifies as a cellular layout because our sections are not placed in any order and movements can go in and out from any direction. The material handling has a layout configuration, which classifies as a multi-floor layout in this research. The flow movement in this research is complex and can have bypassing and backtracking, meaning that products can skip a section and go return to a section, respectively.

The objective function in this research is rectilinear, quantitative, and has a single objective. That is because the objective is to minimize the cost of a warehouse with rectilinear sections. Because the shapes of the sections can be every size, the problem representation is continuous. The modeling is exact, and we will use Mixed Integer Programming to model the problem. This is because we have a continuous FLP with unequal-sized sections. The type of data we input in the model is deterministic. However, by changing the deterministic input, we create several experiments. We have layout and area constraints.

We have a single objective problem formulation and therefore we can choose a resolution approach that is classified as intelligent, stochastic, exact, or approximated. In Section 3.1.3 and Section 3.2.2, we explain more about the resolution approaches and select one, respectively.

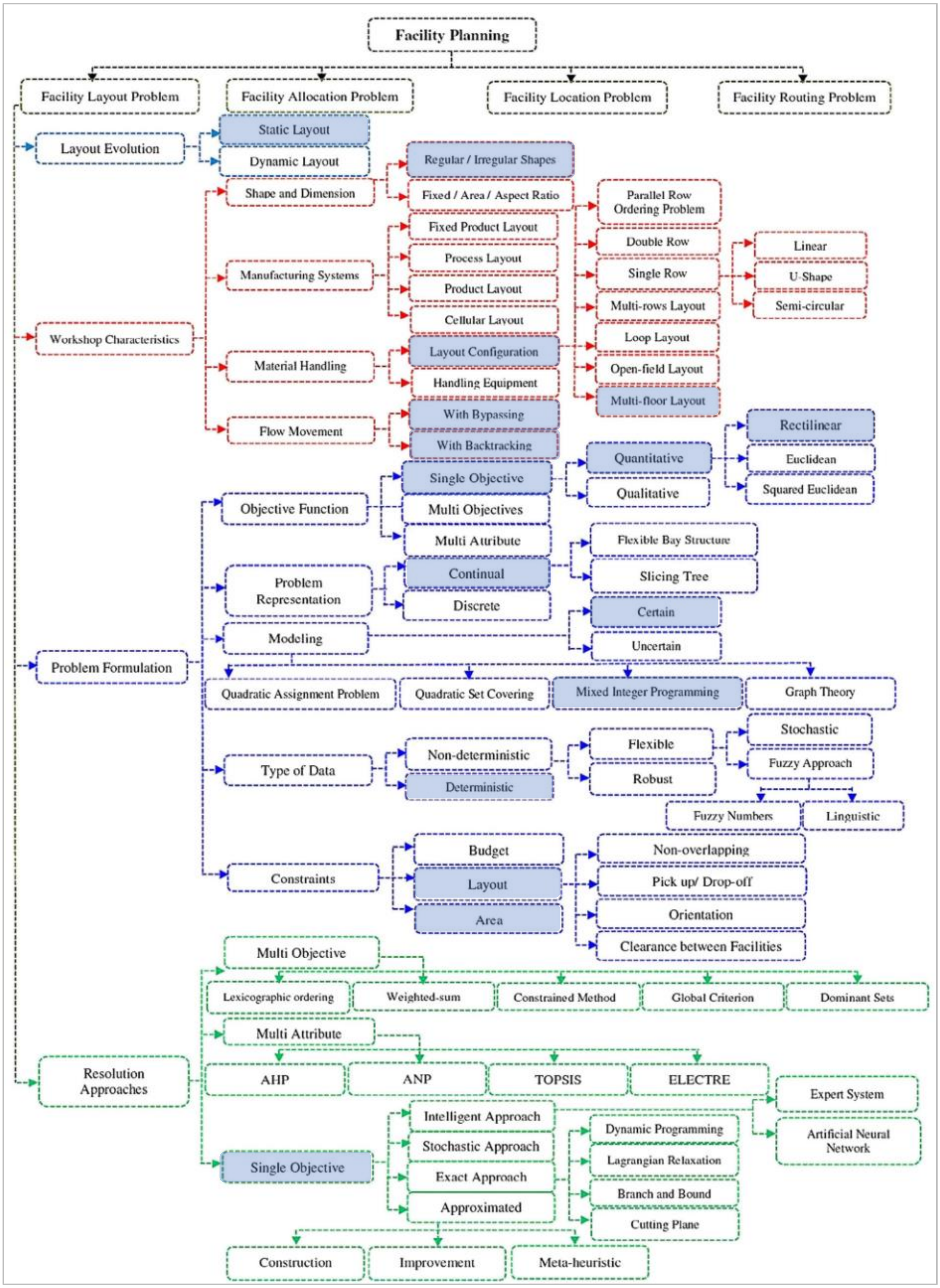

Figure 3.2 - Facility Layout Problem classification tree of [7]. Blue shades indicate the classification of the FLP of this research

3.1.2 FLP FRAMEWORKS

In this research we denote the FLP framework as a methodology to design the facility layout. A FLP framework is composed of steps that are to be taken to get a solution to the FLP. A FLP framework can be focused on a FLP in general, a generic FLP framework, and can be focus specifically on the warehouse FLP, a warehouse FLP framework.

Two generic FLP frameworks are the Systematic Layout Planning (SLP) [8] and the traditional engineering design process (TEDP) [9]. The SLP, which is shown in Figure 3.3, was created by Muther. The traditional engineering design process (TEDP) serves as a systematic approach to problem-solving in general, involving stages such as problem identification, requirements gathering, conceptual design, detailed design, prototyping, testing, and implementation. The steps of the TEDP are shown in Table 3.1. Whereas the SLP is a framework specifically made for the layout design, the TEDP is a more general design framework that can be applied in other design problems as well.

Two frameworks specified for warehouse layout design problems are the proposed framework of Baker and Canessa [11] and the framework proposed by Frazelle. [10] The framework of Baker and Canessa is shown in Table 3.2. The framework of Baker and Canessa include steps for the material handling, but do not pay attention to the flows and facility locations. The framework of Frazelle is shown in Table 3.3. The framework of Frazelle [10] pays less attention to material handling, like Baker and Canessa, but focuses more on department placement and the flow between them.

Table 3.1 - Framework for the Traditional Engineering Design Process [9]

Step	**Task**
1	Define the problem - Define (or redefine) the objective of the facility - Specify the primary and support activities to be performed in accomplishing the objective
2	Analyze the problem • Determine the interrelationships among all activities
3	Determine the space requirements for all activities • Generate alternative facilities plans
4	Evaluate the alternatives
5	Select preferred design
6	Implement the design

Table 3.2 - Framework for Designing Warehouse Layout by Baker and Canessa [11]

Step	**Task**
1	Define system requirements
2	Define and obtain data
3	Analyze data
4	Establish unit loads to be used
5	Determine operating procedures and methods
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

Table 3.3 – Framework for Designing Warehouse Layout by Frazelle [10]

Step	**Task**
1	Determine space requirements for all warehouse functions
2	Locate functions with high adjacency requirements close to one another
3	Assign activities with: 1. High storage requirements to high-bay space. 2. Labor-intensive processes in low-bay space
4	Determine flow paths
5	Assign the optimal material-handling method to each flow path
6	Minimize space requirements
7	Develop and document expansion/contraction strategies

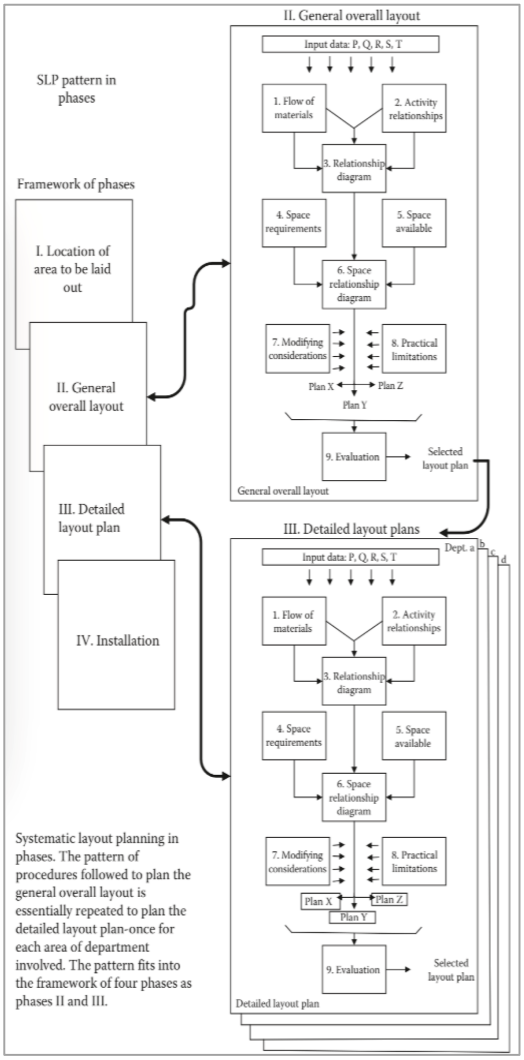

Figure 3.3 - Framework of the Systematic Layout Planning [6]

3.1.3 FLP RESOLUTION APPROACHES

TYPES OF RESOLUTION APPROACHES

We create a solution for the Facility Layout Problem (FLP) using a mathematical model as the resolution approach. In this section we conduct a literature review on resolution approaches that generate layouts for the FLP. In Section 3.1.1 we determined that the resolution approach has a single objective, and that the resolution approach can classify either as exact, stochastic, approximate, or intelligent. After that we perform a literature review on resolution approaches that have these characteristics. The method of searching the literature is given in Appendix B.

Exact resolution approach: Exact methods are useful approaches to find optimal solutions for small-sized FLPs. Dynamic programming, branch and bound method, cutting plane algorithm, and semidefinite programming are examples of exact approaches [15]. In this paper we are dealing with a large-sized FLP with around 30 sections and thus will not use an exact resolution approach.

Stochastic resolution approach: They are algorithms that produce near-optimal solutions with high probability. Discrete event simulation approach is an example of stochastic approaches [15]. For this research, a stochastic approach could be possible. However, this resolution approach requires a lot of input to give results. Because of the huge changes to the warehouse, a lot of these inputs are unknown and need to be approximated. This is not feasible in the amount of time that is available. Therefore, we do not use a stochastic resolution approach.

Approximate resolution approach: [15] shows that the QAP, an exact resolution approach, is NP-complete and that optimization methods are not capable of solving problems with 15 or more facilities within a reasonable amount of time. Therefore, there is a need for approximated algorithms that can provide good suboptimal solutions. These approaches are classified as improvement algorithms, construction algorithms and meta-heuristic algorithms.

The improvement methods start with an initial solution and attempt to improve it by swapping the locations of facilities. The swap that produces the best solution is retained, and the procedure continues until the solution cannot be improved any further. Hence, the solution quality of improvement procedures is very sensitive to initial layouts. Examples of these methods are pair-wise exchange, insertion neighborhood, Lin–Kernighan neighborhood, computerized relative allocation of facilities technique (CRAFT), computerized facility aided design (COFAD). [15].

The construction procedures build a layout from scratch by successively selecting and placing facilities until a completed layout is obtained. These methods have one drawback in common; that is, the final solution may be far from optimal because the methods generate only one layout. Well-known examples of construction algorithms are computerized relationship layout planning (CORELAP), automated layout design program (ALDEP), and programming layout analysis and evaluation technique (PLANET) [15].

There are different meta-heuristics methods are presented to solve FLPs. The best known of these techniques are genetic algorithm, tabu search, simulated annealing, and ant colony optimization [15].

Intelligent resolution approach: Papers about the intelligent resolution approaches emerged in the last five years and are scarce. [16] also discusses that this is partly because Facility Layout Problems are ill-structured, and their information is noisy, uncertain, or incomplete, making it hard to obtain examples that can be used as ‘good’ or ‘bad’ input. Furthermore, because the problem is NP hard the training data for an intelligent approach is of rather subjective quality. Because of these reasons an intelligent resolution approach is not feasible for this research.

SUITABLE RESOLUTION APPROACHES

To determine the best approach for resolving the issue at hand, we conducted a thorough literature review on resolution methods for FLPs that comply to our FLP classification. After reviewing the literature, we have found five approaches that comply to the classification. characteristics of all five papers are listed in Table 3.4 and Table 3.5.

Table 3.4 and Table 3.5 show the five papers that all have a resolution for the multiple floor facility layout problem. We analyzed the papers based on the characteristics that are valuable for our research, as well as the characteristics that the resolution approaches focused at. The characteristic most value for us is the run time of the model. This is due to the large number of sections the FLP of this research has. Three of the five resolution approaches have a specific goal such as a focus on the piping for chemicals [17], dealing with fixed walls and passages [18] and focusing of lifts that serve only part of the floors [19]. [20] distinguishes from the others by developing their resolution approach using two stages, one for assigning the sections to floors and the second for developing a layout for each floor, thereby decreasing the run time. [21] used this concept to create a more comprehensive resolution approach in 2013. In addition to [20], [21] added a stage that created better solutions and added the option to have multiple elevators in the model. This extra stage positions the sections on the floors before creating a definite layout. They show that the benefit of using two or three stages instead of one is the runtime. Solving the two parts separately dramatically reduces the runtime, while not giving in much on the solution quality.

Table 3.4 – Part one of the characteristics of papers that resulted from the literature review

Paper	Stages	Programming type	Elevators	Placement of Elevator	Length & Width layout
[20]	2	*1:* MILP (Assign section to Floor) *2:* MILP (Develop layout for each floor)	Set	No	Set
[17]	1	MILP	No	No	Set
[18]	1	Genetic algorithm	Set	No	Set
[19]	1	MILP	Variable	Yes	Set
[21]	3	*1:* LP (Assign section to floor) *2:* NLP (Position section on floor) *3:* NLP (develop layout for each floor)	Set	Yes	Variable

Table 3.5 - Part two of the characteristics of papers that resulted from the literature review

Paper	Floors	Inner Walls and Passages	Run Time	Additional information
[20]	Set	No	Medium	-
[17]	Variable	No	Long	Focus on chemical plants and piping
[18]	Set	Yes	Long	Focus on passages and inner walls
[19]	Variable	No	Long	Focus on lifts that service only two or three floors
[21]	Set	No	Short	Continues on model of [20]

3.2 SELECTED RESEARCH MODELS

Section 3,1 describes literature about the FLP, FLP design frameworks and FLP resolution approaches. This section uses that information to select a design framework in Section 3.2.1 and a resolution approach in Section 3.2.2.

3.2.1 SELECTED FRAMEWORK

For this research, we adapt the framework of Frazelle [10] as this framework pays more attention to the flow between the departments compared to the other frameworks. The first step is to determine the space requirements for all activities. This is done in Section 4.2, where we translate the real-world data to the model data. The second to third step is done by the mathematical model that is explained in Section 3.2.2. Steps 5, 6 and 7 are not executed because this is not in scope with this research. We do add a new step at the end where we evaluate the created solution and compare it to the existing situation. This results in the framework shown in Table 3.6.

Table 3.6 – Framework for Designing Warehouse Layout by Frazelle, Modified for this Research

Step	Task
1	Determine space requirements for all warehouse functions
2	Locate functions with high adjacency requirements close to one another
3	Assign activities with: 1. High storage requirements to high-bay space. 2. Labor-intensive processes in low-bay space
4	Determine flow paths
5	Evaluation

3.2.2 SELECTED RESOLUTION APPROACH

Out of the five resolution approaches that resulted from the literature review of Section 3.1.3 the resolution approach described by Bernardi et al. [21] is chosen. The approach of Bernardi et al. [21] is chosen because of the fast run times and its general focus on layout design. Moreover, [17] [18] [19] have specific focus on characteristics of facility design that are not applicable in our research and make the models unnecessarily complicated. In the rest of this section, we shortly describe the workings of the resolution approach. The full mathematical descriptions of the model can be found in Appendix C

STAGES OF RESOLUTION APPROACH

Figure 3.4 gives an overview of the way one experiment is executed. In the rest of this section we look at the three stages of Bernardi et al. [21]. The first stage is about assigning the sections to the floors. The second stage finds the relative best positions for each section on a floor. The third stage develops a definite layout for each stage. In this section we take a high overview look at the models as depicted in Figure 3.4.

