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Master Thesis

Towards An Efficient and Standardized Warehouse Optimization Strategy - An Automated Performance Analysis Model

by

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Abstract

This thesis explores the development of an operational-data-driven performance analysis model for warehouse optimization, addressing inefficiencies faced by 4Supplychain Consulting. The model aims to automate warehouse performance measurement, the identification of optimization opportunities, and proposing a narrow scope of optimization measures. It explores a semi-automatic KPI-selection of indicators assessable with WMS-data. Through the integration of a new perspective on activity profiling: performance profiling, the steps of internal benchmarking and justification with statistical analysis, the model provides actionable insights in performance optimization. The case study at AG Logistics demonstrates the model's capability to enhance productivity in order-picking activities. The results highlight significant improvement potentials and underscore the practical value of the model for both consultancy and operational management in the logistics sector.

Management Summary

Introduction

4Supplychain Consulting struggles with time-consuming processes in warehouse performance analysis for its clients. The primary objective of this research is to develop an automated performance analysis model using WMS-data. The research addresses how operational data can be utilized to measure performance, identify optimization opportunities, and narrow the scope of optimization measures.

Problem Context

Warehouses are crucial in the supply chain, but the current optimization strategy at 4Supplychain is inefficient, involving extensive interviews, on-site visits, and data collection. A previous attempt to streamline these processes with the Logresult tool failed due to user commitment issues and data inconsistencies. The new strategy focuses on standard WMS-data sources, such as location and product master data, inbound and outbound data, and inventory adjustments.

Theoretical Framework

Selecting appropriate KPIs is critical for warehouse optimization and can be done with a semi-automatic selection approach, which is based on existing classifications in the literature. This research leverages the existing classifications of warehouse performance indicators. Additionally, it combines a new perspective on activity profiling with steps of the internal benchmarking approach. Statistical analysis substantiates the significance of the quantified performance gaps and improvement potentials in the benchmarking process.

Solution Design

The solution design involves an eight-task strategy for the performance analysis model, scoped to standard warehouse characteristics. The model measures 36 different KPIs and organizes performance profiles by warehouse activity, resulting in 37 different profiles. Internal benchmarking within a single warehouse identifies best practices, calculates performance gaps, determines improvement potentials supported by statistical analysis, and selects target optimization areas. Follow-up questions and optimization measures are derived from these insights to scope the direction for performance optimization.

Case Description and Experimental Settings

The case study at AG Logistics, a 3PL provider, focuses on the order-picking activity in their main warehouse. The model implementation considers three performance threshold scenarios (best-case, base-case, worst-case) to identify opportunities for optimization. The limited scope ensures feasibility within the research timeframe, focusing on four performance indicators and ten performance profiles.

Case Implementation, Evaluation, and Validation

The model successfully measures detailed performance levels, identifies optimization opportunities, and links them to follow-up questions and optimization measures. For AG Logistics, the model highlights recipient, storage, and item profiles as target optimization areas, with an improvement potential of 50% in total labor hours for order picking. A 4Supplychain expert affirms the model's practical value, emphasizing its unique contribution to performance analysis, which enables potential new projects and market share growth.

Conclusions and Recommendations

WMS-exports as operational warehouse data are suitable sources for performance analysis. The model provides detailed performance insights and automates the identification of optimization opportunities through successfully combining performance profiling, internal benchmarking and statistical analysis. While quantifying performance gaps and improvement potential needs refinement, the model's approach to targeting optimization areas is promising. The model holds high practical value for improving warehouse productivity and efficiency in the supply chain consultancy industry. Future research should focus on refining the quantification process and expanding the model's applicability to various warehouse settings.

Preface

This is the master thesis research as the final project of the Master Industrial Engineering and Management at the University of Twente. Central in this research is the development of an automated warehouse performance analysis model based on data provided by exports of a Warehouse Management System (WMS). It is conducted at 4Supplychain Consulting in collaboration with one of its clients, AG Logistics.

Acknowledgements

Here we are, close to finishing my Master's. I am looking back on an exciting time of being a student, achieving goals, sometimes easily, sometimes with more struggles, but often while learning a lot, as was the case for this thesis. I would like to thank a few people who supported me during this last phase of my studies.

First, I would like to thank my university supervisors, specifically Breno Alves Beirigo. He was always very supportive, flexible in meetings, and gave optimistic advice about my progress. Besides the time and effort, I would like to thank him for letting me take my own route with this project while also being adaptive to support me with specific requests.

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Acronyms

3PL Third Party Logistics. ii, 2, 16, 42, 43, 54, 58, 68, 73, 76, 92, 96

ALP Automatic Layer Picker. 54, 93, 96

ANCOVA Analysis of Covariance. 25, 26

ANOVA Analysis of Variance. 25, 26, 46

AS/RS Automated Storage-and-Restrievel Systems. 31, 80

CSF Critical Success Factor. 24, 34–39

DEA Data Envelopment Analysis. 19, 24, 25, 44, 45

DV Dependent Variable. viii, ix, 25–27, 45, 46, 52, 58

EDI Electronic Data Interchange. 96

FEFO First-Expired, First-Out. 76

FIFO First-In, First-Out. 76, 80

FTE Full Time Employee. 37

GHGP Green House Gas Protocol. 1

GUI Graphical User Interface. 49

IDE integrated Development Environment. 49

IV Independent Variable. viii, ix, 25–27, 41, 42, 45, 46, 48, 52, 58, 107

KPI Key Performance Indicator. i, viii, 7, 8, 12, 18, 19, 24, 25, 27, 31, 57, 60, 66, 68

MHE Material Handling Equipment. 7, 20, 54, 95

SCP Supply Chain Planning. 1

SKU Stock Keeping Unit. 16, 77, 79, 96

SKUs Stock Keeping Units. 2

SO&P Sales & Operations Planning. 1

TMS Transport Management System. 34

VAP Value-Adding Processes. 30, 34, 54, 79, 93, 95

WMS Warehouse Management System. i–iii, viii, xii, 6–8, 11, 15–17, 20, 25, 30–34, 36, 52, 54, 55, 57, 58, 69, 72, 75, 77, 78, 80–82, 92, 96

Glossary

Absolute Performance Gap The absolute difference in performance indicator value between an instance's performance and the best practice's performance within the same profile. 45

Activity Any operation or process that takes place within a warehouse to manage the storage, handling, and distribution of goods. 77

Activity Profiling The systematic analysis of item and order activity, seeking to identify and take advantage of patterns of opportunity. 21

Adjusted Performance Gap The difference in performance indicator value between an instance's performance and the best practice's performance within the same profile, adjusted by the performance threshold. 45

Benchmarking The process of systematically identifying best practices, calculating performance gaps, determining improvement potential, and selecting target optimization areas. 23

Best Practice The best-performing instance in a profile. 44

Category A combination of several classifications, resulting in a specific type of performance indicator(s). 34

Classification A scoped selection of performance indicators based on a specified characteristic or perspective. 19

Costs The dimension related to all the financial indicators (e.g. inventory costs, labor costs, or maintenance costs). 19

Dependent Variable A variable whose value and variation does depend on that of another, here the variable used for performance measurement (e.g. the productivity). 25

Dimension A specific aspect or category used to classify performance indicators for measurement of different elements of warehouse performance (e.g. productivity, utilization, or costs). 19

Direct Indicator These 'hard' indicators, are quantifiable elements that can be readily calculated using straightforward mathematical formulas (e.g. cycle time, fill rates, and costs). 19

Equipment The resource related to the tools, machinery, and other physical attributes used to facilitate warehouse operations. 2

Follow-Up Questions The set of questions for a specific target optimization area, selected to identify narrow the scope of optimization measures. 47

Improvement Potential The achievable performance gain based on the performance gap and the statistical significance of the relationship between the instance (IV) and the performance (DV). 45

Indirect Indicator These 'soft' indicators involve qualitative assessments and are often harder to quantify (e.g. customer satisfaction or loyalty). 19

Instance A particular example analyzed in a profile, i.e. the value an Independent Variable (IV) can take (e.g. Client A, or Employee B). 41

Inventory Data The data logs tracking all the low-level inventory levels and movements on a detailed level (e.g. all inventory adjustments over time). 81

Labor The resource related to human workforce involved in the various warehousing activities, i.e. the working hours. 2

Location A unique, specific, designated place within the warehouse where goods are stored or specific activities take place. 77

Master Data The essential root/core data files used as source for other operational data generation (e.g. the product master listing all products possibly present in a warehouse with their characteristics). 81

Model The operational-data-driven warehouse performance analysis model as the developed artifact during the research. 6

Operational Warehouse Data Data generated during operational activities, scoped down to easily obtainable data like WMS-exports. 7

Opportunities for Optimization Possibilities to - if acted on correctly - increase warehouse performance given the current situation. 7

Optimization Measure All possible interventions that aim to improve the performance of (a part of) a warehouse process. 7

Performance Analysis The process involving systematic performance measurement, identification of opportunities for optimization, and support decision making,. 5

Performance Measurement The process of selecting, defining, measuring, and interpreting a selection of KPIs. 7

Performance Profile A scoped focus area for performance-indicator-based activity profiling. 41

Performance Threshold The extent (%) of the best practice performance which we believe is achievable for all instances in a specified profile that are statistically significant. 45

Productivity The dimension related to the efficiency of the use of resources. Productivity is the ratio of output to resource consumption (e.g. order picking productivity, or shipping productivity). 20

Profile A scoped focus area for activity profiling. 22

Quality The dimension related to the degree to which products or services meet or exceed customer expectations and requirements (e.g. customer satisfaction, order fill rate, or shipping accuracy). 19

Resource Any asset or input utilized to carry out warehousing activities (e.g. space, labor, or equipment). 2

Space The resource related to the physical area available for storing goods and conducting warehouse operations. 2

Statistical Significance The extent to which the instance's value (the Independent Variable (IV)) influences the value of the analyzed performance indicator (the Dependent Variable (DV)) (i.e. how much an instance relates to the measured performance. 25

Strategy The warehouse performance optimization strategy. 3

Target Optimization Areas The most prioritized profiles for optimization, based on the highest improvement potential. 46

Time The dimension related to time-measurement activities, such as receiving time, order picking time, dock-to-stock time. 19

Trailer One truckload of products, generally up to 33 pallets. 34

Transaction Data The data logs of higher-level logistical decisions in a warehouse (e.g. goods receipt or shipments). 81

Utilization The dimension related to the efficiency of the use of resources. Utilization is the ratio of resource consumption to its capacity (e.g. storage space utilization or inbound-area utilization). 20

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Chapter 1

Introduction

This chapter introduces the reason for the research and its design. The first part until Section 1.5 contains the problem identification. From Section 1.6 on, this chapter explains the research approach.

Section 1.1 provides the company background of 4Supplychain, its services, capabilities and client portfolio. Section 1.2 briefly introduces the main warehouse processes and causes for performance challenges.Section 1.3 explains the assignment as given by 4Supplychain. Section 1.4 provides the context of the challenges from the company's perspective. Last, Section 1.5 explains the selection of the core problem.

Section 1.6 provides the research problem. Section 1.7 states the objectives to achieve. Section 1.8 provides the scope and limitations of the research. Section 1.9 states the research questions and their sub-questions. Section 1.10 provides the thesis's research design and structure.

1.1 Company Background

4Supplychain is a consulting and interim management firm founded in The Netherlands in 2013. Their goal is to understand the supply-chain-related objectives of their clients in the best possible way to find solutions that fit best. The twelve-person entrepreneurial and driven team supports clients' performance and strategic objectives with several services at all company levels.

The services of 4Supplychain are divided into three categories: consulting, project management, and interim management. Their consulting services provide expert-level, pragmatic consultation, including a feasible and realistic implementation plan. The project manager service is about fulfilling a role (project manager, program manager, project expert) in a supply chain transition project. Last, the interim management service provides clients temporary support in their supply chain (logistics) team.

The three central capabilities of 4Supplychain are Supply Chain Planning (SCP)/Sales & Operations Planning (SO&P), distribution network and warehousing, and sustainability. SO&P focuses on demand and supply planning, store and replenishment processes, trade promotions, and product life cycle management. Distribution network and warehousing include the design of networks and warehouses, outsourcing, relocation, and continuous improvement projects. Sustainability is about the footprint of the supply chain. The expertise of 4Supplychain is supporting the implementation of the Green House Gas Protocol (GHGP) with footprint calculations and optimization.

With its different services and capabilities, 4Supplychain serves dozens of clients in complex supply chains. The client portfolio contains a broad range of companies, and warehouse productivity can significantly influence the performance of a supply chain active in various sectors. Many are active in a food-related industry, differing from vegetables, dairy, and candy to beer, cattle feed, or wholesale. Some other clients are active in office equipment or steel. Another significant part of their clients are Third Party Logistics (3PL) providers.

A corresponding characteristic of most companies is that they deal with large, complex warehouses. Warehouses are a central part of most supply chains, and warehouse productivity can significantly influence the performance of a supply chain. Especially for 3PL providers, where the margins are often small, high warehouse productivity is critical for profitable business operations.

1.2 Warehouse Performance Challenges

Warehousing is holding inventory to satisfy customer orders quickly, handling and storing items, consolidating products, customizing orders, and offering added-value service, among others (Frazelle, 2015). As pivotal components of supply chain operations, warehouses synchronize these activities. Furthermore, recognizing their strategic importance, companies allocate substantial resources to optimize warehouse operations. The term Resource refers to any asset or input utilized to carry out warehousing activities, including space, labor, and equipment. Typically, products arrive in high volume and leave in smaller volume. This means that breaking down the 'large chunks' of product into the 'pick-size' is an important function of the warehouse (Bartholdi and Hackman, 2019).

The general operations of a warehouse consist of five steps: two inbound activities, two outbound activities, and storage in between. Figure 1.1 gives an overview of the phases. Replenishment is another common activity that often occurs during the storage phase. This is when a product is moved from its bulk storage location to its pick-storage location.

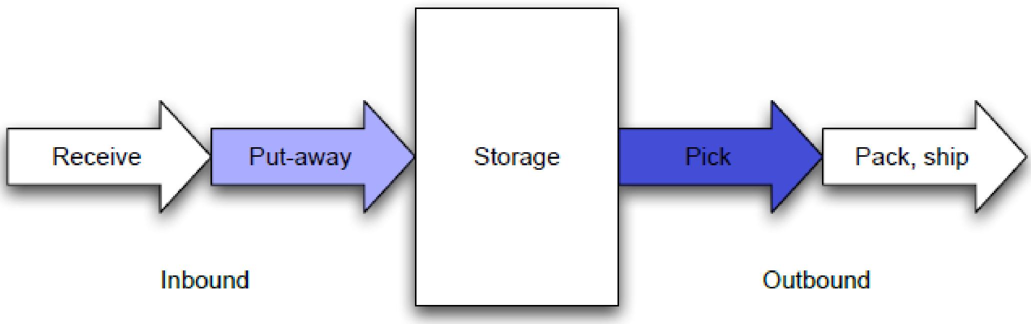

Figure 1.1: The five steps in a typical warehouse (Bartholdi and Hackman, 2019)

Resources like space, labor, and equipment should be efficiently divided and planned across these steps and activities to ensure a high-performing warehouse. The term Space refers to the physical area available for storing goods and conducting warehouse operations. Labor refers to the human workforce involved in the various warehousing activities. Equipment refers to the tools, machinery, and other physical attributes used to facilitate warehouse operations.

Large-size warehouses could easily employ over 100 workers, cover 50,000 m^2 of ground, contain over 10,000 Stock Keeping Units (SKUs), and even more storage locations. On this scale, efficiently dividing the resources becomes incredibly complex. This complexity is the cause of a lot of challenges for the warehouse performance.

Often, warehouse, logistics, or supply chain management cannot face and overcome these challenges alone. They have trouble assessing warehouse performance, identifying causes for lacking performance, and devising and implementing optimization measures. This is when the expertise of a company like 4Supplychain is consulted.

1.3 Assignment as Given by 4Supplychain

4Supplychain is regularly approached by new or existing clients about challenges with their warehouse productivity. Often, the clients do not exactly know the cause of a problem. Even though the clients can provide 4Supplychain with operational warehouse data, finding the best applicable method for performance optimization is often time-consuming.

4Supplychain believes there is a possibility of making this analysis more efficient and helping more clients with warehouse performance challenges. Their ambition is to use a 'data dump' of clients' operational warehouse data to identify promising opportunities for optimization quickly. This analysis should narrow the scope of possible optimization measures to apply to a specific target optimization area. The target optimization areas are parts of a warehouse or a process with the most significant opportunities for optimization. They should be identified by quantitatively measuring inefficiencies leading to prioritizing these opportunities. In short, 4Supplychain is looking for a more efficient warehouse performance optimization strategy.

The main starting point of the new strategy should be the operational 'data dump'. The term Strategy refers to the warehouse performance optimization strategy. The quantitative data should provide the possibility for some standardized technical analysis. This analysis should measure performance and identify and quantify opportunities for optimization. If standardized, the 'data dump' can quickly narrow the scope for optimization measures. This technical analysis, in combination with limited (time-consuming) qualitative analysis, should form the warehouse optimization strategy.