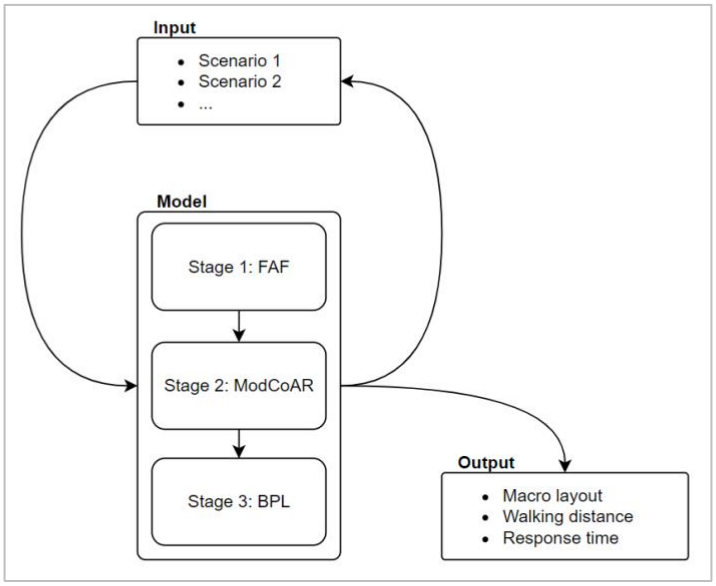

Figure 3.4 - Global overview of the model that is used in this research. Multiple scenarios go through the model, the model creates an output for each scenario

STAGE 1: FIRST ASSIGN FLOORS (FAF)

The first stage assigns the sections to the floors. As can be seen in Figure 3.5, the sections, floors, surface area of sections, surface area of the floors, and the costs to move between sections are given. This information is put as input into the FAF model and will output the assigned floor for each department.

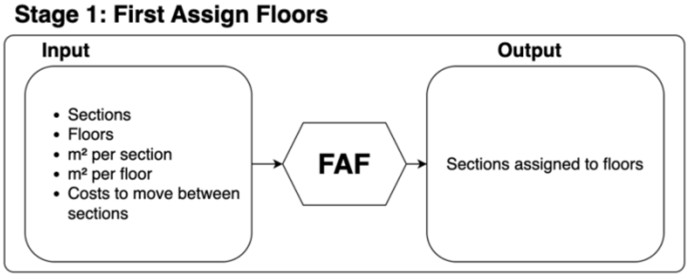

Figure 3.5 - Flow of stage one: First Assign Floors

STAGE 2: MODIFIED CONVEX ATTRACTOR REPELLER (MODCOAR)

Stage two of the model takes the output of stage 1 and uses this to calculate coordinates for each department, as seen in Figure 3.6. This stage uses two scaling parameters, KMOD and α, to change the outcome. The outcome generates an outcome of T_{ij} and D_{ij}, which are the Target Distance and the actual Distance. We want this number to be as close to one because that is optimal. Based on this information, we choose and give the coordinates of the departments.

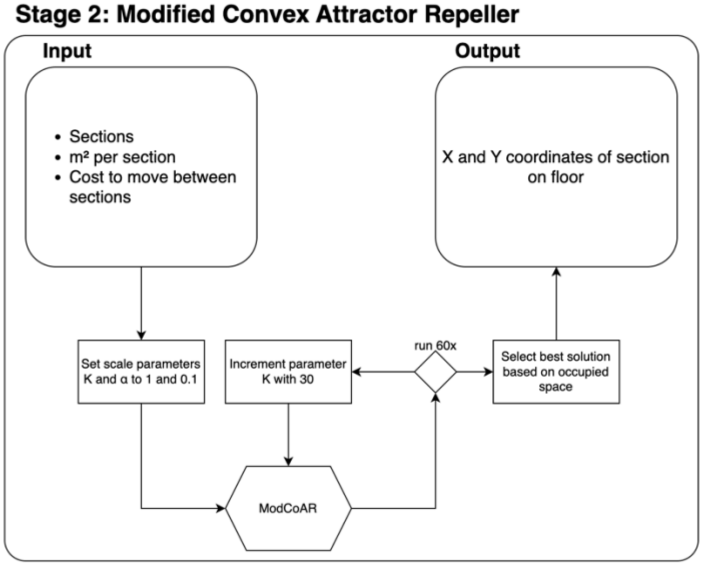

Figure 3.6 – Flow of stage two: modified Convex Attractor Repeller.

STAGE 3: BILINEAR PENALTY LAYOUT MODELER (BPL)

Stage 3 of the model uses the output of ModCoAR, the coordinates of the sections, and the costs to move between them to output the height and width per section. Using this information, we can create a macro layout and calculate KPIs. The flow is shown in Figure 3.7.

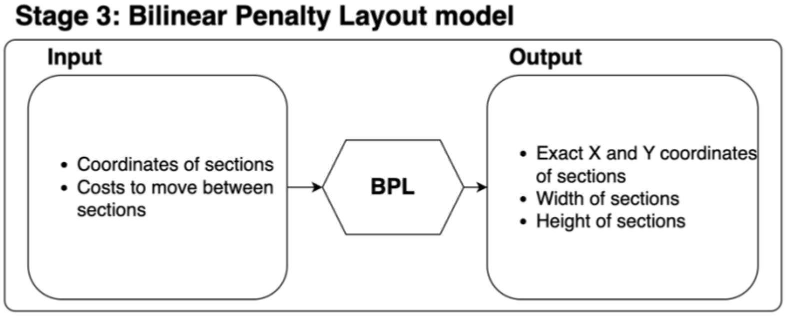

Figure 3.7 – Flow of stage three: Bilinear Penalty Layout model

3.3 CONCLUSION

This chapter provided a literature study on the Facility Layout Problem and answered RQ 3:

3. *What insights can be gathered from literature regarding the design of a new layout?*
   a. *How can the problem of this research be classified?*
   b. *What framework for designing a macro layout fits this research best?*
   c. *What mathematical models can be used to create a macro layout?*

The classification of the FLP is visually shown in the classification tree in Figure 3.2 and answers RQ 3.a. The FLP has a static layout, has irregular shapes, a cellular layout, is multi-floor, has both bypassing and backtracking movements, has a single objective that is both quantitative and rectilinear, has a continual problem representation, has Mixed Integer Programming with deterministic data, and has layout and area constraints.

Using the classification of the FLP we selected and modified the design framework of Frazelle, [10] answering RQ 3.b. The design framework we selected has a more focus on the placement and flow between the sections, compared to the other suitable design frameworks. We modified the design framework to fit the framework to the scope of this research, leaving out the selection of storage equipment.

As resolution approach we selected the three-stage linear programming model of [21]. This is a rather ‘general’ model that does not focus on a specific goal such as fixed walls or elevator placement but suited this research. We choose this model as it has the best score on runtime, making it able to run models with many sections.

4. SOLUTION DESIGN

This chapter describes how we translate the theory from Chapter 3 to a model that can be used for the experiments and answers Research Question 4:

4. *How do we translate the theoretical model to practice?*
    a. *What should the input data for the model be?*
    b. *How do we translate real-world data to input data?*
    c. *How should the output of the model look like*?

Section 4.1 describes the procedure of the model and clarifies the input that the model needs, answering RQ 4.a. Section 4.2 then clarifies how real-world data is translated into model data, answering RQ4.b. Using the model procedure and the model input data, Section 4.3 describes how the experiments are set up. Section 4.4 gives the results from each experiment, answering RQ4.c.

4.1 MODEL PROCEDURE

To execute an experiment, we employ Excel for data storage, Aimms for solving non-linear programs, and Python for data visualization. The entire process is depicted in Figure 4.2 showcasing the synergy between these three programs chosen for their convenience and interconnected capabilities.

The procedure initiates with the input of sections, surface areas, and the relationship diagram into the data storage. Section 4.1 describes how the data is established. The non-linear programming (NLP) solver then retrieves this data, embarks on solving Stage 1: FAF, and subsequently stores the results back in the data storage for utilization in Stage 2: ModCoAR. The input for Stage 2: ModCoAR includes the sections allocated per floor and their corresponding relationship diagrams.

The NLP solver processes the input for Stage 2: ModCoAR, executing the model multiple times while maintaining a constant Alpha parameter and incrementally adjusting the KMOD. After each run, the model generates X and Y coordinates for each section. The model's output varies with the KMOD, producing different graphs, three of which are illustrated in Figure 4.1. Figure 4.1 shows circle diagrams for run 1, run 12 and run 60. Run 1 has a KMOD of 1, resulting in a circle diagram where all circles are very close together. Run 60 has a KMOD of 1771, resulting in a circle diagram where all circles are pushed to the edges of the warehouse. In-between run 1 and 60 there are runs that show results where circles are less extremely bundled or pushed to the edge. To evaluate the quality of the circle diagram we calculate the unoccupied space of the circle diagram (the grey space) and select the run with the lowest unoccupied space. In this case this is run 12 with an unoccupied space of 31%.

The selected run is then translated from the output of Stage 2: ModCoAR to the input for Stage 3: BPL. This stage uses the X and Y coordinates of the circles as the basis of the solution. Using the coordinates and space requirements of the sections it tries to find a solution where the squares are transformed to rectangles without overlap.

Because it is not always possible to find a feasible solution using the X any Y coordinates from stage 2, we introduce a new parameter; flexibility. The flexibility parameter gives the model the option to diverge from the output of stage 2. As stage 2 gives the optimal placement of the sections the model tries to find a flexibility as low as possible. Next to the flexibility parameter we introduce the ratio parameter. This parameter sets the max ratio that a section can adopt where a ratio of 1:1 means that the height and width of a section are the same. Because section with lower ratios are generally easier to implement in practice, the low ratios a preferred. However, filling the warehouse with only square sections cannot create feasible solution and therefore we run with increasing values for the ratio.

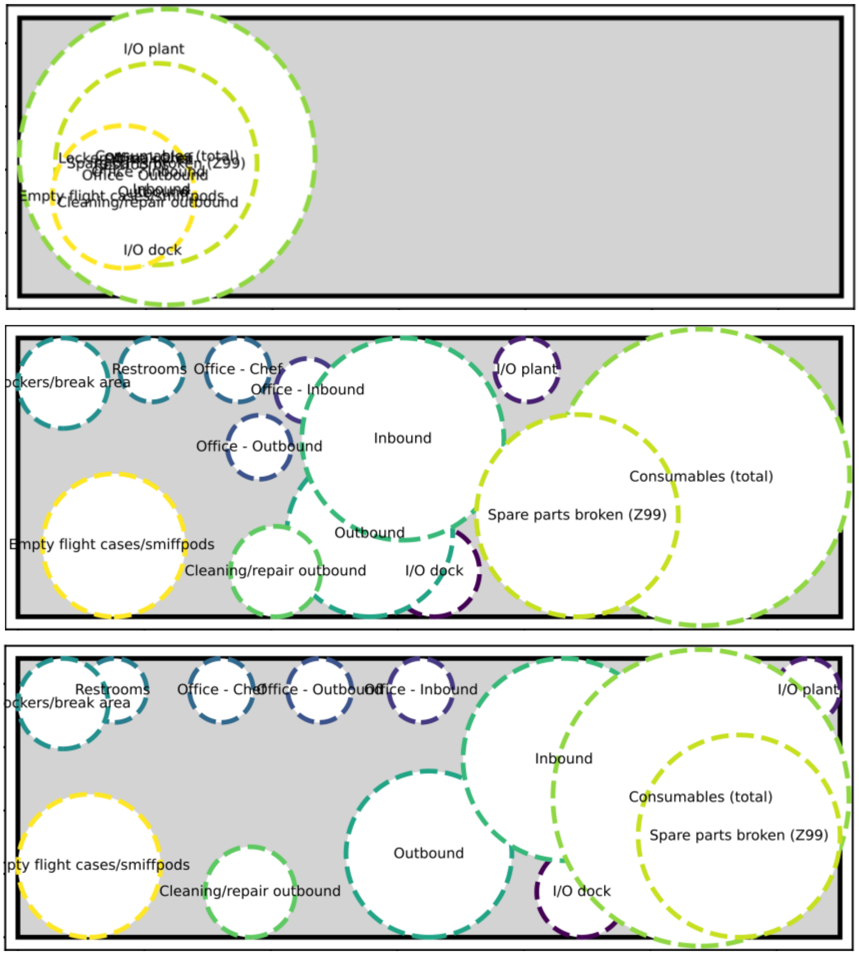

Figure 4.1 - Circle diagrams that result from stage 2 of the model. Run 1 (top, KMOD =1, grey space = 76%), Run 12 (middle, KMOD = 331, grey space = 31%), and Run 60 (bottom, KMOD = 1771, grey space = 40%).

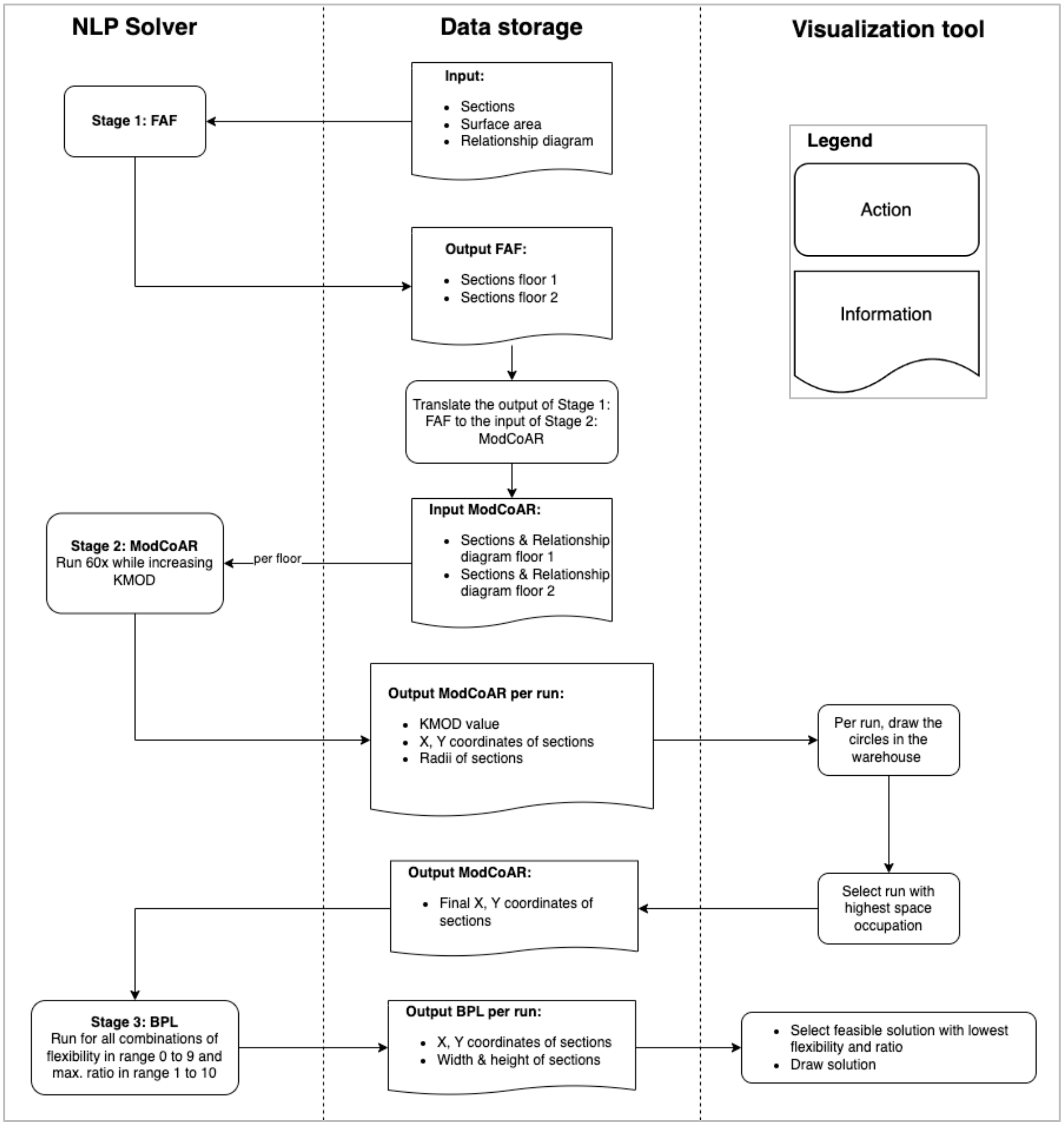

Figure 4.2 – Steps for executing one experiment using an NLP solver, data storage tool and a visualization tool

4.2 MODEL DATA

To initiate an experiment, it is imperative to supply the model with the right input data. Figure 4.3shows the necessary data for the model. Each experiment encompasses a unique scenario, comprising various sections. Each section set possesses distinct surface areas and an assortment of qualitative and quantitative flows. Given that the section surface area and the relationship diagram depend on the scenario, this data is named scenario dependent. Elaborations on determining the section surface area and flow are available in Sections 4.2.2 and 4.2.3, respectively.