To accomplish the ambition of a new warehouse optimization strategy based on this operational warehouse data, 4Supplychain conceived three goals:

- measure the performance of a warehouse on a detailed level
- identify the target optimization areas by quantifying and prioritizing opportunities for optimization
- propose a narrowed scope of optimization measures for each target optimization area

4Supplychain believes that if the three goals can be accomplished with the operational 'data dump' as a starting point, the new warehouse optimization strategy strengthens their consultancy business. It should create an opportunity to approach clients proactively. Eventually, more clients can be helped, more turnover can be made, and a more significant market share can be acquired.

1.4 4Supplychain challenges

4Supplychain perceives the main challenge as inefficient warehouse optimization. Inefficient problem-solving for warehouse optimization has two causes. First, it is often hard to choose the best optimization measures. Second, during the implementation phase, the full potential impact of a chosen optimization measure is not always achieved. Both problems have several causes.

Figure 1.2 shows the problem cluster of the problems as encountered by 4Supplychain. The problem cluster shows the causal relationship between all problems. It highlights the perceived 'end problem' and the chosen core problem, which Section 1.5 elaborates on.

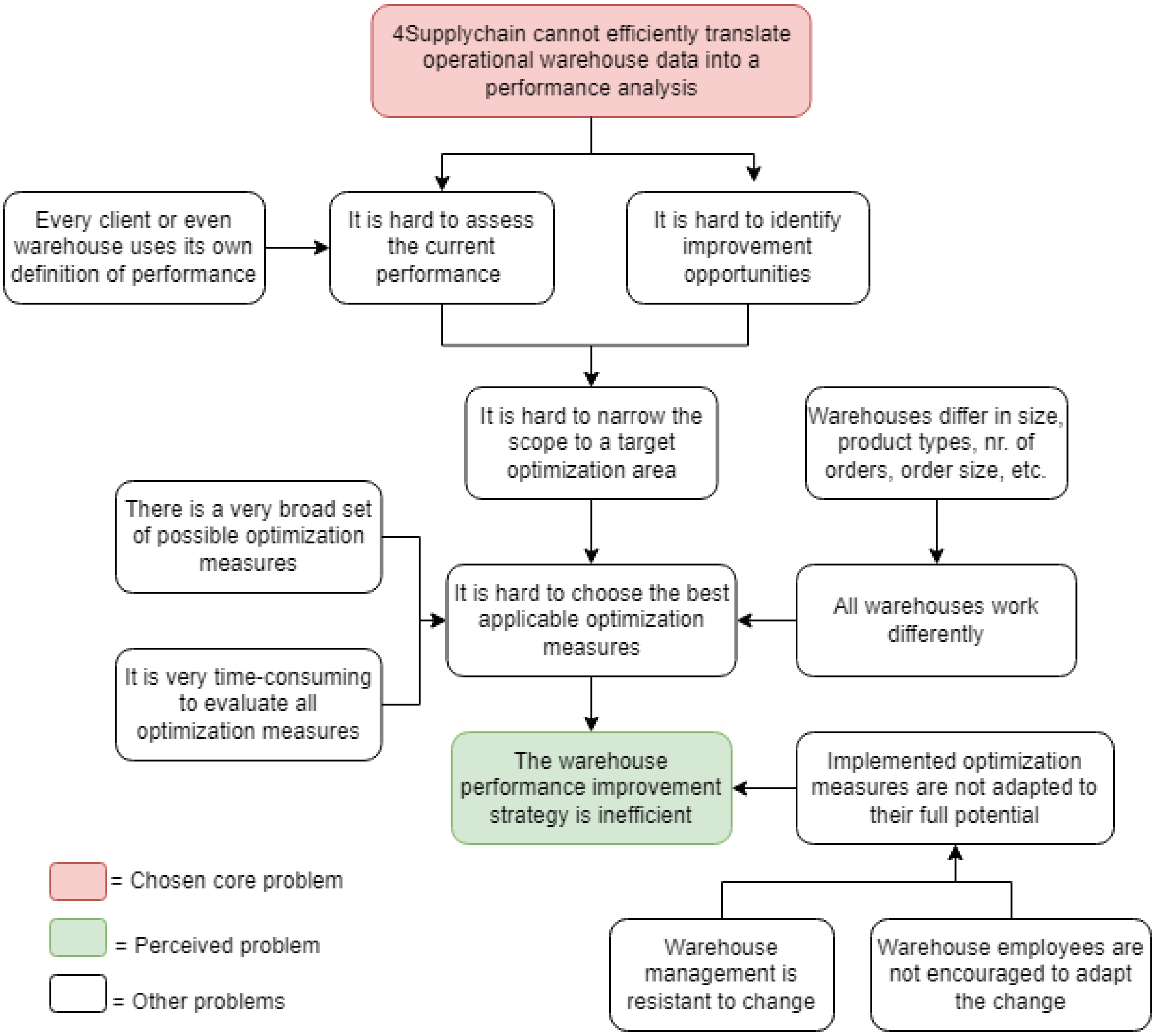

Figure 1.2: Problem cluster of warehouse performance optimization

4Supplychain is often involved in the implementation phase. Here, they tackle problems regarding warehouse management that are resistant to change or employees who are not encouraged to adapt to change. For example, when employees are only expected to meet a minimum standard level of productivity, more efficient equipment will not directly lead to more productive employees.

Before that, when an optimization measure has to be chosen, several problems exist that limit the influence of 4Supplychain. For example, the clients' warehouse characteristics and original performance definitions are regarded as given constraints. Next, the broad set of possible optimization measures and the time-consuming process of evaluating all of them are given in the broad context of warehouse performance optimization.

A problem that may also be influenced by 4Supplychain is the selection of the best applicable optimization measure. It is currently hard to narrow the scope to a target optimization area. On the one hand, this is caused by difficulties in assessing the current warehouse performance. On the other hand, it is hard to identify the opportunities for optimization. 4Supplychain believes this process can be improved by using the 'data dump' of warehouses' operational data for tracking warehousing and picking operations. The millions of records used for traceability purposes include valuable data about warehouse performance. However, this is often not used for performance optimization.

1.5 Core Problem

Figure 1.2 shows the chosen core problem in the problem cluster:

> 4Supplychain cannot efficiently translate operational warehouse data into a performance analysis

The term Performance Analysis refers to the process involving systematic performance measurement, identification of opportunities for optimization, and support decision-making, which is the core of this problem. According to Heerkens and Winden (2021), there are four criteria a core problem should meet. This section explains the motivation for the core problem based on these criteria.

- It should be sufficiently clear that the problem occurs and has a relationship with the other problems: 4Supplychain confirms the absence of the ability for efficient warehouse performance analysis, and Figure 1.2 presents the causal relationship.
- The problem can have no cause itself: Figure 1.2 shows no cause for the problem, and 4Supplychain does not know a cause either.
- It must be a problem that can be influenced by the problem owner (4Supplychain): 4Supplychain believes that the combination of analysis of existing methods in the literature, the knowledge within the company, and the available warehouse data should make this efficient performance analysis possible. Besides, they have trust that clients will be able to share the needed operational data.
- The most important core problem should be selected: Figure 1.2 shows several 'initial problems'. Solving the chosen core problem contributes the best to the assignment's goals, as given by 4Supplychain. It contributes to:
  - measuring the current performance
  - identifying opportunities for optimization
  - narrowing the scope for optimization measures

1.6 Main Research Question

Based on the assignment given by 4Supplychain, the problem description, and the core problem identification, this research will address one main research problem, i.e., the main research question. It describes the knowledge that needs to be acquired. The solution design and research to be conducted are focused on solving this problem. The main research problem states:

> *To what extent can operational warehouse data be used to automatically (i) measure warehouse performance, (ii) identify opportunities for optimization, and (iii) narrow the scope of optimization measures?*

The definition of the different components of the research problem can best be described within the scope of the research. This is explained in Section 1.8. First Section 1.7 states the research objectives to explain the practical application of solving the research problem.

1.7 Research Objectives

The research aims to improve the warehouse optimization strategy of 4Supplychain. The main focus within this improved strategy is creating a model that efficiently translates operational warehouse data (WMS-exports) into warehouse performance analysis with a focus on optimization. From this point, the term Model refers to the operational-data-driven warehouse performance analysis model as the artifact of development during the research. The model's objective can be divided into three sub-objectives to which the research should contribute:

1. The model can assess the current warehouse performance based on indicators that can be measured with operational data.
2. The model can identify opportunities for optimization based on the performance assessment and patterns in the operational data.
3. The model narrows the scope for optimization measures based on the opportunities for optimization.

1.8 Scope and Limitations

This section describes the scope and limitations of the research. Section 1.8.1 describes the methodological scope of the research. Section 1.8.2 describes the practical scope. Section 1.8.3 describes the limitations within these scopes.

1.8.1 Methodological Scope

The scope of the research is within the "science of the middle range" as described by Wieringa (2014). The middle range is achieved on two levels: generalization and realism.

For generalization, this means that the new warehouse optimization strategy will not be designed for universal use for every warehouse performance analysis. However, it is broader than one specific case since we develop a model that (with some adjustments) should apply to most typical warehouses and common performance challenges of clients of 4Supplychain.

For realism, it means that the conditions for which the model is designed will not be idealized, as in complete theoretical optimization models. On the other hand, it will not always completely represent the practical situation. The middle range here implies realistic conditions that can be regarded as close to the practical situation under certain assumptions that will be stated clearly.

1.8.2 Practical Scope

Since 4Supplychain has a broad range of customers, the way they work in their warehouses differs greatly. This is largely a logical consequence of the different markets in which they are active and the different roles they fulfill in a supply chain. They have a diverse portfolio of product characteristics, number and size of orders, size of the warehouses, and packaging in different kinds of warehouses in different markets. The impact of different optimization measures will vary significantly as well.

For this research, it is important to scope down warehouse optimization. Since 4Supplychain aims to ensure certain generic applicability, the research will focus on warehouses with mostly typical characteristics. These characteristics are described in Section 4.1.2. Although details will always deviate from the typical standard, this impact can be assessed case by case.

The term Operational Warehouse Data is data generated during operational activities. For the model, this is scoped down to data that is easily obtainable from clients, even though their current level of performance analysis is low. This is because it should be an efficient analysis model for 4Supplychain, where the data collection should not take a significant amount of time. In practice, most data should be derived directly from a Warehouse Management System (WMS). Using such a system is general practice for the clients of 4Supplychain. The model should efficiently deal with different data formats from WMSs when necessary. Section 2.3 describes the data types in more detail.

The term Performance Measurement is the process of selecting, defining, measuring, and interpreting a selection of KPIs. For this research, the selection of KPIs is scoped down to KPIs that can be measured with our scoped definition of operational warehouse data. In Chapter 4, this selection is elaborately assessed.

The Opportunities for Optimization are possibilities to - if acted on correctly - increase warehouse performance given the current situation. These possibilities should be indicated and demarcated enough that there is a clear focus so it can easily be determined if performance optimization is indeed possible. For example, a focus point could be the productivity of a certain (group of) employees, the storage time of certain warehouse products, or the utilization of certain warehouse locations during a specific period.

The narrow scope of Optimization Measure are all possible interventions that aim to improve the performance of (a part of) a warehouse process. For example, using zoning of MHE to decrease travel distance order pickers. The research includes a broad set of optimization measures. However, they will be assigned to specific target optimization areas.

1.8.3 Limitations

The research limitations highly depend on the availability, content, and quality of the WMS-data of the cooperating warehouses of a client of 4Supplychain. The goal is to answer the question of to which extent this kind of data can be used to analyze warehouse performance. Our scoped input data definition causes several limitations in answering the research question.

First, the performance measurement is limited to performance indicators that can be assessed with the operational WMS-data. If certain classifications of warehouse performance do not relate (enough) to the acquired data, these aspects are left out of scope. Section 4.2.1 comprehensively describes which performance classifications are within this scope and which are left out.

The second limitation follows from the fact that the WMS-a small set of warehouses provides data. These warehouses can be assessed based on their performance; however, in identifying best practices, we can only use theoretical best practices or the best practices of these warehouses. The limitation is that we cannot identify best practices within an industry.

The third limitation also follows from this small set of warehouses. A case study of these warehouses validates the performance analysis model. The model may function as required for this case, however, it is hard to assess the general applicability of the performance assessment model, which is a limitation. The extent of this limitation depends on the diversity of clients and their data formats.

These three limitations follow from the pre-determined scope of the research. These limitations may reduce the value of certain conclusions from the performance assessment model. However, this scope ensures that the model is usable for a relatively easily applicable and quick performance assessment. This way, there is no need for extensive, time-consuming data collection and validation processes or contact with dozens of other parties for comparison purposes.

Furthermore, the second and third limitations currently follow from the small set of warehouses on which the model is validated. The impact of these limitations can be diminished over time when 4Supplychain adds more clients to its portfolio. First, the model can be finetuned to improve its functionalities and applicability. Second, the results of these extra cases can, in the future, be used as benchmarks so that each case's performance can be compared with more and more historic cases.

1.9 Research Questions

This chapter states the research questions that will be addressed in the research to solve the research problem stated in Section 1.6.

The first research question is about the analysis of the problem context. It investigates main warehousing concepts, the current situation at 4Supplychain, and the WMS-data as the main input for the new strategy. Answering these questions provides the *problem context*.

1. How is warehouse performance optimization currently working?
    (a) What are the main warehouse concepts and terminology?
    (b) What is the current warehouse optimization strategy of 4Supplychain?
    (c) How can WMS-data as operational warehouse data be used for performance optimization?

The second research question focuses on existing methods in literature to measure performance and identify opportunities for optimization. Answering this question provides the *theoretical framework* of the research.

2. What does theory propose for operational-data-driven warehouse performance analysis?
    (a) What are good methods to determine KPIs?
    (b) What classifications and performance indicators exist for warehouse performance measurement?
    (c) Which are good methods to identify opportunities for optimization in warehousing?
    (d) Which are good methods to link optimization opportunities to warehousing optimization measures?

The third question regards the development of the model for performance analysis. Answering it provides the *solution design*.

3. How should the operational-data-driven warehouse performance analysis be modeled?
    (a) What is the scope of the model?
    (b) Which KPIs are measured by the model?
    (c) How does the model identify opportunities for optimization?
    (d) How does the model narrow the scope for optimization measures?
    (e) How does the model function?

The fourth research question regards the functioning of the model in practical cases. Answering the question should provide the *evaluation and validation* of the model.

4. How does the model function in a practical case?

(a) What are the characteristics of the case?

(b) What experimental settings are regarded in the case?

(c) To what extent can the model measure warehouse performance?

(d) To what extent can the model identify opportunities for optimization?

(e) To what extent can the model propose a narrowed scope for optimization measures?

(f) What do experts say about the contribution of the model?

The fifth research question focuses on the *conclusions and recommendations* of the research. Answering this question will provide both the business and academic world with the contributions of this research.

5. What conclusions and recommendations can be drawn and formulated from the model functioning?

   (a) What are the conclusions of the research?

   (b) What can be recommended to 4Supplychain?

   (c) What can be recommended to the case client about warehouse performance optimization?

   (d) What are recommendations for further research?

1.10 Research Design and Thesis Structure

This section provides the strategy for solving the research problem. It contains the steps taken and data sources to be used to answer the research questions. The design of the research forms the structure of the thesis report

Figure 1.3 shows the overview of the research design. The flow chart shows the chronological order in which the research questions are addressed. It shows all input data sources for each question. Furthermore, it shows the relationship between the research questions and which output is input for the next question. Last, it outlines the thesis report by stating which chapters are dedicated to which research questions.