In addition to scenario-dependent data, there exists data consistent across all scenarios, including the building dimensions and the I/O points' locations. This constant data is referred to as scenario-independent, with further details provided in Section 4.2.1.

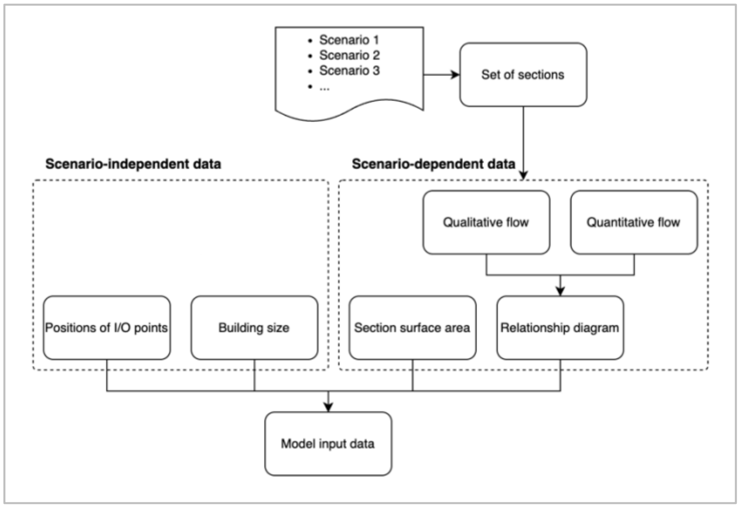

Figure 4.3 - Flowchart for translating a scenario into model-input data

4.2.1 SCENARIO DEPENDENT PARAMETERS

Defined as data consistent across experiments, scenario-dependent input data encompasses the number of floors, floor dimensions, and sections anchored to specific locations, all of which are tabulated in Table 4.1. Three sections are affixed to a floor and location: the dock, plant, and FAB I/O points. The dock I/O point is situated on the first floor, facing the road; the plant I/O point is also on the first floor but faces the plant side; and the FAB I/O point is located on the second floor, facing the FAB. While designing the macro layout we disregard the placement of the stair, lifts, or any of such obstacles.

Table 4.1 - Scenario-independent input values

Input	**Value**
Number of floors	2
Floor Height	22 m
Floor Width	65 m
I/O Dock	Floor 1, South-West
I/O Plant	Floor 1, North-East
I/O FAB	Floor 2, North-East

4.2.2 SECTION SIZE PARAMETERS

Translating real-world data into model input for section size varies across sections. Some sections, like raw wafer storage, follow a straightforward calculation process due to uniform size and storage equipment across SKUs. This process involves current size evaluation and application of a growth factor. Conversely, other sections necessitate a more complex approach due to unknown SKU sizes and storage equipment diversity, rendering direct volume and surface area calculations impractical.

USING EXISTING SURFACE AREA

Certain sections, such as offices, restrooms, and I/O points, permit direct current size adoption for future scenarios. This method also applies to SKU-storing sections, pending growth factor evaluation to ensure future adequacy. Sections utilizing this method include the kitcar forwarding area, cleaning/repair outbound area, and raw wafer area, with Figure 4.4 providing a corresponding flowchart.

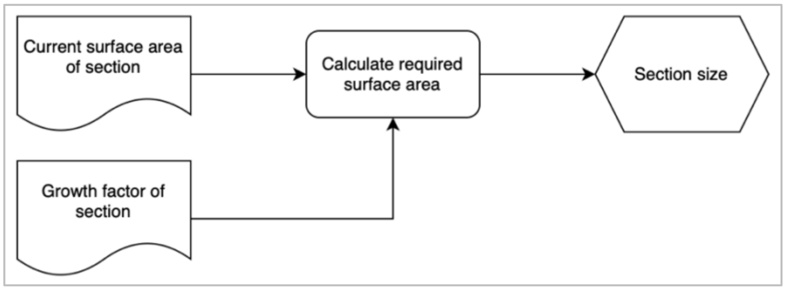

Figure 4.4 - Flow to get the new section size based on the size of the old section

COUNTING SKUS

The spare parts and consumables section requires storage space type and size enumeration, followed by size calculation per section. This process, detailed in subsequent paragraphs and illustrated in Figure 4.5, involves storage equipment categorization by size and storage space counting within each section.

The warehouse houses standard and variable-sized storage spaces, categorized into five volume groups: pallet, large box, small box, paternoster box, and deep large boxes (exclusive to one section). Each storage space is assigned a volume group, facilitating storage space, and required surface area calculations per section, as detailed in Table 4.2.

Table 4.2 – Dimensions and the storage equipment by volume group

Volume Group	**W x H x D (cm)**	**Storage Equipment**
Pallet	120 x 100 x 120	Pallet rack
Large Box	80 x 60 x 120	Pallet rack (smaller shelves)
Small Box	80 x 30 x 60	Boxes rack
Paternoster Box	20 x 10 x 40	Paternoster
Deep Large Box	120 x 100 x 240	Double Pallet Rack

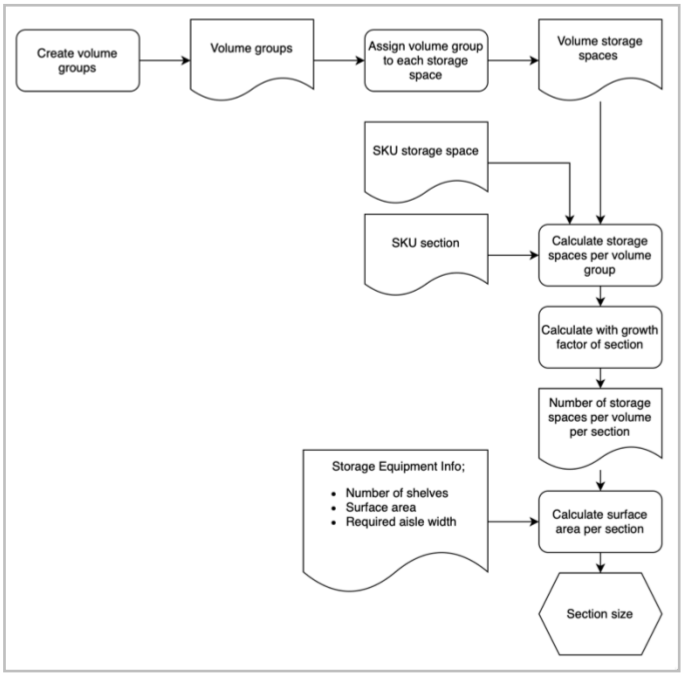

Figure 4.5 - Flow to decide the section size based on the counted SKUs

SPECIAL CASE

The Dry Etch section, due to its complexity and SKU dispersion, necessitates a unique calculation method. This involves determining the SKU percentage relative to the overarching department and calculating the section size based on this percentage of the overarching department surface, as depicted in Figure 4.6.

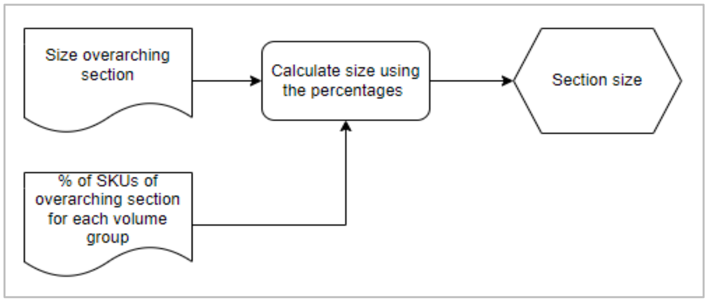

Figure 4.6 - Flow to decide the section size based on percentage used of the overarching section

4.2.3 SECTION FLOW PARAMETERS

Translating the real-world section flow into input data necessitates two key components. Initially, it is crucial to secure the quantitative flow amongst the warehouse sections, representing the tangible movements occurring within. Subsequently, attention must be directed towards the qualitative flow between sections, encapsulating non-physical interactions such as the communication between the inbound section and its corresponding office. Upon establishing both the quantitative and qualitative flows, the next step involves combining these flows to forge a comprehensive relationship diagram encompassing all sections. The ensuing paragraphs delve into the methodologies employed to determine the quantitative and qualitative flows, as well as the relationship diagram, with Figure 4.7 providing a visual representation of the process through a flowchart.

QUANTITATIVE FLOW

To discern the quantitative flow between warehouse sections, we leverage historical order data pertaining to the SKUs, spanning a maximum duration of 2.5 years, extracted from the ERP system of NXP. This dataset encompasses details such as SKU, digital storage section, quantity adjustments, and movement type. By integrating additional data, including SKU specifics, section information, storage bin particulars, and process insights, with the historical data, we are equipped to ascertain the quantitative flow.

A table is constructed, positioning the ‘Sloc’ (digital storage location) on the y-axis and the movement type on the x-axis, with table values representing the average orders per day. This arrangement yields insights into the flow magnitude between sections, with all flows subjected to monthly, daily, and hourly seasonality checks, and any identified seasonality duly incorporated into the calculations.

Given that orders comprise one or more SKUs, each with unique weight and volume characteristics—albeit these are not always recorded—we resort to employing a weight factor to adjust the flow based on order contents. These factors are derived from physical SKU inspections and discussions with employees, with the product of the average orders per day and the weight factor yielding the sections' quantitative flow.

QUALITATIVE FLOW

The qualitative flow between sections is collaboratively determined by the researchers and stakeholders. A rating system, ranging from 1 to 6, is employed to gauge the necessity of proximity between each section pair; with 1 indicating a high importance and 6 signifying negligible importance.

RELATIONSHIP DIAGRAM

The relationship diagram materializes through the synthesis of quantitative flow matrix and qualitative flow matrix, the process is shown in Figure 4.7. The quantitative flow matrix is created by analyzing the historical order data of the past 2.5 years. After the creation, the quantitative flow matrix is normalized to enable the merger with the qualitative flow matrix. Normalization is achieved by scaling the maximum and minimum flow values to a range of 1 to 5, where 1 represents maximum flow, 5 denotes minimal flow, and 6 indicates a complete absence of quantitative flow between sections. In the qualitative flow matrix, there exists a flow indicator that can range from 1, indicating a very important flow, to 6, indicating a very unimportant flow.

With the obtained flow matrixes, both with flows rated from 1 to 6, we merge them to create a relationship diagram that is ready to be used as input for the model. Merging the qualitative flow and quantitative flow is done by taking the average of both flows.

After experimenting with the merger of the two flow matrixes we concluded that the results were dominated by the quantitative flow matrix. This problem was remedied by calculating the averages of both flow matrixes and factorizing the quantitative flow matrix. With a factorization of the quantitative flow, equalizing both flows, the results were not dominated by either the qualitative or quantitative flows.

4.3 EXPERIMENTAL SETUP

In each experiment, we generate outputs for varying sets of sections. The consumables section is divisible into three segments, while the spare parts section can be divided into five. This division allows for experimentation and evaluation across a total of 128 potential scenarios. However, due to time constraints, it is impractical to explore every available option. Consequently, our initial focus is on determining the optimal division for the consumables section before proceeding to split the spare parts section. This approach is feasible because the consumables and spare parts sections exhibit minimal interaction.

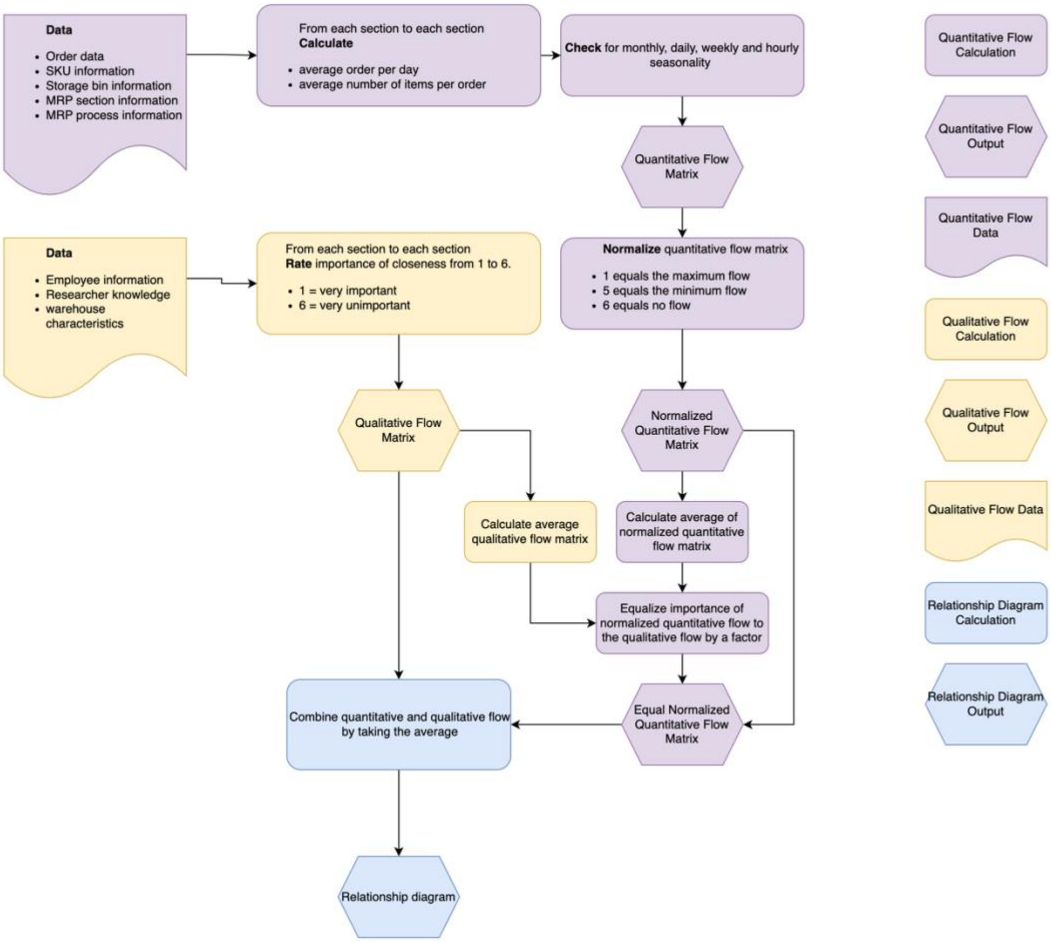

Figure 4.7 - Flow to create the relationship diagram that is used as input for the model.

4.3.1 CONSUMABLES SECTION EXPERIMENTS

To identify the optimal subdivision of the consumables section, we maintain the spare parts section as a whole. As outlined in Section 2.2.3 the consumables section can be segmented into four parts: packaging, TWM, grab supplies, and cleanroom. The packaging segment predominantly serves the outbound section of the warehouse, while TWM and grab supplies primarily cater to the production floor, and the cleanroom segment chiefly supplies the plant's facilities.