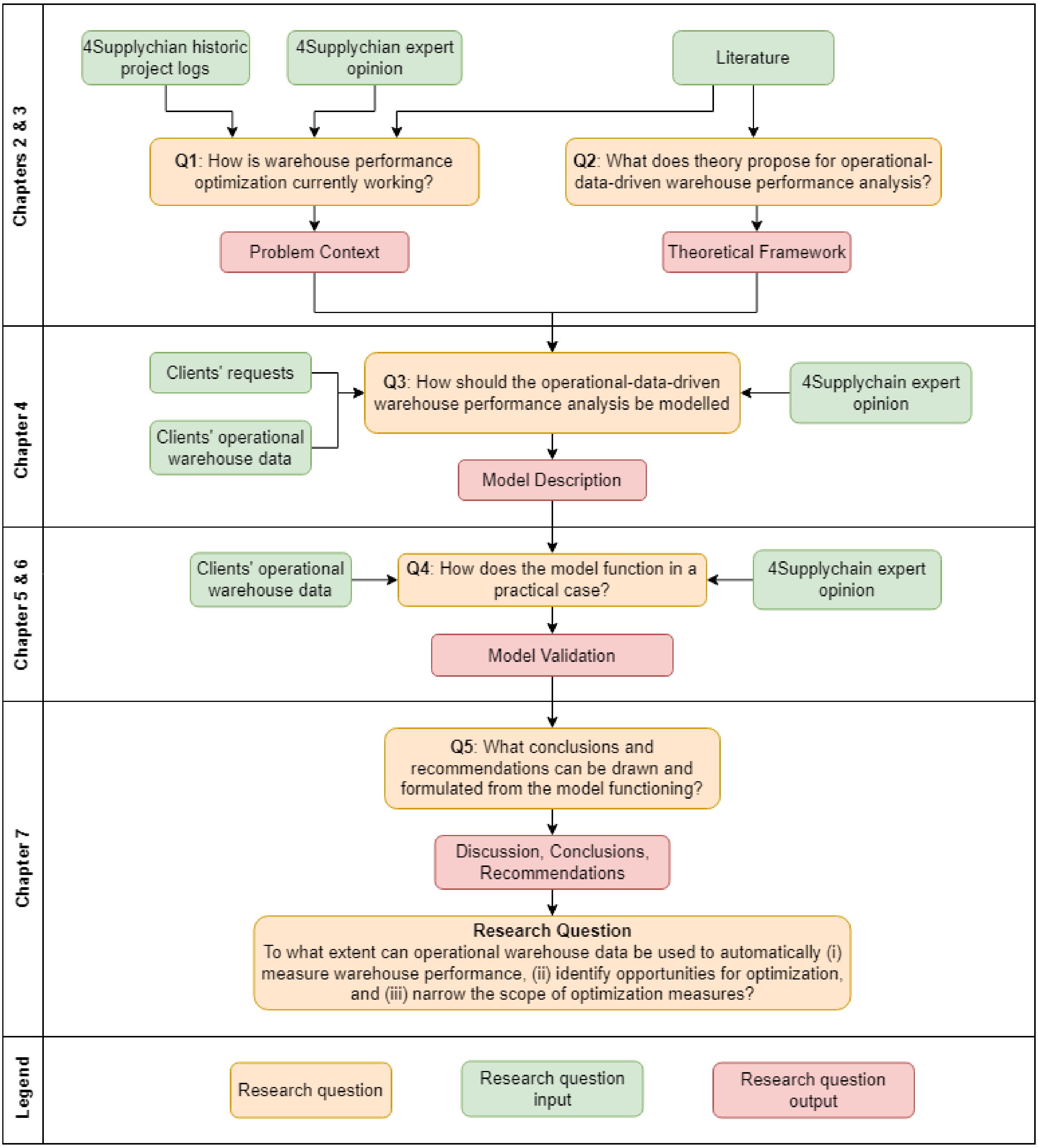

Figure 1.3: The research design showing the connection between the research questions, the input data, and the output data

Chapter 2

Context Analysis

This chapter provides a detailed description of the problem and its context. Section 2.1 briefly introduces warehousing concepts and terminology. Section 2.2 explains the current warehouse performance optimization strategy of 4Supplychain and its inefficiencies in more depth. Section 2.3 describes the characteristics of the WMS-data used as the main input for the performance analysis part of the new warehouse optimization strategy.

2.1 Warehousing Concepts and Terminology

Warehouses add significant value to the supply chain. To analyze a warehouse's performance, it is helpful to determine its type, the units of handling it uses, and the storage strategy it applies.

The main warehouse activities are receiving, put-away, replenishment, order picking, and shipment, where order picking normally accounts for the most operational costs. Identifying the flow of products and the moments the activities are carried out helps analyze warehouse performance.

There are many forms of warehouse equipment for storage and material handling. Each has advantages and limitations and can greatly influence the warehouse's performance.

A WMS facilitates all operational processes in a warehouse. These systems store a large database with different types of operational data. 4Supplychain believes the data stored by such a system can be used for performance optimization.

For readers unfamiliar with basic warehousing concepts and terminology, Appendix A provides context descriptions of warehouse functioning. It explains the fundamental concepts and terminology. It illustrates the role of warehouses and provides a more detailed explanation of the basic characteristics mentioned in this section. Besides, it explains the functions of a WMS and the operational data it can use, create, and store on which the model is based.

2.2 4Supplychain's Warehouse Optimization Strategy

4Supplychain currently does not have a fixed warehouse performance optimization strategy. There are some general guidelines with steps to be taken, but the approach to warehousing projects also significantly depends on the consultant's own experiences and vision. 4Supplychain management believes this may result in inefficiencies or unfulfilled opportunities.

Despite the considerable experience possessed by some consultants at 4Supplychain, the company has not yet carried out many large-scale warehouse performance optimization projects. The projects that have been completed were frequently scaled down significantly before initiation. Additionally, there is often only sparse documentation of the optimization strategies employed.

Now, 4Supplychain wants to enhance its warehouse performance optimization strategy. Section 2.2.1 describe the general guidelines that are currently applied. Section 2.2.2 describes a previous attempt by 4Supplychain the enhance their strategy. This attempt provides a good insight into their ambition and lessons learned for this next attempt.

2.2.1 The Current Approach

The sparse documentation of completed warehousing projects and discussions with 4Supplychain consultants offer some insights into their general project steps. Based on this, we outline a stepwise approach that describes 4Supplychain's current method:

1. **Initial Consultation and Data Collection:**
   - 4Supplychain initiates the process by conducting initial consultations with key stakeholders at the client's warehouse.
   - They gather preliminary information regarding the warehouse layout, current processes, and available performance metrics.
2. **On-Site Visits and Interviews:**
   - Following the initial consultation, 4Supplychain schedules one or two physical visits to the warehouse.
   - During these visits, consultants conduct interviews with warehouse managers, supervisors, and frontline staff to gain insights into operational challenges and potential areas for optimization.
3. **Data Analysis and Evaluation:**
   - After the on-site visits, 4Supplychain collects additional data, including performance metrics, operational data, and process documentation.
   - They analyze this data to identify patterns and opportunities for optimization.
4. **Stakeholder Alignment and Goal Setting:**
   - 4Supplychain collaborates with the client's management team to align on optimization goals and priorities.
   - Together, they define KPIs and establish targets for enhanced warehouse performance.
5. **Optimization Measure Selection:**
   - Based on the data analysis and stakeholder input, 4Supplychain evaluates various optimization measures.
   - Consultants engage in discussions with stakeholders to narrow the options and select the most promising methods.
6. **Implementation Planning:**
   - Once the optimization measures are chosen, 4Supplychain develops a detailed implementation plan.
   - This plan includes timelines, resource allocation, training programs, and change management strategies.

7. **Implementation and Monitoring:**
    - 4Supplychain supports the client during the implementation phase, providing guidance and assistance as needed.
    - They monitor progress closely, adjusting strategies as necessary to ensure successful implementation.
8. **Post-Implementation Review:**
    - After the optimization initiatives are implemented, 4Supplychain conducts a post-implementation review.
    - They assess the impact of the changes on warehouse performance and identify any areas for further improvement.

4Supplychain divides these eight steps over four phases of the project:

1. performance analysis
2. decision making
3. implementation
4. review

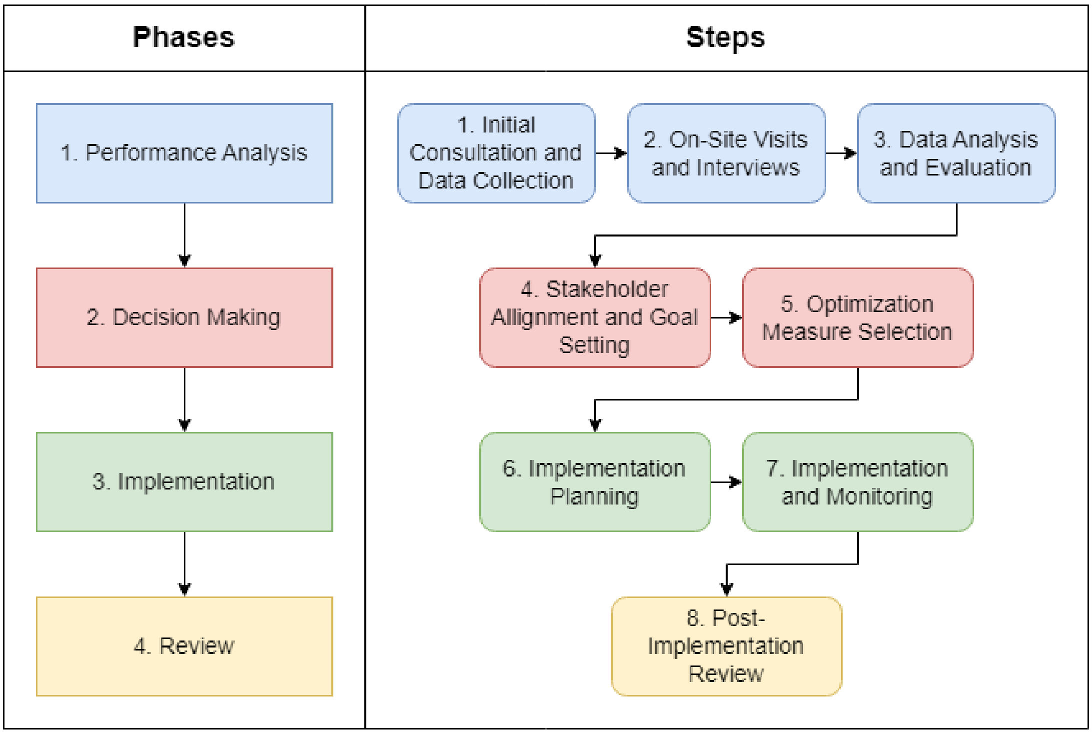

Figure 2.1: 4Supplychain's current strategy-phases and -steps

During the first phase and, therefore, the first three steps of this approach, a lot of time is spent on the performance analysis to identify opportunities for optimization eventually. This part of the strategy is where the core problem lies and where improvement is needed. Significant time is spent on three topics:

- initial consultations and interviews
- on-site visits
- data collection, analysis, and evaluation

Often, these three types of actions are applied repeatedly and alternate in varying order. Generally, the first 2-4 weeks of a project are made up of these actions, and there are even cases where it took several months. For example, an interview triggers a request for data, which analyzed triggers the need for an on-site visit, which triggers a new data request and interview, and so on.

These actions currently demand a considerable investment of time from 4Supplychain consultants as well as cooperation and time from the clients. Consequently, most historic warehousing projects commenced only when the scope was narrow, and there was a strong belief in significant improvement potential. In other cases, 4Supplychain and/or the clients were not prepared to make this investment to identify potential optimization opportunities. Ultimately, this inefficiency in 4Supplychain's consultancy strategy results in lost projects and potential profit.

2.2.2 Previous Strategy Improvement Attempt

The ambition of 4Supplychain to improve its warehouse optimization strategy and enable the opportunity to approach clients efficiently and proactively is not new. During the first years after founding 4Supplychain in 2013, one of the managing consultants had already developed an extensive warehouse optimization strategy. This was a "digital performance improvement" tool called Logresult, which focused on "ideal warehouse benchmarking".

The goal of the Logresult tool was to work towards an "ideal warehouse", which was defined as "A performance improvement mindset to achieve the 'Ideal State': best possible service against the lowest possible cost (and impact)".

This goal should be reached by aiming at three sub-objectives:

- to increase the knowledge level of the logistics managers (best-practice sharing)
- to increase the central knowledge level of the logistics network in a simple way
- to know where to save cost and improve performance

The strategy followed five steps:

1. deploy a questionnaire
2. analyze the data
3. feedback to the community
4. decide on projects
5. implement projects

These five steps were thought out elaborately. The questionnaire consisted of about 140 questions regarding productivity performance, cross-checks for validation, and supporting questions to identify optimal way-of-working methods. The analysis of the data validated the answers, set benchmarks at different levels, and decided on a realistic improvement potential. The feedback to the community, decisions on projects, and implementation steps were thought out in a detailed plan to be implemented over 6-9 months and could be repeated for multiple cycles over different years.

With this attempt, the goal also was to limit the number of interviews and on-site visits and use just one loop of data collection, analysis, and evaluation per year. This tool and strategy should have overcome the inefficiencies stated in Section 2.2.1. 4Supplychain management believed this was how to extend their market in warehouse optimization consultancy projects.

However, despite this extensive effort in the development of this tool and strategy, it never really got off the ground. The attempt faced several problems during the first two steps of the strategy: deploying the questionnaire and analyzing the data. The main problem was that clients did not complete the whole questionnaire and results were not as easily comparable as hoped. Eventually, the method was never completely applied, and 4Supplychain went on to focus on other topics of supply chain consultancy in the years after.

According to 4Supplychain management, there were several underlying reasons why the performance analysis of the new warehouse optimization strategy failed. The most important were:

- it was hard to find the commitment of all users needed per warehouse
- it was hard to find a highly-committed person (the key user) for every warehouse of a client
- there were too many questions; it was a high workload for clients to comply completely
- metrics definition and scope were interpreted in different ways
- metrics were measured incorrectly
- data sources of the client were unavailable
- metrics of different warehouses were not always comparable in improvement potential

Lessons from this failed attempt should be considered for the new warehouse optimization strategy to ensure its general applicability. The main lessons are:

- minimize the number of committed users involved
- minimize the workload for key-user
- standardize metrics definition and scope
- standardize measurement methods
- limit the number of data sources
- use standard available data sources
- simplify comparability of metrics

4Supplychain already scoped the new strategy by assessing the lessons about the data sources. The main data source should be the WMS-exports. These files are common practice for most medium- to large-size warehouses, which are the main focus of the clients of 4Supplychain, which means it is a standard available data source. Furthermore, the scope of this data is limited, which means no high number of additional sources is required. Section 2.3 describes this WMS-data in more detail as the main starting point of the performance analysis model as part of the improved strategy.

2.3 The Avalaible WMS-Data

Appendix Section A.5.2 explains the different types of WMS-data. Most types of data can contribute to performance measurement and the identification of optimization opportunities. However, not all WMS-systems use and/or log all these types of data. Limiting the number of data sources to those generally available is important to assure the applicability of the model.

In historic warehousing projects of 4Supplychain, there are three main types of WMS-data that are generally collected:

- master data (generally location-master and product-master)
- transaction data (generally inbound- and outbound data)
- inventory data (generally current stock levels and inventory adjustments)

The master data files do not indicate the performance of a warehouse, but they provide additional information on potential target optimization areas of warehouse optimization. The location and product master are static data files. It concerns the most recent versions of all warehouse locations and products the warehouse deals with. Every row in the location master describes the characteristics of a unique location, like the position (aisle, row, level) in the warehouse, the dimensions (height, width, depth) of the location, etc. Every row in the product master describes a unique SKU, with its dimensions, weight, special requirements, amount per pallet/layer/case, etc.

The inbound and outbound data provide a high-level overview of the work that is done. This can be used for high-level performance measurement of a warehouse. The number of trucks and pallets the warehouse receives and ships can be measured over time. Every row in the inbound or outbound data describes an arrival or shipment of a truck, the number of pallets loaded, the time between arrival and departure, the client served, and the transporter, etc. These files, however, lack the level of detail to see what exactly is loaded at which moment in time and by whom, as well as other additional information.

Current stock levels are also static data, just a snapshot of the inventory at a certain point in time. In itself, they are of no use for performance measurement over time. Every row in the current stock level simply describes the amount of inventory of a certain product from the product master. Only when a large number of current stock levels are logged over time can we analyze certain productivity or utilization performance metrics.

The inventory adjustment data is the most promising source for warehouse performance measurement. It logs all the moments when a product is moved from one location to another over time in the warehouse. Every row represents an amount of a certain product taken from a certain location (negative inventory adjustment) or placed in a certain location (positive inventory adjustment). Each row also logs the timestamp, who has done it, which amount is adjusted, which pallet, for which client, for which activity, etc. Clients often only use this data for tracing purposes, i.e., to know where a product is. However, these logs tell a lot about the performance in terms of productivity and how the different characteristics influence it.

A WMS does not necessarily provide a layout of the warehouse, which is data that is often collected by 4Supplychain consultants. This layout is generally very relevant for the interpretation of performance analysis. However, it cannot be used to identify opportunities for optimization by itself. Since the WMS-data analyzes does provide location data, performance can still be analyzed in terms of physical places. This lack of physical visualization by a layout may complicate the interpretation of results at first. Still, since it does not influence performance analysis, it can be taken into account afterward when opportunities for optimization are identified.

As described in Chapter 1, the performance analysis model will be validated by a case of a warehouse of a client of 4Supplychain. The main client cooperating in the research is AG Logistics. This 3PL-provider has these types of WMS-data available for the research.

2.4 Summary

Warehouses are a fundamental part of the supply chain. Warehouse characteristics like the type, handling units, storage strategy, main activities carried out, equipment used, and functions of a WMS are key in understanding warehouse optimization.

The current warehouse optimization strategy of 4Supplychain is not fixed but consists of some general guidelines. This strategy is regarded as inefficient and hinders the start of new and broader warehousing projects. The inefficiency is mostly emphasized in the beginning when opportunities for optimization are identified, i.e. in the performance analysis part. It requires a high time investment in multiple loops of interviews, on-site visits, and data collection, analysis, and evaluation.

4Supplychain has previously attempted to improve its warehouse optimization strategy with a tool and strategy called Logresult. This attempt was unsuccessful because of several challenges, including the requested commitment of multiple users, the different interpretations of metrics, the high workload, and the unavailability and necessity of multiple data sources. The lessons learned from this attempt should be considered for the new strategy.

4Supplychain scoped the new strategy by determining that it should be more based on standard available quantitative data sources from a WMS. The standard data sources used as input for the new strategy are location and product master, inbound and outbound data, and inventory adjustments. These are available in historic warehousing projects of 4Supplychain and from the client case assisting in this research, for which they are considered common practice.