We conduct experiments across three scenarios, detailed in Table 4.3: (1) consolidating all parts of the consumable section, (2) segregating the packaging and cleanroom parts into new sections, and (3) combining the packaging and cleanroom parts into a single new section. Given that TWM and grab supplies predominantly serve the same user, we combine them into one section in scenarios 2 and 3. Notably, the packaging and cleanroom parts supply users on floor 1, whereas TWM and grab supplies cater to a user on floor 2. This distribution rationalizes the combination of the packaging and cleanroom parts in scenario 3.

Table 4.3 – Selection of consumable subsection per scenario. Same number in the column indicates that sections are combined.

Consumables Section	**Consumables Scenario 1**	**Consumables Scenario 2**	**Consumables Scenario 3**
TWM + Grab	1	1	1
Cleanroom	1	2	2
Packaging	1	3	2

4.3.2 SPAREPARTS SECTION EXPERIMENTS

Building on the experimental framework established in Section 4.3 for the consumables section, this segment of the research describes the experimental setup for identifying the optimal subdivision of the spare parts section. Prior to initiating this series of experiments, the division of the consumables section is conclusively determined and fixed.

Figure 4.8 presents a Venn diagram illustrating the relationship between the spare parts section and its subsections. It reveals that the 'Z01' subsection (fast movers) and the 'Z02' subsection (slow movers) do not share any SKUs. The 'clean process' and 'consignment' subsections are entirely encompassed by the 'Z01' subsection. Conversely, the 'Dry Etch' subsection spans both the Z01 and Z02 subsections, with a majority of its SKUs situated in 'Z01', thereby categorizing it as a 'Z01' subsection. The Dry Etch section also contains parts that are in the consignment section.

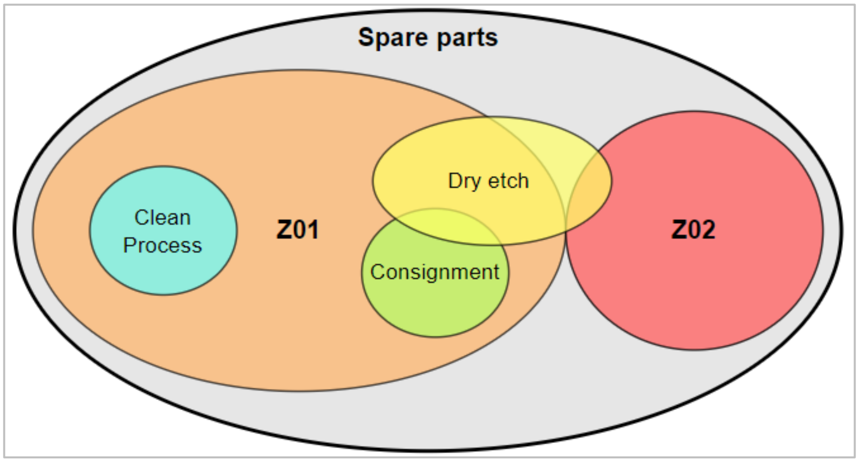

Figure 4.8 - Venn diagram of the contents of the spareparts section and the parts that can be split

The experimental sequence starts with the division of Z02, assessing its impact on the outputs. If this division yields positive results, it is retained for subsequent experiments. The next three experiments evaluate potential splits for the Clean Process, Consignment, and Dry Etch subsections. The final experiment explores the implications of segregating all spare parts subsections. Table 4.4 provides a comprehensive overview of these experiments.

Table 4.4 - Selection of spare parts subsections per scenario. Same number in the column indicates that sections are combined. X indicates that the split is not yet decided upon in that stage.

Spareparts Section	**SP – Z02 Split**	**SP – Clean Process Split**	**SP – Consignment Split**	**SP – Dry Etch Split**	**SP – Split All**
Z01	1	1	1	1	1
Z02	2	x	x	x	x
Clean Process	1	2	1	1	2
Consignment	1	1	2	1	3
Dry Etch	1	1	1	2	4

4.4 OUTPUTS

The model eventually outputs a macro layout of the warehouse. The model's objective is to minimize the movement costs between the sections. The movement costs is a combination of the qualitative flow costs and the quantitative flow costs. The outcome of the model says something about the theoretical performance but a little real world value.

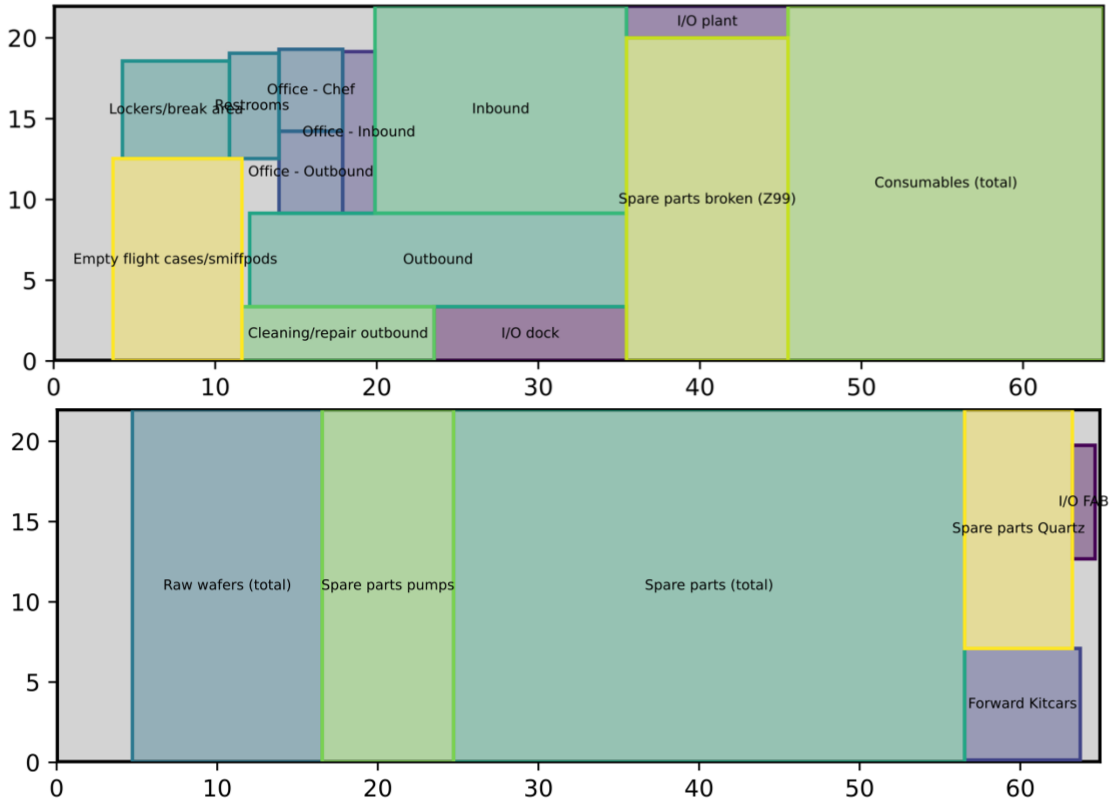

Figure 4.9 – Example of a macro-layout of floor 1 (above) and floor 2 (below) that results from the experiment as an output

We solve this by calculating the KPI that we want to know, the average walking distance, based on the macro layout that the model puts out. The average walking distance is calculated by summing the multiplication of the distance between sections with the flow between the sections. Figure 4.9 shows an example of the macro layout output. For the calculations of the average walking distance, we assume to have one stair/lift in the middle of the warehouse as a reference point. In the real-world application NXP ICN8 is not limited to this solution.

4.5 CONCLUSION

This chapter addressed the solution design of the research, answering Research Question 4:

4. *How do we translate the theoretical model to practice?*
    a. *What should the input data for the model be?*
    b. *How do we translate real-world data to input data?*
    c. *How should the output of the model look like*?

The model procedure is explained, providing the answers RQ 4.a. The input data can be categorized as data that is fixed for each experiment and data that varies trough the experiments. Fixed data are the building dimensions and the fixed locations of certain sections. The data that varies throughout the experiments are the section specific data, such as the section size, and the quantitative and qualitative flow between the sections. Translating the real-world data to model input is explained. Specifically, the determination of the section size and the quantitative and qualitative flow are discussed. The section size is calculated by using existing section size or by calculating the expected volume of the section. The quantitative flow is determined by 2.5 years of historical order data. The qualitative flow is determined by employee input, warehouse characteristics and the researcher’s knowledge. The output of the model is given and consist of a macro layout of both floor of the warehouse and the average walking distance that results from this macro layout.

5. EXPERIMENTAL EVALUATION

In this chapter we intend to answer research question 5:

5. *How do we execute and evaluate the model?*
    a. *How does the current situation perform?*
    b. *How do the experiments compare to each other and the current situation?*
    c. *What conclusions on how the layout of the warehouse can be drawn from the experiment?*

Section 5.1 presents a comparative analysis between the existing operational scenario and the experimental setup proposed in this research. Despite significant differences between the current and proposed scenarios, an effort is made to assess the performance of the current situation in the context of this study's findings.

In Section 5.2, the outcomes of the experiments are detailed and critically examined. This section undertakes a comprehensive evaluation of the experimental results, comparing them with findings from other experiments. It highlights the positive aspects, identifies any drawbacks, and notes any particularly noteworthy outcomes.

Finally, Section 5.3 synthesizes the conclusions drawn from the experiments. It provides insights into the recommended layout, offering a conceptual vision of how the optimized arrangement should be structured based on the experimental data.

5.1 PERFORMANCE CURRENT SITUATION

Chapter 2 outlines significant differences between the current and proposed warehouse setups. Presently, the warehouse operates across four separate buildings, each hundreds of meters apart. In contrast, the proposed solution consolidates operations into a single building. This section aims to contrast these two scenarios effectively.

A key metric for comparison is average walking distance. However, accurately calculating this for the current setup is challenging due to incomplete data. The existing warehouse's space constraints have led to a scattered arrangement of Stock Keeping Units (SKUs) across various sections, complicating the task of determining average distances between these sections.

Nevertheless, it is feasible to measure the average external distance traversed between buildings, which stands at approximately 15,310 meters daily. This external travel, primarily conducted via small cars and forklifts, adds to the internal distances covered within each building. Notably, this external movement, absent in the proposed single-building setup, increases both the handling frequency of SKUs and the risk of damage. Additionally, the maintenance requirements and space usage of the vehicles on the plant's roads present further disadvantages.

Moreover, the current multi-building arrangement necessitates increased administrative efforts. Each building, such as BF and AO, operates its own office to monitor in-and-out movements, often staffed by a single employee. This setup has been reported as isolating and monotonous by the staff.

The warehouse's current state is the result of gradual evolution, with buildings being repurposed over time. Consequently, certain facilities, like the I/O dock in building FD, no longer align with the warehouse manager's criteria. The dock and its adjoining areas are too small, and the lack of restrictions on delivery personnel access leads to unsupervised entry of non-employees, posing a security concern.

5.2 EXPERIMENTAL RESULTS

In Section 4.3, we initiate our experimentation with the consumables section. The outcomes of these initial tests will guide the division strategy for the consumables, setting a precedent for subsequent experiments. Following the consumables trials, we introduce an additional experiment, informed by the earlier results. This new test involves selecting a specific division for consumables and adjusting some input data.

Subsequently, our focus shifts to the spare parts section. The initial experiment in this phase centers on determining the feasibility of dividing the Z02 section. The insights gained from this first experiment will inform our decision on whether to proceed with splitting the Z02 section. Once this decision is made, we will extend our experimentation to consider the division of the remaining sections of the spare parts.

5.2.1 CONSUMABLES SECTION EXPERIMENTS

Section 2.2.3 profiles the consumables section, while Section 4.3 details the setup of various scenarios. Briefly, the consumables section comprises four subsections: TWM, Grab Supplies, Cleanroom Consumables, and Packaging. Due to similar flows, TWM and Grab Supplies are combined in all scenarios.

Scenario one keeps the consumables section intact without any division. Scenario two divides it into three parts: TWM + Grab, Cleanroom, and Packaging, to observe the independent functioning of each section. The third scenario merges TWM + Grab and Cleanroom + Packaging, based on their shared reliance on Floor 1's I/O points.

Table 5.1 presents numerical outcomes, indicating the first scenario as the most efficient in terms of average walking distance. Scenario two shows overlapping sections, while scenario three records the lowest maximum ratios for both floors. However, these numerical results do not fully capture the experiment's scope. Figure 5.4, Figure 5.3, Figure 5.2, and Figure 5.1 display the macro layouts for each scenario, revealing a consistent clustering of offices, lockers, break areas, and restrooms. Additionally, plant and dock I/Os, along with inbound, outbound, and cleaning repair outbound areas, are centrally located on Floor 1. Raw wafers are consistently positioned on the left side of Floor 2 in all scenarios.

Two observations are noteworthy regarding the consumables section split. Firstly, splitting the section relocates Spareparts Pumps, Spareparts Quartz, and Kitkars to Floor 1, likely due to the resultant space availability. Secondly, contrary to expectations, the average walking distance is shortest in the unsplit scenario (scenario 1) and longest in the TWM+Grab split scenario (scenario 3).

Considering these findings, we introduce a new experiment. This experiment consolidates the Offices, Lockers, and Restrooms into a single section, reflecting their natural clustering and enhancing overall layout efficiency. We adopt the consumables split from scenario 3, merging the Consumables Cleanroom and Consumables Packaging sections as observed in scenario 2. Additionally, we position the Kitkars on Floor 2, leveraging available space and optimizing the response time from an order by proximity to the I/O FAB point.

Table 5.1- Numerical results of the first three scenarios for the consumables section and the intermediate experiment.

	Consumables Section Scenario:			
	1	2	3	Intermediate Experiment
Average Walking Distance (m)	11.900	14.016	15.523	**10.380**
Overlap	**No**	Yes	**No**	**No**
Max Ratio Floor 1	5	9	5	**4**
Max Ratio Floor 2	5	**4**	**4**	6

INTERMEDIATE EXPERIMENT

In the subsequent experiment, informed by the consumables section analysis, we implemented three key changes: (1) merging the Offices, Lockers, and Restrooms into a single section, (2) adopting the consumables section division as per scenario 3, and (3) permanently positioning the Kitcars section on the second floor. The intermediate experiment's outcomes, detailed in Table 5.1 reveal a reduction in average walking distance. These modifications were then applied to the spare parts section experiments.

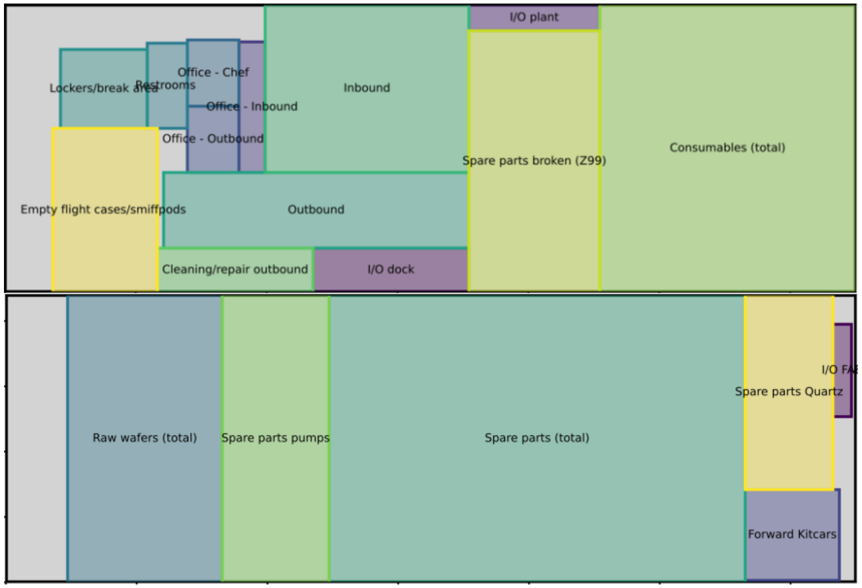

Figure 5.4 - Macro layout of Floor 1 (top) and Floor 2 (bottom) resulting from the experiment on scenario 1.