Chapter 3

Theoretical Framework

This chapter provides the theoretical framework for improving the performance analysis phase of the warehouse optimization strategy. This includes developing an automated operational-data-driven warehouse performance analysis model. It elaborately analyzes different performance indicators and classifications for performance measurement, approaches for identifying opportunities for optimization, and how to narrow the scope of optimization measures. warehouse layout, which is data Section 3.1 briefly describes some methods for exploring KPI with core principles to use when selecting them. Section 3.2 analyses the classification of warehouse performance indicators. Section 3.3 examines several methods to identify opportunities for optimization. Section 3.4 describes statistical methods to analyze the significance of performance gaps. This substantiates the opportunities for optimization by prioritizing them in target optimization areas. Section 3.5 describes a qualitative method as the last step from a target optimization area to promising optimization measures.

3.1 Exploring the KPIs

The first objective of the research is to measure the performance of the warehouse. Essential to performance measurement is to use the right KPIs and supporting performance indicators. This section explains the requirements and considerations in the KPIs exploration.

Parmenter (2010) and Eckerson (2009) describe several important characteristics of the KPIs. These core principles — sparse selection, drillability, simplicity, actionability, and accountability — emerge as critical for their effective implementation and utility in measuring warehouse performance.

A well-considered KPIs framework prioritizes comprehensible and actionable metrics that can drive significant improvements aligned with strategic objectives. This KPIs are characterized by their capacity to be drilled into for detailed analysis, ensuring transparency and depth of understanding. The emphasis on simplicity aids in universal comprehension across the board, ensuring that each team member understands what is measured and the actions required to influence these metrics positively.

Badawy et al. (2016) distinguishes three types of KPI exploration approaches: manual, selection and prediction. The manual approach consists of a complete qualitative analysis based on a set of already existing KPIs. The selection approach is a structured, semi-automatic way to evaluate KPIs based on existing classifications. The prediction approach is relatively new, where KPIs are explored when no starting point is determined.

For warehouse performance analysis, quite some KPIs, and classifications exist already. This fits the selection approach, where the KPIs are explored throughout existing classifications. For example, Diamantini et al. (2014) uses this approach for a semi-automatic methodology devoted to checking if a set of KPIs can be measured from a company's available data. This is similar to checking if warehouse performance can be measured from the available operational data.

3.2 Indicator Classifications

This section analyses the different classifications used in the literature for warehouse performance indicators. The term Classification refers to the scoped selection of performance indicators based on a specified characteristic or perspective. Using the correct classifications of indicators provides a strong framework for performance analysis. It increases the cooperation of stakeholders and supports the alignment of strategic goals with operational improvements (Badawy et al., 2016). Knowledge of the classifications, their differences, limitations, and opportunities support the selection of KPIs.

3.2.1 Direct and Indirect Indicators

In academic literature, logistics performance indicators are typically classified into two distinct types: *direct* and *indirect* (see, e.g., Chow et al., 1994; Fugate et al., 2010). The term Direct Indicator, often referred to as 'hard' indicators, encompasses quantifiable elements such as order cycle time, fill rates, and costs. These indicators can be readily calculated using straightforward mathematical formulas. In contrast, the term Indirect Indicator or 'soft' indicator involves qualitative assessments, including managerial perceptions of customer satisfaction and loyalty. These softer aspects of logistics performance are more complex to quantify and often require advanced measurement tools, such as regression analysis, fuzzy logic, or Data Envelopment Analysis (DEA) (Staudt et al., 2015).

3.2.2 Classification by Dimensions

The performance of a warehouse is often measured in several dimensions. The term Dimension refers to a specific aspect or category used to classify and measure different elements of warehouse performance. Frazelle (2002a), distinguishes financial, productivity, quality, and response time performance dimensions. Bartholdi and Hackman (2019) uses operating costs, operating productivity, order accuracy, and response time, which indicate the same topics. Manzini (2012) also emphasizes the importance of financial, productive, and quality (including time indicators) performance measurement. Frazelle (2002a) adds utilization as a separate dimension. However, Staudt et al. (2015) includes the utilization as part of the productivity dimension.

In general, the performance assessment dimensions can be summarized as follows:

- *Time* refers to the indicators related to time-measurement activities, such as receiving time, order picking time, dock-to-stock time, etc.
- *Quality* refers to the degree to which products or services meet or exceed customer expectations and requirements. This includes customer satisfaction, order fill rate, shipping accuracy, etc.
- *Costs* refers to all the financial indicators, such as inventory costs, labor costs, maintenance costs, etc.

- *Productivity* encompasses the efficiency of the use of resources. Productivity is the ratio of output to resource consumption (Frazelle, 2015). Examples are order-picking productivity, shipping productivity, etc.
- *Utilization* also encompasses the efficiency of the use of resources. However, utilization is the ratio of resource consumption to its capacity (Frazelle, 2015). Examples are storage space utilization, inbound-area utilization, etc.

The distinction between productivity and utilization is ambiguous in literature. As stated, both dimensions have a resource-related character. However, since the definitions of Frazelle (2015) make a clear distinction, which does measure different aspects of performance, we regard them as separate dimensions.

Table B.4 in Appendix B shows the classification of 38 indicators in different dimensions based on an extensive literature of 43 publications by Staudt et al. (2015). It provides examples as background information on the performance dimensions.

3.2.3 Classification by Resources

An extra classification becomes relevant when assessing the performance of the productivity and utilization dimensions. As explained, both of these dimensions focus on resource consumption. Several articles also use a resource-based classification of performance indicators.

Staudt et al. (2015) distinguishes labor and equipment & building as two resources. Karim and Shaiful Fitri (2018) and their later work (Karim et al., 2020) extend the model of Staudt et al. (2015) by separating equipment and building. Furthermore, they add the WMS as an extra resource. Figure B.1 in Appendix B shows this resource based classification.

Although other articles in literature do not extensively use a resource-based classification, the stated resources are generally applied in indicators used to assess the productivity and utilization in almost all literature about warehouse performance, from textbooks ((Bartholdi and Hackman, 2019), (Frazelle, 2015), (Frazelle, 2002a)) to literature reviews (Staudt et al., 2015).

In short, the four resources consumed by a warehouse are:

- *labor*: the hours worked by the warehouse personnel
- *space*: the physical locations where products are stored and handled
- *equipment*: the MHE used to handle the products
- *Warehouse Management System (WMS)*: the digital system described in Appendix Section A.5

3.2.4 Classification by Activities

Another basic classification of warehouse performance indicators is based on the warehouse activities. Frazelle (2002a) already made this distinction based on receiving, put-away, storage, order picking, and shipping. His classification is shown in Table B.3 in Appendix B. This classification often specifies well-defined boundaries for the warehouse performance indicators.

Other researchers do not use the activity-based classification like Buonamico et al. (2017), Hackman et al. (2001) and Johnson and McGinnis (2010). However, these performance assessments are often very generic, i.e., expressed in one or a few indicators, or very complex, i.e., expressed in multiple indirect indicators. Both extremes will complicate quickly identifying promising warehouse performance optimization measures.

An activity-based classification is extensively studied and widely used to assess warehouse-wide performance. Publications from Cormier and Gunn (1992), van den Berg and Zijm (1999), Gunasekaran et al. (1999), Kiefer and Novack (1999), Gu et al. (2007), Rimiene (2008), Karagiannaki et al. (2011), Cagliano et al. (2011), Gallmann and Belvedere (2011), Lao et al. (2012), Yang and Chen (2012), Ramaa et al. (2012), Mentzer and Konrad (1991), Ellinger et al. (2003), Wu and Hou (2009), Lu and Yang (2010), Sellitto et al. (2011)) all encompassed the entire warehouse process with their activity classification. Staudt et al. (2015) derived the receiving, storage, picking, shipping, and delivery activities from all these papers.

Although extensively studied, there is still no unambiguous distinction between definitions of these activities. For example, Frazelle (2002a) uses the term storage to describe the products being in their storage location. In contrast, Staudt et al. (2015) uses storage to describe the movement of products to their storage location (regarded as put away by other researchers, including Frazelle (2002a)). Besides, some researchers like Adedu et al. (2023) include packing as a main activity between order picking and shipping.

Since this classification is used to determine the boundaries for the indicators and definitions in literature are ambiguous, it is important to define the activities again for this research.

Appendix Section A.3 describes the main and optional warehouse activities in more detail. The activities for the activity-based classification encompass activities that occur in a typical warehouse according to Bartholdi and Hackman (2019) and consume a significant amount of resources. We distinguish six main activities.