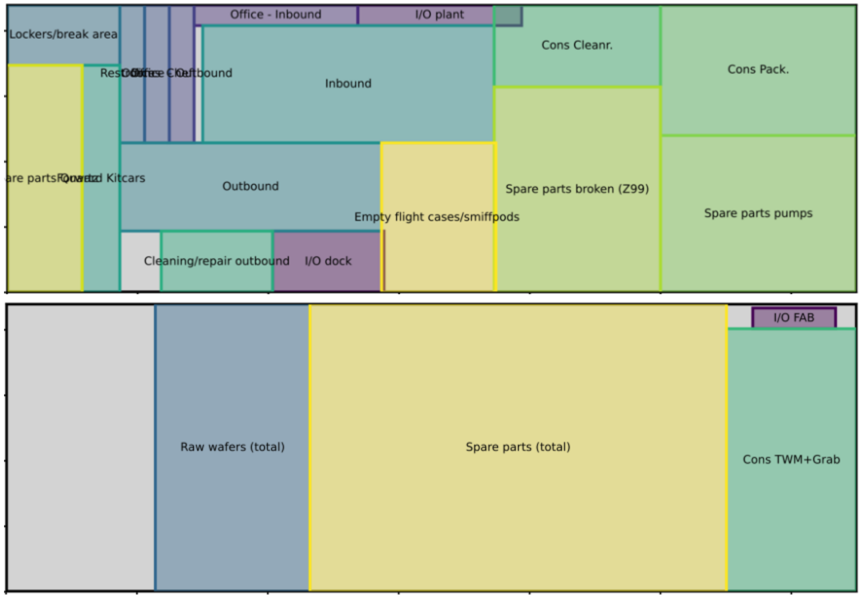

Figure 5.1- Macro layout of Floor 1 (top) and Floor 2 (bottom) resulting from the experiment on scenario 2

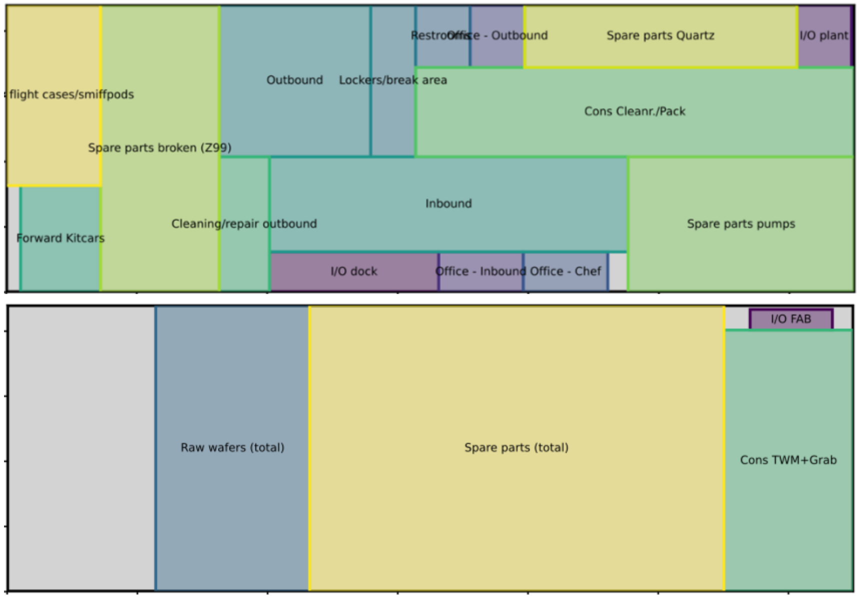

Figure 5.3- Macro layout of Floor 1 (top) and Floor 2 (bottom) resulting from the experiment on scenario 3

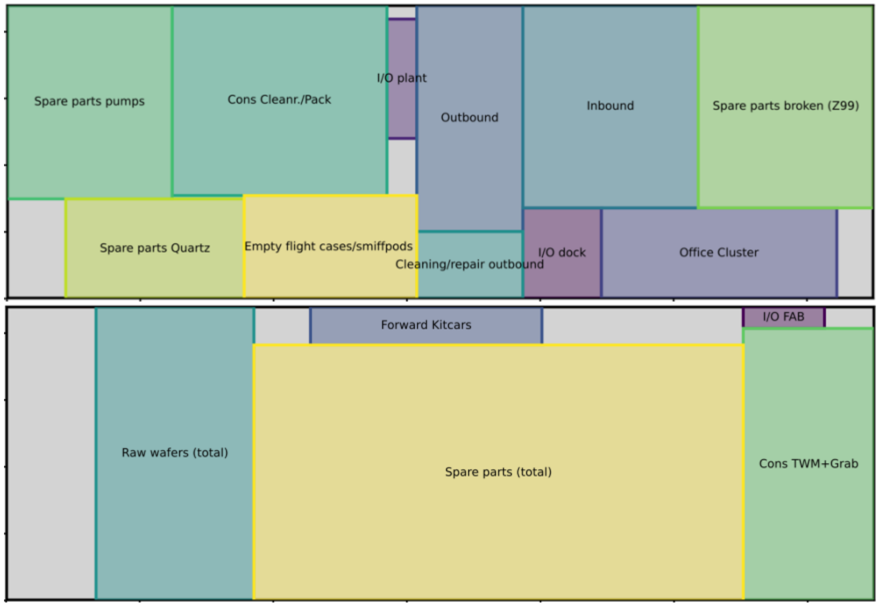

Figure 5.2- Macro layout of Floor 1 (top) and Floor 2 (bottom) resulting from the intermediate experiment

5.2.2 SPAREPARTS SECTION EXPERIMENTS

Z01 – Z02 SPLIT

In the initial experiment for the spare parts section, we explored the feasibility of segregating the Z02 section from the overall spare parts area. As detailed in Section 2.2.3, the Z01 and Z02 sections exhibit distinct characteristics, particularly in SKU usage frequency. The Z01 section houses frequently used SKUs, while the Z02 section contains items unused for over five years, suggesting a potential relocation of Z02 away from the primary I/O points.

The experiment's outcomes, which are crucial in deciding whether to maintain the Z02 division in subsequent scenarios, are compared with the intermediate experiment results. These findings are quantitatively presented in Table 5.2, and the corresponding macro layouts are illustrated in Figure 5.5 and Figure 5.6.

The experiment yielded encouraging results: the average walking distance was significantly reduced from 10.380m to 4.702m. We observed a decreased maximum ratio on the first floor and an unchanged ratio on the second floor of the layout. The macro layouts, depicted in Figure 5.5 and Figure 5.6, show the Z02 section strategically positioned on the far left of the first floor, distant from the I/O points. This reorganization led to a more compact spare parts section on the second floor, accommodating the spare parts pumps and Quartz, which are frequently moved to the I/O FAB. This strategic placement contributed to a substantial reduction in average walking distance. Given these positive outcomes, the Z02 split will be retained in the forthcoming experiments for the spare parts section.

Table 5.2 - Numerical results of the intermediate experiment and the Z02 split

	Intermediate Experiment	SP - Z02 Split
Average Walking Distance (m)	10.380	**4.702**
Overlap	No	No
Max Ratio Floor 1	4	**3**
Max Ratio Floor 2	6	6

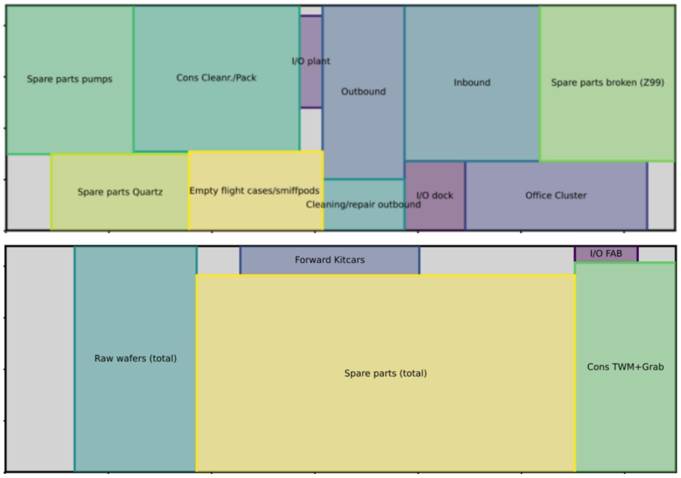

Figure 5.6 - Macro layout of Floor 1 (top) and Floor 2 (bottom) resulting from the intermediate experiment

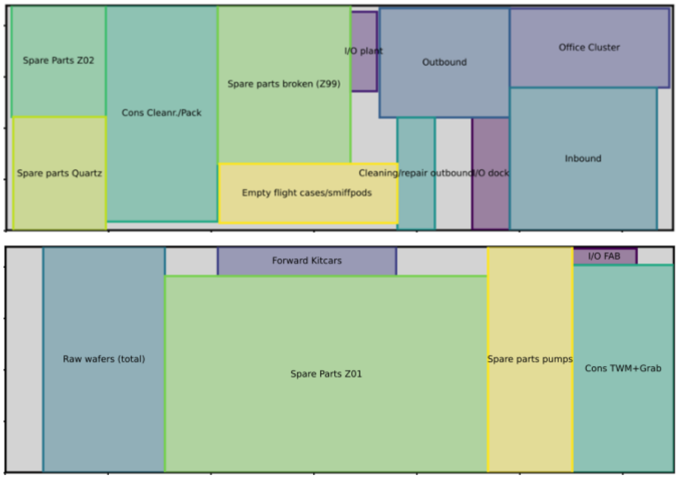

Figure 5.5 - Macro layout of Floor 1 (top) and Floor 2 (bottom) resulting from the Z02 split scenario

OTHER SPLITS

In our analysis of the spare parts section, we developed four scenarios, each involving the separation of different sections from the Z01 spare parts area. Specifically, these scenarios entail: isolating the Clean Process Section in the first scenario, the Consignment section in the second, the Dry Etch section in the third, and dividing all three sections in the fourth scenario. The quantitative outcomes of these scenarios are detailed in Table 5.3, while the corresponding macro layouts are illustrated in Figure 5.9, Figure 5.10, Figure 5.7, and Figure 5.8.

Section 2.2.3 and Section 4.3 of the report provide a comprehensive profile of the spare parts section and outline the experimental setup for these scenarios. The Clean Process, Consignment, and Dry Etch SKUs are identified as being used more frequently compared to other SKUs in the Z01 section. We hypothesized that splitting these specific sections could enhance overall efficiency. The complete separation of all three sections in the fourth scenario was designed to assess their performance when operating independently.

Table 5.3 - Numerical results of the Z02 split and the four spare parts scenarios

		Spare Parts Scenario			
	Z02 Split	**Clean Process Split**	**Consignment Split**	**Dry Etch Split**	**Split All**
Average Walking Distance (m)	**4.702**	4.847	4.948	4.850	13.376
Overlap	No	No	No	No	No
Max Ratio Floor 1	**3**	5	4	6	9
Max Ratio Floor 2	6	4	4	4	**3**

The data presented in Table 5.3 indicates that the results of scenarios 1, 2, and 3 are similar to those observed with the Z02 split alone. However, scenario 4, which involves splitting all sections, leads to a significantly higher average walking distance and a greater maximum ratio on the first floor. The macro layouts, illustrated in in Figure 5.9, Figure 5.10, Figure 5.7, and Figure 5.8 show that the sections separated in scenarios 1, 2, and 3 are all positioned on the first floor of the layout. Notably, the Clean Process section, which has bidirectional flow to both the I/O FAB and the I/O dock, is not situated near the I/O dock point. In contrast, scenario 4 positions the Dry Etch section on the second floor, suggesting that its placement on the first floor incurs higher costs compared to the Clean Process and Consignment sections.

Considering these findings, we conclude that the division approach in scenario 4 is not advantageous. While the splits in scenarios 1, 2, and 3 do not appear to offer significant improvements, they also do not detrimentally impact the overall efficiency.

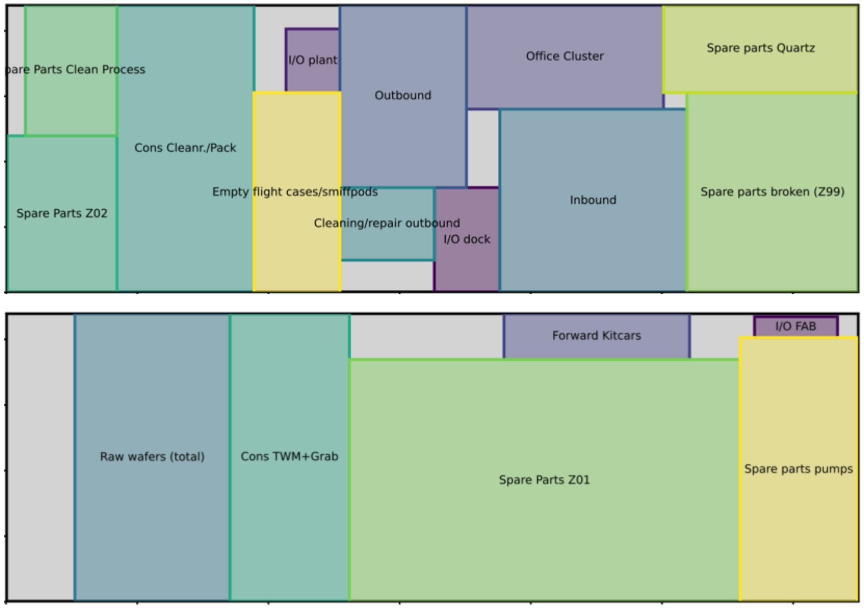

Figure 5.10 - Macro layout of Floor 1 (top) and Floor 2 (bottom) resulting from the spare parts scenario 1 experiment

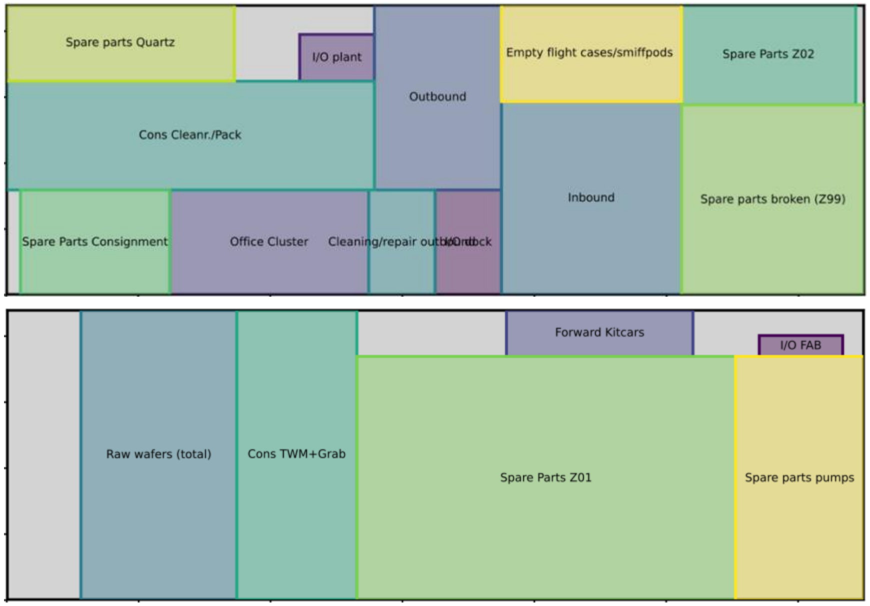

Figure 5.9 - Macro layout of Floor 1 (top) and Floor 2 (bottom) resulting from the spare parts scenario 2 experiment

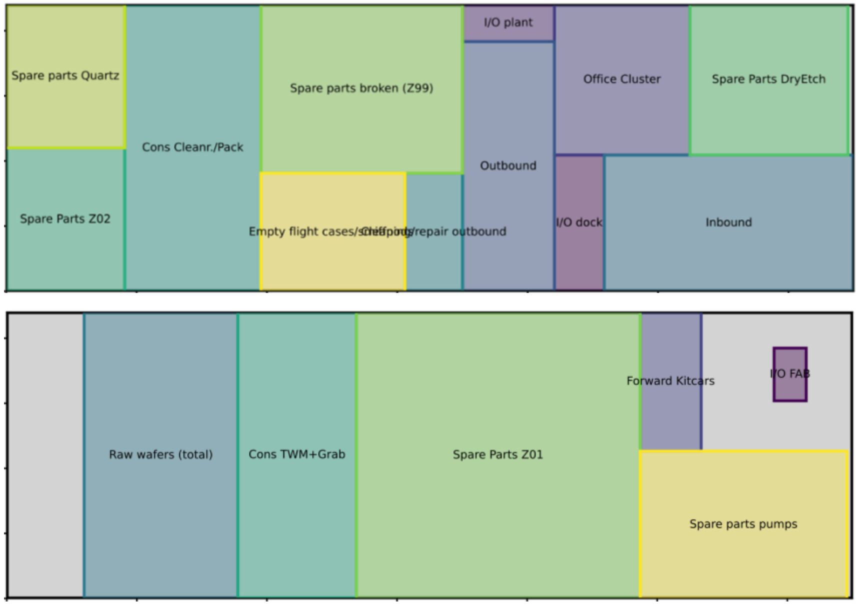

Figure 5.8 - Macro layout of Floor 1 (top) and Floor 2 (bottom) resulting from the spare parts scenario 3 experiment

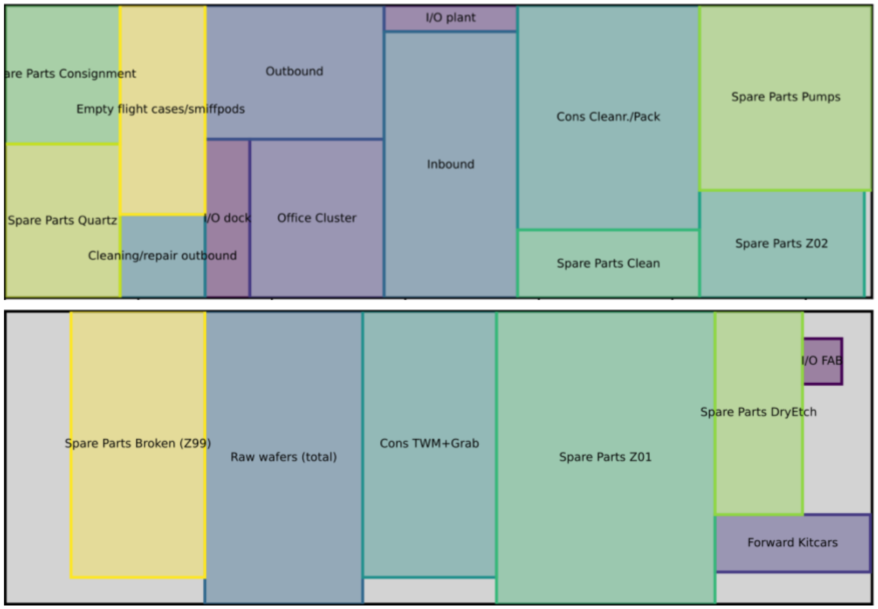

Figure 5.7 - Macro layout of Floor 1 (top) and Floor 2 (bottom) resulting from the spare parts scenario 4 experiment

5.3 OPTIMAL WAREHOUSING LAYOUT

This section discusses all conclusions from the experiments. We select the most promising results of the experiments and explain why it is the most promising. Next to the most promising result the experiments gave more key insights into what would be most promising in the warehousing layout. These key insights are discussed and based on these insights and the most promising result we make a sketch of a layout.

The most promising result of the experiment is the experiments where we split off the Z02 section from the Z01 section, shown in Figure 5.6. This experiment gave the lowest average walking distance and produced a macro layout with relatively low ratios on the sections. However, there are still some artifacts in the macro layout that would not completely make sense to apply in the real world. The sections do not align to each other on both floors. Moreover, gaps are created between the sections on both floors. The most obvious gap is located on floor 1 between the I/O Dock section and the Cleaning/Repair outbound section in Figure 5.10.

It would make little sense to apply the macro layout directly in the real world. Moreover, the most promising macro layout does not provide any flexibility to the problem owner. To accommodate for this, we derive conclusions from the experiments to provide the problem owner guidelines for modifying the final layout without losing the macro layouts effectiveness. Based on these guidelines, we created a layout that can be modified to the wishes of the warehousing management. The layout is shown in Figure 5.11.

Starting on floor 1, we divide the floor into roughly two parts. The first part, on the right of the floor, accommodates the I/O points, inbound, outbound, offices, and clean/repair outbound sections. In the first part, the sections do not store SKUs. The sections are used for temporary storage and forwarding of SKUs. The second part on floor 1 accommodates sections that do store SKUs. These are the consumables section for the Cleanroom and the Packaging and the Spare parts sections that contain SKUs that are rarely picked. Furthermore, the second part of floor offers space that can be used as a flexible storage area.

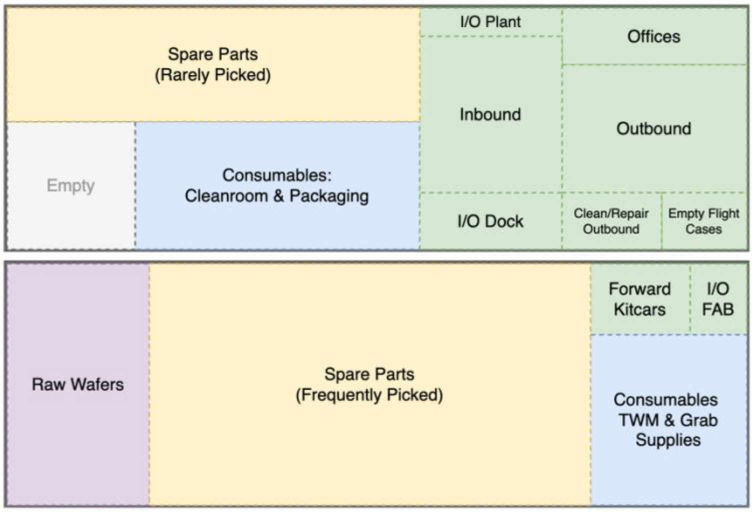

Figure 5.11 - Proposed macro layout of floor 1 (top) and floor 2 (bottom) based on the conclusions of the experiments

Floor 2 of the warehouse consists of the raw wafers, the spare parts that are frequently used, the Consumables for TWM and Grab Supplies, and the forwarding area for the

Kitcars. Following the results of the experiments, we place the Consumables on the right, spare parts in the middle and the raw wafers on the left. The Forwarding area for the Kitcars is placed on the top right, next to the I/O to the FAB.

In this proposed layout we offer some flexibility in the green area on floor 1, where the I/O points, inbound, outbound, and offices are located. This area is meant to move goods through the warehouse, storing the goods for not more than a few days. Within this area, the sections, except the I/O points, can be replaced and dimensioned.

On floor 1 and floor two, in yellow, the Spare Parts sections are located. The spare parts sections combine should house all spare parts SKUs of the plant. On floor 1, the experiments guide to place the rarely picked SKUs. The rarely picked SKUs are the Z02, Z99 sections. On floor 2, the experiments guide to place the frequently picked SKUs. In general, these are the Z01 SKUs, which can be sub divided in the Pumps, Quartz, Dry Etch, Clean Process flow, and Consignment.

GREEN SECTION FLOOR 1:

We start by discussing the flexibility of the green area on floor 1. This section consists of sections that do not store SKUs for longer than a few days. Within this section we can dimension and relocate the sections, except the I/O points. Next to that, we need to respect the surface area that they require. For this section we created two options, although, more options can be made.

In the first option, the office section is in the top right. Positive about the layout is that the clean/repair outbound is close to the I/O of the dock, this creates low walking distances between those two. The drawback of this option is that the offices are far away from the dock, making it harder to see and welcome the deliverers.

In the second option we switched the offices with the clean processes with the offices. Positive is that incoming deliverers are directly contacting the offices. They do not need to enter any further. However, the drawback is that the clean/repair outbound area is now further away.

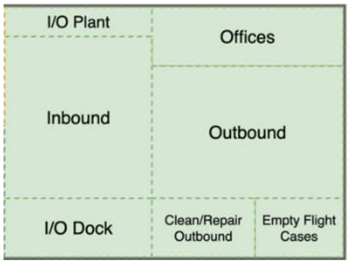

Figure 5.13 - Option 1 for the layout of the green area of floor 1

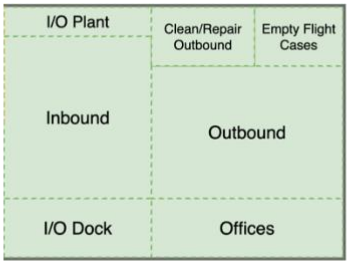

Figure 5.12 - Option 2 for the layout of the green area of floor 1

SPARE PARTS DIVISION

Flexibility within the warehouse is further examined in the context of the spare parts section, represented by the yellow areas on both floors of the facility. It is proposed that sections containing seldom-picked stock keeping units (SKUs) be allocated to the first floor, while those with frequently picked SKUs be assigned to the second floor. The Z99 section, owing to its interrelations with adjacent sections, is necessarily positioned on the first floor. Additional space accommodates up to two other sections comprising infrequently picked SKUs, selected from Z02, Pumps, Quartz, and Consignment. It is important to note that the sequential placement of these three sections has been determined to be neutral in its impact on warehouse operational efficiency.

To explore the range of configurational possibilities, two distinct layout options have been developed. Option 1 advocates for the maximal separation of sections to leverage spatial flexibility, while Option 2 suggests the consolidation of sections to optimize collective utility. The ultimate configuration may be chosen from within the spectrum delineated by these two alternatives.

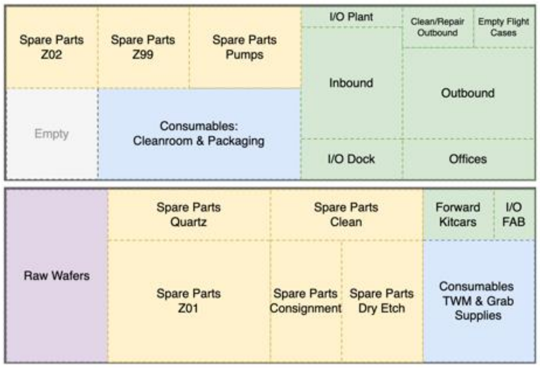

Figure 5.15 - Spareparts flexibility option 1: Separation

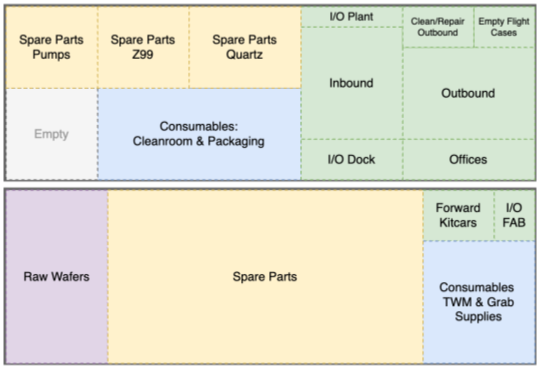

Figure 5.14 - Spareparts flexibility option 2: Consolidation

OPTION 1: SEPARATION

Shown in Figure 5.15, this configuration advocates for the segregation of sections as deduced from the research findings. The first floor accommodates sections Z02, Z99, and Pumps. The second floor is systematically arranged with sections Z01, Quartz, Consignment, Clean Process, and Dry Etch, ordered from the least to the most frequently picked SKUs.

Advantages: A notable advantage of this layout is the proximity of frequently picked SKUs to the input/output (I/O) of the FAB, which optimizes the average walking distances. The distinct separation of sections could simplify SKU retrieval for pickers, enhancing search efficiency and providing a clearer operational overview of the warehouse.

Limitations: However, this option requires a larger spatial allocation to maintain the separation, which could be a drawback during volume fluctuations. For instance, if the Dry Etch section reaches capacity, reallocating SKUs to an alternate section is not feasible without pre-emptive sizing adjustments to accommodate overflow. This necessitates sections to be dimensioned with additional buffer space. Additionally, a segregated layout increases administrative tasks, necessitating meticulous classification and placement of SKUs.

OPTION 2: CONSOLIDATION

Shown in Figure 6.5, this variant adopts a consolidation strategy, combining as many sections as feasible. Necessitated by operational requirements, sections Z99, Quartz, and Pumps remain distinct entities, while the remainder of the SKUs are collectively situated on the second floor.

Advantages: A primary benefit of this approach is the administrative efficiency it offers. The placement of SKUs becomes more flexible, as their classification has a reduced impact on storage location. This adaptability also results in decreased spatial requirements, providing a buffer against inventory fluctuations. Furthermore, the consolidation facilitates the unification of material storage systems; for instance, pallet storage or storage rows need only be established in one section rather than multiple.

Limitations: However, this configuration may lead to increased average walking distances as frequently accessed items could be positioned anywhere within the section. Additionally, the integration of seldom-used items like the Z02 SKUs, which may remain untouched for years, with regularly accessed items could impede operational efficiency.

5.4 CONCLUSION

This chapter answered research question 5:

5. *How do we execute and evaluate the model?*
   a. *How does the current situation perform?*
   b. *How do the experiments compare to each other and the current situation?*
   c. *What conclusions on how the layout of the warehouse can be drawn from the experiment?*

In the current situation, various elements are widely dispersed, leading to complications in communication and the transportation of goods and people. There are inherent risks associated with transporting goods between different warehouses in the current currency situation. In contrast, the new situation brings everything into proximity, eliminating many of these issues.

To provide a quantitative perspective, we calculated the average walking distance in the current situation, which involves walking just outside the building. The results indicate that the average walking distance in the current scenario is higher than the total average walking distance in the new situation.

In Section 5.2, the experiment's results were examined, focusing on the numerical outputs and macro layouts for the consumable section experiments. It was determined that Scenario Three is the most advantageous for progression. This scenario integrates the clean room and packaging sections on the first floor, while situating the TWM plus grab supplies section on the second floor. Additionally, insights from the initial three section experiments led to the decision to group offices, restrooms, and lockers. This clustering enhances the macro layout's clarity without compromising the solution's effectiveness, as these sections were consistently found to be closely aligned.

Section 5.3 delves into the conceptualization of an optimal warehouse layout. A model layout was developed, offering a balance between a well-structured design and adaptability to meet specific company needs. This flexibility is particularly evident in the allocation of the spare parts section and the arrangement of the warehouse's inbound and outbound areas. This approach ensures that the problem owner is provided with an efficient layout while retaining the ability to make minor modifications tailored to the company's requirements.

6. CONCLUSIONS AND RECOMMENDATIONS

In the comprehensive analysis of warehouse design and efficiency, our investigation has resulted in critical findings and actionable recommendations outlined in the subsequent sections of this report. These insights address the main research question: 'What are adequate layouts for the new warehouse at NXP that minimize walking distances, considering the functionalities of the current warehouses, the multi-level layout problem, and the different warehousing sections?'

Section 6.1 presents the conclusions of the study, synthesizing the answers to our research questions and providing a holistic overview of the research's key outcomes. Specifically, Section 6.1.1 delves into these outcomes, offering a strategic framework for the problem owner to optimize warehouse efficiency. Section 6.1.2 provides a reflective evaluation of the chosen design framework and resolution approach, detailing their advantages and limitations within the context of the Facility Layout Problem (FLP).

The detailed recommendations are methodically categorized and presented in Section 6.2, with subsections 6.2.1 discussing size recommendations for the warehouse, 6.2.2 offering advice on data management improvements, and 6.2.3 addressing other miscellaneous suggestions to enhance operational effectiveness.

Looking ahead, Section 6.3 outlines areas for future research, emphasizing the need for further study into intra-warehouse movement and SKU management, and concludes by acknowledging the limitations encountered during the research process, providing a roadmap for ongoing inquiry and optimization efforts.

6.1 CONCLUSIONS

The last chapters addressed all research questions, thereby laying the groundwork for resolving the primary research question. In this section we shortly recap the answers to the sub research questions before answering the main research question. In Section 6.1.1 we dive into the key outcomes of the research. Section 6.1.2 reflects on the selected design framework and resolution approach of this research.

1) The initial segment of Chapter 1 undertakes a context analysis, delineating the anticipated attributes of NXP's new warehouse. It has been established that the warehouse's location is predetermined, with a dual-level structure granting direct access to the NXP ICN8 plant's FAB from the second floor. The warehouse's width is constrained at 65 meters, whereas its height is variable, approximately 22 meters. An examination of the ICN8 plant forecasts modifications in flight case usage owing to environmental considerations, an uptick in product refurbishment, and a marginal increase in output.

2) The latter portion of Chapter 1 examines the warehouse's present configuration, identifying storage and support sections. Three principal storage sections have been identified: raw wafers, consumables, and spare parts. Each section, given its distinct contents, necessitates individual treatment. The consumables section is further segmented into packaging, cleanroom, TWM, and Grab supplies, whereas spare parts are categorized into sub-sections such as Pumps, Quartz, and Z99, with additional divisions based on SKU pick frequency, including Z02, Consignment, Clean Process, and Dry Etch.

3) Chapter 2 delves into the Facility Layout Problem (FLP), informed by the context analysis from Chapter 1. A comprehensive literature review identified the design framework of Frazelle as the most applicable, subsequently adapted for this

research's scope. A literature search on FLP resolution approaches yielded five potential models; from which Anjos's three-stage Non-Linear Programming model was selected for its suitability.

4) Chapter 4 articulates the transformation of 2.5 years of historical order data into flow matrices compatible with the chosen model, details the computation of section sizes, and outlines the sequence of experimental procedures.

5) Chapter 5 contrasts the existing warehouse's performance with the newly proposed solution, concluding that the proposed solution is in many ways an improvement over the old situation. The chapter progresses to document the execution and analysis of experiments, leading to the derivation of guidelines for the final macro layout. These guidelines underpinned the development of a recommended layout, ensuring retained adaptability.

MAIN RESEARCH QUESTION:

'What are adequate layouts for the new warehouse at NXP that minimize walking distances, considering the functionalities of the current warehouses, the multi-level layout problem, and the different warehousing sections?'

In Section 5.3 we proposed an adequate layout that still offers flexibility to the problem owner and is pictured again in Figure 6.1. Whitin the flexibility of this layout we find all adequate layouts. The flexibility lies within relocating some of the sections within the green area on floor 1 and splitting the Spareparts section.

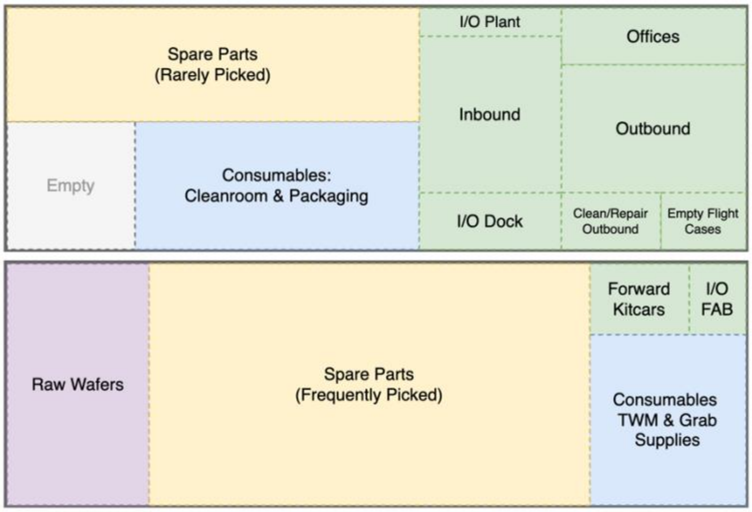

Figure 6.1 – Macro layout for the warehouse of floor 1 (top) and floor 2 (bottom) that still offers flexibility

The green area on floor 1 offers the flexibility to transform the sections within. For example the inbound and outbound can be switched with each other or the offices can be put below the outbound. As long as the sections remain their original size.

The Spareparts section offers the flexibility to split the sections to the needs of the user. It is advised to place the rarely picked sections on floor 1 and the frequently picked sections on floor 2. The amount of sections influences the characteristics of the warehouse. More sections create the need for more space because SKUs need to be placed in that specific section, rather than somewhere in the warehouse. This reduces the flexibility. However, splitting sections creates a better overview and has the potential to reduce the walking distances of the employees.

6.1.1 KEY OUTCOMES

This research has culminated in several critical findings that are instrumental for the problem owner. The principal conclusion drawn from the investigation is the absence of a singular, optimal warehouse layout. Instead, multiple viable configurations have been identified, each contingent upon the strategic placement of specific sections within the warehouse.

It is imperative that the input/output (I/O) points for both the dock and the plant are strategically positioned to the right of the warehouse's central axis, both on the upper and lower levels, to ensure streamlined logistical operations. Proximity and operational synergy are key, with areas designated for forwarding processes—namely inbound, outbound, and clean/repair outbound—benefiting from being in close association with the administrative offices. This clustering facilitates communication and the efficient movement of goods.

Furthermore, the consolidation of storage areas is recommended to augment spatial efficiency and inventory accessibility. An efficient distribution strategy dictates that sections containing frequently picked stock keeping units (SKUs) be situated towards the right-hand side of the warehouse, while areas housing less frequently picked SKUs are aligned to the left. Such a delineation ensures that the flow of operations is maintained with minimal disruption and that the spatial layout is conducive to the varying frequencies of SKU retrieval.

In summary, while the research does not prescribe a definitive layout, it offers a framework within which the problem owner can navigate to optimize warehouse efficiency. The identified parameters for the positioning of I/O points, the clustering of related functional areas, and the strategic placement of SKU sections provide a robust foundation for developing an effective warehouse layout.

6.1.2 REFLECTION ON SOLUTION MODEL

In addressing the Facility Layout Problem (FLP), our decision was to implement the design framework proposed by Frazelle [10] and the resolution approach articulated by [21]. This segment evaluates the merits and limitations of both the design framework and the resolution model utilized in this research.

The chosen design framework by Frazelle is characterized by its broad application to FLPs, emphasizing warehouse flow optimization over functional considerations. This was particularly applicable to our research due to the multitude of sections and resultant complex flow paths within the warehouse. A limitation, however, was noted in the framework's overarching nature, which presented challenges in detailing the macro layout's specifics.

The complexity of FLPs, with their high number of exceptions and classifications, requires a flexible yet specific framework. Our selected framework successfully strikes a balance, providing enough generality for broad application while retaining the adaptability necessary for this research's unique requirements.

Our macro layout's development leveraged a three-stage resolution approach conceived by [21]. This methodological process entailed assigning sections to appropriate floors, arranging them based on surface area radius, and finally determining their dimensions. While the approach's generality omitted considerations for fixed architectural elements and infrastructure like chemical piping, it offered simplicity and adaptability. We specifically tailored the model to our context by anchoring the I/O points to predetermined locations and floors, proving the model's applicability to our needs.

Upon retrospection, we consider the possibility of forgoing the third stage of the resolution approach. The resulting macro layouts from the model, which delineated section dimensions, were less instrumental to our findings than the placement of sections by floor and location. In hindsight, the effort and computational time invested in the third stage could have been more effectively allocated to other facets of the research, given that the strategic positioning of sections was the pivotal outcome.

6.2 RECOMMENDATIONS

To facilitate the effective implementation of this research's conclusions, we have categorized our recommendations into three distinct groups: size-related, design-related, and other recommendations.

6.2.1 SIZE RECOMMENDATIONS

Current projections suggest that the warehouse's dimensions are adequate for long-term sustainability. However, an expanded space allows for greater adaptability to unforeseen strategic shifts. Additionally, a larger warehouse offers enhanced maneuverability and more effective utilization of material handling equipment, such as forklifts. Therefore, we recommend exploring options for expanding the warehouse's size.

Specifically, the warehouse's footprint is presently established at 65 by 22 meters. While the width is fixed, there is flexibility in the height. Given the ample space available on the site, we advocate for an increase in height, which would proportionally augment storage capacity and operational space without incurring significant additional costs.

Regarding floor height, we endorse maintaining the 6.5 meters outlined in the initial warehouse sketches. This height optimizes storage volume per floor and minimizes the necessity for vertical movement, which is time intensive. We suggest retaining a two-floor structure for optimal use of vertical space.

6.2.2 DATA RECOMMENDATIONS

Alongside physical dimensions, data management within the warehouse requires refinement. Firstly, we advise dedicating individual storage bins to a single SKU type. Current practices of storing multiple SKUs per bin have resulted in discrepancies and inefficiencies in SKU retrieval. A dedicated bin system would ensure accurate inventory counts and facilitate easier access.

Improved data administration is also necessary. At present, identical SKUs may be cataloged under different '12NC' identifiers, complicating inventory tracking and skewing data analytics. Additionally, accurately recording SKU weights and dimensions is crucial, providing valuable data that could aid future warehouse optimization initiatives. Furthermore, enhanced monitoring of SKUs involved in the clean process is recommended. Better oversight can reduce losses and yield insights into the life cycle and utility of these SKUs

6.2.3 OTHER RECOMMENDATIONS

We suggest retaining the majority of non-active SKUs, particularly spare parts for obsolete machinery, as the new warehouse design accommodates these items at minimal cost. However, a thorough analysis to eliminate duplicates and SKUs for defunct equipment is warranted.

For the warehouse I/O dock, we recommend the installation of a full-size dock for trucks and a large roller shutter door, sufficient for the volume of deliveries. Additional barriers or protocols should be established to prevent unsupervised access by delivery personnel, ensuring security and safety.

6.3 FUTURE RESEARCH & LIMITATIONS

This section delves into both the prospective avenues for future research and the inherent limitations of our current study on warehouse layout optimization at NXP. By identifying areas that merit further investigation, we aim to pave the way for subsequent research endeavors that can build on our findings and address the existing gaps. Concurrently, we acknowledge the constraints and challenges faced during our research, which shaped the outcomes and insights obtained. This dual focus not only enhances the depth and applicability of our study but also serves as a guiding framework for future research in this evolving domain.

6.3.1 FUTURE RESEARCH

Before proceeding with the implementation, additional research is advised to enhance our understanding of internal warehouse movement and the effective employment of storage equipment. Investigations should delve into the nuances of vertical movements—quantifying the necessity for stairs and lifts, and their strategic positioning. Additionally, research should explore the pathways correlating with the warehouse's input/output points, lifts, and the utilization of material handling equipment, recognizing the interconnectedness of these factors.

A re-evaluation of the classification system for spare parts SKUs is also recommended. The current separation, particularly between Z02 and Z01 SKUs, is ill-defined and infrequently revised. A thorough reclassification could potentially lead to significant improvements in warehouse operations.

Reassessing the approach to calculating safety stocks is crucial. The current application of safety stock as a reorder point is suboptimal, heightening the risk of stock shortages and consequent machinery downtime. Conversely, overestimated safety stocks inflate inventory levels and associated costs. Revising the uniform safety stock level, currently set at 96%, is suggested to achieve a balance between reducing stock-outs and managing inventory costs, especially for non-critical machinery.

6.3.2 LIMITATIONS

The research presented here is subject to certain limitations that could be addressed in future studies. A lack of comprehensive data, particularly concerning SKU dimensions and volumes, constrained our ability to construct accurate profiles. This led to reliance on shelf size estimations to approximate dimensions, a method that may not yield precise results due to variability in SKU sizes.

Data quality issues were also observed, particularly concerning the classification of SKUs within the MRP system and the tracking of their movements. The current practice of using 'Electronic Order Forms' (EOFs), which are not digitally integrated with NXP's ERP system, further contributed to data inconsistencies.

The absence of a pilot testing environment is another limitation, preventing pre-implementation validation of the research findings. Such validation could reveal potential issues that may not be evident without practical testing.

Finally, due to the broad scope that the FLP can have and the constraints of time and project scope, not all strategic, tactical, and operational decisions were fully explored within this research. Given the complex and multifaceted nature of FLPs, it is challenging to address all potential decision-making scenarios in a single study.

BIBLIOGRAPHY

[1] 'NXP in the Netherlands webpage'. Accessed: Jun. 13, 2023. [Online]. Available: https://www.nxp.com/company/about-nxp/worldwide-locations/netherlands:NETHERLANDS

[2] H. Davarzani and A. Norrman, 'Toward a relevant agenda for warehousing research: literature review and practitioners' input', *Logist. Res.*, vol. 8, no. 1, p. 1, Dec. 2015, doi: 10.1007/s12159-014-0120-1.

[3] H. Heerkens and A. Van Winden, *Solving Managerial Problems Systematically*, 1st ed. Routledge, 2021. doi: 10.4324/9781003186038.

[4] Pieter Hofman, 'New warehouse information', Sep. 16, 2023.

[5] 'Sustainability and ESG | NXP Semiconductors'. Accessed: Nov. 12, 2023. [Online]. Available: https://www.nxp.com/company/about-nxp/sustainability-and-esg:CORP_SOCIAL_RESP

[6] Hoogboom, Andre, 'SKU information interview', Feb. 05, 2023.

[7] G. Richards, *Warehouse management: a complete guide to improving efficiency and minimizing costs in the modern warehouse*. London ; Philadelphia: Kogan Page, 2011.

[8] S. S. Heragu, *Facilities design*, Fourth edition. Boca Raton: CRC Press, Taylor & Francis Group, CRC Press is an imprint of the Taylor & Francis Group, an informa business, 2016.

[9] J. A. Tompkins, Ed., *Facilities planning*, 4th ed. Hoboken, NJ: J. Wiley, 2010.

[10] E. Frazelle, *World-class warehousing and material handling*, Second Edition. New York: McGraw-Hill Education, 2016.

[11] P. Baker and M. Canessa, 'Warehouse design: A structured approach', *Eur. J. Oper. Res.*, vol. 193, no. 2, pp. 425–436, Mar. 2009, doi: 10.1016/j.ejor.2007.11.045.

[12] B. Rouwenhorst, B. Reuter, V. Stockrahm, G. J. Van Houtum, R. J. Mantel, and W. H. M. Zijm, 'Warehouse design and control: Framework and literature review', *Eur. J. Oper. Res.*, vol. 122, no. 3, pp. 515–533, May 2000, doi: 10.1016/S0377-2217(99)00020-X.

[13] J. Gu, M. Goetschalckx, and L. F. McGinnis, 'Research on warehouse design and performance evaluation: A comprehensive review', *Eur. J. Oper. Res.*, vol. 203, no. 3, pp. 539–549, Jun. 2010, doi: 10.1016/j.ejor.2009.07.031.

[14] A. Drira, H. Pierreval, and S. Hajri-Gabouj, 'Facility layout problems: A survey', *Annu. Rev. Control*, vol. 31, no. 2, pp. 255–267, Jan. 2007, doi: 10.1016/j.arcontrol.2007.04.001.

[15] H. Hosseini-Nasab, S. Fereidouni, S. M. T. Fatemi Ghomi, and M. B. Fakhrzad, 'Classification of facility layout problems: a review study', *Int. J. Adv. Manuf. Technol.*, vol. 94, no. 1–4, pp. 957–977, Jan. 2018, doi: 10.1007/s00170-017-0895-8.

[16] P. Burggraf, J. Wagner, and B. Heinbach, 'Bibliometric Study on the Use of Machine Learning as Resolution Technique for Facility Layout Problems', *IEEE Access*, vol. 9, pp. 22569–22586, 2021, doi: 10.1109/ACCESS.2021.3054563.

[17] D. I. Patsiatzis and L. G. Papageorgiou, ‘Optimal multi-floor process plant layout’, *Comput.-Aided Chem. Eng.*, vol. 9, pp. 475–480, Jan. 2001, doi: 10.1016/s1570-7946(01)80074-2.

[18] K.-Y. Lee, M.-I. Roh, and H.-S. Jeong, ‘An improved genetic algorithm for multi-floor facility layout problems having inner structure walls and passages’, *Comput. Oper. Res.*, vol. 30, no. 1, pp. 117–138, Jan. 2003, doi: 10.1016/s0305-0548(01)00085-5.

[19] M. Goetschalckx and T. Irohara, ‘Efficient Formulations for the Multi-Floor Facility Layout Problem with Elevators’, Jan. 2007.

[20] R. D. Meller and Y. A. Bozer, ‘Alternative Approaches to Solve the Multi-Floor Facility Layout Problem’, vol. 16, no. 3, 1997.

[21] S. Bernardi and M. F. Anjos, ‘A two-stage mathematical-programming method for the multi-floor facility layout problem’, *J. Oper. Res. Soc.*, vol. 64, no. 3, pp. 352–364, Mar. 2013, doi: 10.1057/jors.2012.49.

[22] R. D. Meller and K.-Y. Gau, ‘The facility layout problem: Recent and emerging trends and perspectives’, *J. Manuf. Syst.*, vol. 15, no. 5, pp. 351–366, Jan. 1996, doi: 10.1016/0278-6125(96)84198-7.

[23] M. F. Anjos and A. Vannelli, ‘A New Mathematical-Programming Framework for Facility-Layout Design’, *Inf. J. Comput.*, vol. 18, no. 1, pp. 111–118, Feb. 2006, doi: 10.1287/ijoc.1040.0103.

[24] Surya Prakash Singh, S. P. Singh, R. R. K. Sharma, and R. Sharma, ‘A review of different approaches to the facility layout problems’, *Int. J. Adv. Manuf. Technol.*, vol. 30, no. 5, pp. 425–433, Sep. 2006, doi: 10.1007/s00170-005-0087-9.

[25] M. F. Anjos and A. Vannelli, ‘An Attractor-Repeller approach to floorplanning’, *Math. Methods Oper. Res. ZOR*, vol. 56, no. 1, pp. 3–27, Aug. 2002, doi: 10.1007/s001860200197.

APPENDIX A – SECTION SIZE OVERVIEW

Table A.1 - Section Names and Surface Area by Building

Building	**Section**	**Surface Area (m^2)**
FD	Storage	500
FD	Forwarding area kit cars	50
FD	Office Chef	10
FD	Office Inbound	50
FD	Office warehouse	20
FD	Office outbound	20
FD	Forward area Clean process	20
FD	Yellow Area	75
FD	Red Area	25
FD	Counter outbound	5
FD	Changing rooms	30
FD	Inbound area	100
AO	Inbound/outbound area	45
AO	Office AO	15
AO	Storage	550
AO	Blocked Wafers	45
AO	Other Wafers	15
BF	Quartz	90
BF	Refurbish/Repair	90
BF	Storage	600
BF	Pumps ready	150
BF	Pump refurbishment/repair	90
BQ	Storage	250

APPENDIX B - LITERATURE REVIEW SEARCH METHOD RESOLUTION APPROACH

We started the search to finding a resolution approach by searching for existing literature review papers about the facility layout problem (FLP) on the Scopus database. Scopus is a big and comprehensive database for peer reviewed literature. The search on Scopus delivered us one book and four literature reviews on FLP; [8], [14], [15]and [22] and [23][24]

We used the literature that resulted from the Scopus search to classify our FLP. We narrowed down that the FLP in our research was ‘multi-floor’ and ‘unequal area’. The book and literature reviews also gave multiple papers of problems in the same classification. These papers are used in the next step of the search.

We put the papers about solving the FLP for problems that are in the same classification as ours in one folder and upload this to the website ‘researchrabbitapp.com’. The papers are used as our seed papers and are used to find similar work based on citations. This resulted in a map of papers that have similar citations. The suggested papers by ‘researchrabbitapp.com’ are then sorted by citations to get the most used literature on top. We outcomes of research rabbit are analyzed and the papers that are most suitable for our research are selected.

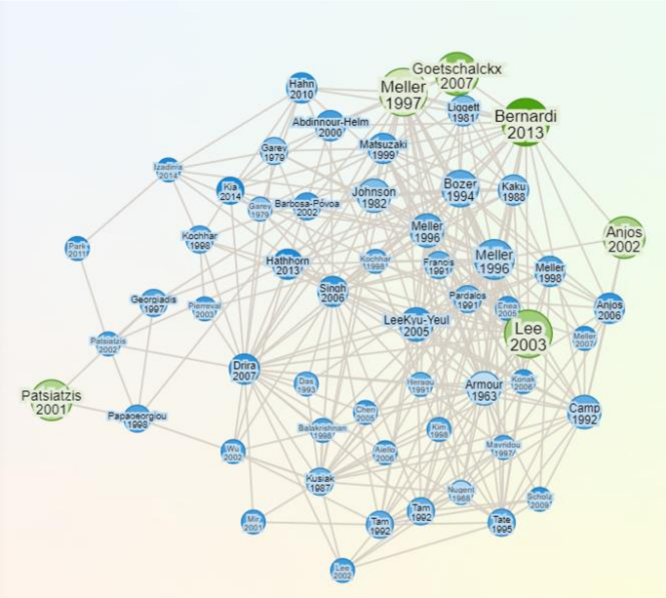

Figure 0.1 - web of outputs suggested by researchrabbitapp.com

APPENDIX C - MATHEMATICAL DESCRIPTION OF MODELS

C.1 STAGE 1: FIRST ASSIGN FLOORS

In the first stage of the proposed method, sections are assigned to floors such that the total of the vertical section interaction costs is globally minimized. With the exception of some changes in notation, this method is equivalent to First Assign Floors. [20]

In this stage we use the following sets;

- i, j = Departments (1,...,N)
- l = Floors (1,…,K)

the following parameters;

- a_i = Required surface area (m^2) per section i
- A_l = Maximum surface area (m^2) of floor l
- δ = Distance between floors
- c_{ij}^V = Vertical travel cost from section i to section j

and the following variables;

- y_i = Floor number of section i
- V_{ij} = Vertical costs depending on y_i and y_j

The model is defined as follows:

$$\min \sum_{i=1}^{N} \sum_{j=1}^{N} V_{ij} \qquad (23)$$

$$s.t. \sum_{l=1}^{K} l x_{il} = y_i \quad \forall i = 1, \ldots, N \qquad (24)$$

$$V_{ij} \geqslant (y_i - y_j)\delta c_{ij}^V \text{ and } V_{ij} \geqslant (y_j - y_i)\delta c_{ij}^V$$
$$\forall i, j = 1, \ldots, N \qquad (25)$$

$$\sum_{l=1}^{K} x_{il} = 1 \quad \forall i = 1, \ldots, N \qquad (26)$$

$$\sum_{i=1}^{N} a_i x_{il} \leqslant A_l \quad \forall l = 1, \ldots, K, \qquad (27)$$

where

$$x_{il} := \begin{cases} 1, & \text{if department } i \text{ is assigned to floor } l \\ 0, & \text{otherwise.} \end{cases} \qquad (28)$$

The objective function (23) minimizes the vertical flow costs between sections i and j. Constraint (25) ensures that this is the maximum of the costs between two sections. Constraint (24) ensures that a floor is assigned variable y_i. Constraint (26) ensures that each department is assigned to a floor. Constraint (27) ensures that the total surface areas od the sections assigned to a floor does not exceed the surface area of the floor.

C.2 STAGE 2: MODCOAR

The FBF (Floor-By-Floor), solves the layout of each floor independently of the other floors by applying to each floor l. The new models are denoted ModCoAR(l) – stage 2 - and

BPL(l) – stage 3. This allows for several smaller problems to be solved separately as opposed to solving the one larger, more complex problem of solving for the layout of all floors simultaneously. However, it is only suitable for problems with up to one elevator location. This is because the layout on another floor is not known until the end of the procedure, so the elevator that will minimize the travel distance between two sections on different floors cannot be determined throughout the optimization procedure. For the FBF model, to account for the interaction between sections on different floors, say for department i on floor k and for department j on floor g, the (target) distances are split into three parts; the distance between department i and the elevator, the elevator travel, and the distance between the elevator and department j. The interaction from department i to the elevator is handled within the objective function of the ModCoAR(k) and BPL(k) models by using a (target) distance between i and the elevator and the C_{ij} between department i and section j. Similarly, the interaction between the elevator and section j can be handled within the ModCoAR(g) and BPL(g) models. The travel through the elevator is simply a constant and is added to the objective function.

The **ModCoAR** is a 'modified' (Mod) - 'convex' (Co) – 'attractor-Repeller' (AR) model, which is a relaxation of the layout problem defined by [25]. Its purpose is to find good initial values for the next step in which the final layout is determined. In this model, each section is approximated by a circle of radius r_i and centre (x_i, y_i). Constraints provide a bound for the dimensions of the facility and ensure that all the circles remain completely inside of these bounds.

The ModCoAR originates from the AR model of [25]. Because the AR model is not convex, meaning that the solution space has local optima, the AR model was transformed to the 'convexified' AR model; CoAR. The CoAR model also had a problem, namely that it would require a specialized algorithm to solve. [21] This problem is remedied by creating a modified convex AR model with scaling parameters α and K_{MOD}.

We first address all definitions of the sets, parameters, and variables. After that we present and explain the ModCoAR model.

In this stage we have the following sets;

- i, j = Departments (1, ... ,N)

the following parameters;

- w_F, h_F = width and height of floor
- a_i = surface of section i in m^2
- r_i = radius of section i
- K_{MOD} = adjusting parameter
- α = adjusting parameter
- ϵ = small error
- c_{ij} = costs from section i to section j
- $t_{ij} := \sqrt{\alpha\left(r_i + r_j\right)^2}$ = target distance between two circles i and j
- $T_{ij} := \sqrt{\frac{t_{ij}}{c_{ij}+\epsilon}}$ = generalized target distance

and the following variables:

- x_i, y_i = respectively the x and y coordinate of section i
- $D_{ij} := \left(x_i - x_j\right)^2 + \left(y_i + y_j\right)^2$ = Square distance between i and j

The final model is defined by [21] as follows:

$$\min_{(x_i,y_i),h_F,w_F} \sum_{1\leqslant i<j\leqslant N} F_{ij}(x_i,x_j,y_i,y_j) - K_{MOD}\ln\left(\frac{D_{ij}}{T_{ij}}\right) \quad (9)$$

$$\text{s.t. } \frac{1}{2}w_F \geqslant x_i + r_i \quad \text{and} \quad \frac{1}{2}w_F \geqslant r_i - x_i \quad \text{for } i = 1,\ldots,N \quad (10)$$

$$\frac{1}{2}h_F \geqslant y_i + r_i \quad \text{and} \quad \frac{1}{2}h_F \geqslant r_i - y_i \quad \text{for } i = 1,\ldots N \quad (11)$$

$$w_F^{\max} \geqslant w_F \geqslant w_F^{\min} \quad \text{and} \quad h_F^{\max} \geqslant h_F \geqslant h_F^{\min}, \quad (12)$$

where K_{MOD} is a scaling factor and

$$F_{ij}(x_i,x_j,y_i,y_j) := \begin{cases} c_{ij}D_{ij} + \frac{t_{ij}}{D_{ij}} - 1, & D_{ij} \geqslant T_{ij} \\ 2\sqrt{c_{ij}t_{ij}} - 1, & 0 \leqslant D_{ij} < T_{ij}. \end{cases} \quad (13)$$

The objective function consists of two parts: $F_{ij}(x_i, x_j, y_i, y_j)$ and $-K_{MOD}\ln\left(\frac{D_{ij}}{T_{ij}}\right)$. $F_{ij}(x_i, x_j, y_i, y_j)$ is a piecewise function that aims to 'attract circles' if the distance D_{ij} is bigger than the generalized target distance T_{ij} and 'repel circles' if the distance D_{ij} is smaller than the generalized target distance T_{ij}. The second part: $-K_{MOD}\ln\left(\frac{D_{ij}}{T_{ij}}\right)$ is added in the transition from the CoAR to the ModCoAR to create a model that is solvable by standard algorithms. The term K_{MOD} is a parameter that needs adjusting to find the optimum where $\left(\frac{D_{ij}}{T_{ij}}\right) \approx 1$.

Constraints (10) and (11) ensure that the circles are within the boundaries of the facility. Constraint (12) is used when the width and height of the facility are variables. In this research however we set $w_F^{max} = w_F^{min} = w_F$ and $h_F^{max} = h_F^{min} = h_F$ because the dimensions of our warehouse are already set.

C.3 STAGE 3: BPL

Bilinear Penalty Layout Model (BPL) uses the solution of ModCoAR as initial values to solve the layout problem. In fact, BPL is an exact formulation of the facility layout problem. First, we define the sets, parameters, and variables of the BPL, then we show the model.

In this stage we have the following sets;

- i, j = Departments (1, ... ,N)

the following parameters;

- c_{ij} = cost matrix from section i to section j
- K_{BPL} = penalty constant
- x_i, y_i = initial values of model, resulting from the ModCoAR model
- w_F, h_F = width and height of the facility
- a_i = surface area of section a_i in m^2

and the following variables:

- X_{ij}, Y_{ij} = the horizontal and vertical distance between section i and j, dependent on w_i, h_i
- w_i, h_i = width and height of section i

$$\min_{(x_i,y_i),h_i,w_i,h_F,w_F} \sum_{1 \leqslant i<j \leqslant N} c_{ij} d_{ij} \tag{14}$$

$$\text{s.t. } X_{ij} \geqslant \frac{1}{2}(w_i + w_j) - |x_i - x_j| \quad \text{for all } 1 \leqslant i<j \leqslant N \tag{15}$$

$$Y_{ij} \geqslant \frac{1}{2}(h_i + h_j) - |y_i - y_j| \quad \text{for all } 1 \leqslant i<j \leqslant N \tag{16}$$

$$X_{ij} \geqslant 0,\ Y_{ij} \geqslant 0, \quad \text{and} \quad X_{ij} Y_{ij} = 0 \quad \text{for all } 1 \leqslant i<j \leqslant N \tag{17}$$

$$\frac{1}{2} w_F - \left(x_i + \frac{1}{2} w_i\right) \geqslant 0 \quad \text{and} \quad \left(x_i - \frac{1}{2} w_i\right) + \frac{1}{2} w_F \geqslant 0 \quad \text{for } i = 1, \ldots, N \tag{18}$$

$$\frac{1}{2} h_F - \left(y_i + \frac{1}{2} h_i\right) \geqslant 0 \quad \text{and} \quad \left(y_i - \frac{1}{2} h_i\right) + \frac{1}{2} h_F \geqslant 0 \quad \text{for } i = 1, \ldots, N \tag{19}$$

$$w_i h_i = a_i,\ w_i^{\max} \geqslant w_i \geqslant w_i^{\min}, \quad \text{and} \quad h_i^{\max} \geqslant h_i \geqslant h_i^{\min} \quad \text{for } i = 1, \ldots, N \tag{20}$$

$$w_F^{\max} \geqslant w_F \geqslant w_F^{\min} \quad \text{and} \quad h_F^{\max} \geqslant h_F \geqslant h_F^{\min}, \tag{21}$$

The constraints (15–17) are non-overlap constraints. To solve BPL, the complementarity constraints $X_{ij}Y_{ij} = 0\ for\ all\ i, j$ are penalized in the objective function. Specifically, (14) is replaced by

$$\sum_{1 \leqslant i<j \leqslant N} c_{ij} d_{ij} + K_{BPL} X_{ij} Y_{ij} \tag{22}$$

where K_{BPL} is a penalty constant, and (17) is replaced by

$$X_{ij} \geqslant 0,\ Y_{ij} \geqslant 0 \quad \text{for all } 1 \leqslant i<j \leqslant N.$$

Handling the problem in this way often successfully leads to solutions where $X_{ij}Y_{ij} = 0\ for\ all\ i, j$, that is, where there is no overlap between any two rectangles. [21]

The constraints (18) and (19) ensure that all sections remain inside the facility. These constraints ensure that for each section, the right wall is to the left of the facility's right wall, and the left wall is to the right of the facility's left wall. Similarly, they ensure that each section's upper wall is below the facility's upper wall, and that the lower wall is above the facility's lower wall.

Constraint (20) consists of three parts. $w_i h_i = a_i$ makes sure that the size of the section is equal to the requires surface area. $w_F^{max} \geq w_F \geq w_F^{min}$ and $h_F^{max} \geq h_F \geq h_F^{min}$ make sure that the department is not wider or higher than the facility.