- *Receiving*: operations that involve the assignment of trucks to docks and the scheduling and execution of unloading activities (Gu et al., 2007).
- *Put-away*: the movement of products from the unloading area to its designated storage place (Mentzer and Konrad (1991) and Yang and Chen (2012)).
- *Storage*: although not exactly an activity, storing products requires significant resources like space and equipment. Besides, managing performance indicators like storage time is key in warehouse performance (Gallmann and Belvedere, 2011).
- *Replenishment*: product transfer from reserve storage area to forward pick area (Manikas and Terry, 2010), to prepare for the order picking of less-than-pallet units of measure.
- *Order picking*: the process of obtaining the right amount of the right products for a set of customer orders (Koster et al., 2007). This is the main and labor-intensive activity of warehouses (Dotoli et al., 2009).
- *Shipping*: execution of packing and truck's loading after picking, also involving the assignment of trucks to docks (Gu et al., 2007).

3.3 Identifying Opportunities for Optimization

The next step in a warehouse optimization strategy is to link performance measurement to opportunities for optimization. This section describes the method to identify these opportunities for optimization.

3.3.1 Activity Profiling

One of the main methods to identify opportunities for optimization is *activity profiling*. Frazelle (2015) explains Activity Profiling as the "systematic analysis of item and order activity, seeking to identify and take advantage of patterns of opportunity". Applying correct profiling contributes to "highlight the root cause of material and information flow problems, pinpoint major opportunities for process improvements, and provide an objective basis for project-team decision making". Bartholdi and Hackman (2019) phrase it as "the careful measurement and statistical analysis of warehouse activity". They emphasize its relevance as "a necessary first step to almost any significant warehouse project".

Frazelle (2015) distinguishes a range of warehouse activity profiles based on years of experience, a proprietary pattern recognition algorithm, and a supply chain data warehouse. Figure 3.1 shows the organization behind these profiles. The term Profile refers to a scoped focus area for activity profiling. All profiles contribute to certain aspects of identifying opportunities for optimization.

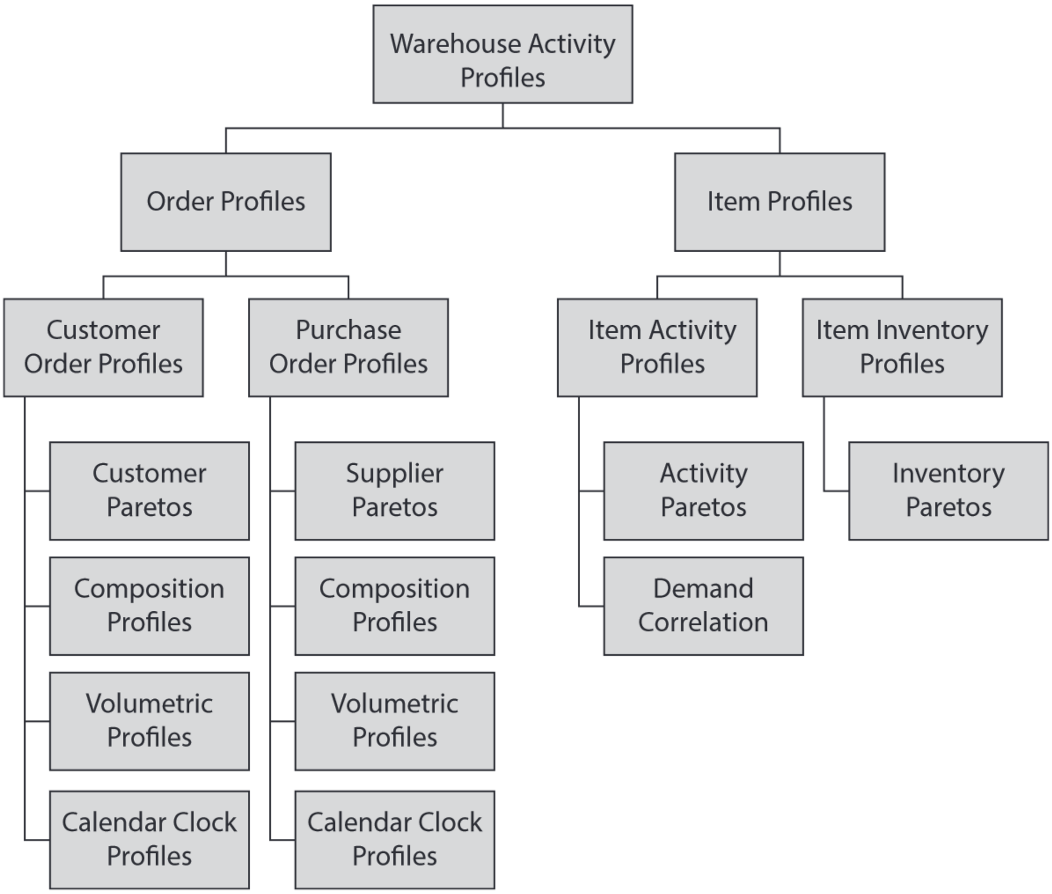

Figure 3.1: The organization of the warehouse activity profiles by Frazelle (2015)

The value of these activity profiles in identifying opportunities for optimization can be best described with some examples. These examples from Frazelle (2015) show how systematic analysis and pattern recognition leads to this identification. In these examples, the opportunities for optimization are directly linked to proposed optimization measures as well:

- A full/partial-pallet mix profile is an example of a handling-mix profile, which is part of the composition profiles as part of the customer order profiles in Figure 3.1. If only a small part of the orders requires a mix of full and partial pallets, this suggests an opportunity for optimization for separate areas in the warehouse layout.
- An hour-of-day distribution profile for dock-door receiving activity is an example of a calendar clock profile as part of the purchase order profiles in Figure 3.1. Offsetting peaks in such a profile suggest an opportunity for optimization in labor planning. This can be exploited with shift staggering (i.e., workers start and finish work at different times) or inter-

department workforce shifting (i.e., workers move from departments with a low workload to the receiving department during peak periods.

Although these activity profiles provide valuable insights and result in the proposition of relevant optimization measures, the focus lies on identifying patterns without quantifying performance. A full/partial-pallet mix profile may suggest separate areas in a warehouse, but how much time or cost would it save? Also, shift staggering may increase productivity or idle time of employees, but which improvement can we expect? These questions are not answered with activity profiling alone.

The lack of a direct link with indicator-based performance assessment causes this. This makes it hard to asses which performance indicators can be improved, especially to which extent, based on these activity profiles only. This inability to link the activity profiles with a quantifiable performance improvement is a disadvantage of the way profiling is currently done by researchers like Frazelle (2015) and Bartholdi and Hackman (2019).

3.3.2 Benchmarking

According to Bartholdi and Hackman (2019), there are two main approaches in evaluating a warehouse: one is comparing measured performance with an ideal expressed as a mathematical model, and the other is comparing it with an actual warehouse to suggest achievable standards. They state that, in general, there is not much to learn from the ideal because it might not be practical and it lacks the pathway for practical implementation.

This means it makes more sense to use *benchmarking*, which is the "comparison of one warehouse with others" (Bartholdi and Hackman, 2019). This is another method to identify opportunities for optimization. It comprehends "the process of systematically assessing the performance of a warehouse, identifying inefficiencies, and proposing improvements" (Gu et al., 2010). Another way to phrase it is that "benchmarking is the process of gathering and sharing assessments of the performance of some aspect of an organization. It may include developing an improvement plan of action based on the assessment" (Hackman et al., 2001). Benchmarking contributes to bridging the gap from performance assessment to optimization measures. We combine the definitions and refer to the term Benchmarking as the process of systematically (a) identifying best practices, (b) calculating performance gaps, (c) determining improvement potential, and (d) selecting target optimization areas.

According to Frazelle (2002b) and Bartholdi and Hackman (2019), there are three main perspectives of benchmarking: internal, external, and (external) competitive. Internal benchmarking is done within a single company. External benchmarking is done using the same process in another industry. (External) competitive benchmarking is a comparison within the same industry. CH Consulting Group (2021) describes the main aspects of internal and external (including competitive) benchmarking:

Internal Benchmarking

Internal benchmarking requires comparing a company's data against its own performance. This process often involves analyzing the effectiveness of various organizational locations or departments to discern successful strategies from less effective ones. Systematic collection and analysis of this data are essential for establishing optimal operating practices and creating a uniform standard across the company. Regular updates and monitoring of this data are crucial for evaluating the organization's progress and assessing current and past performances.

A thorough internal examination of organizational practices enhances functionality across different departments and facilitates improved communication and outcomes. Once a comprehensive understanding of internal data and operations is achieved, the focus can shift to external benchmarking, allowing for a comparison of the company's practices and performance with those of other entities in the industry.

Durst and Binder (2006) provides a complete framework for the internal benchmarking process. Figure 3.2 shows all three phases: planning, analysis, and implementation, and the nine steps of the benchmarking process. Chapter 4 describes how these steps are implemented in the solution design for this research. It also states the explanation of the Critical Success Factor (CSF)s and definitions of the KPIs.

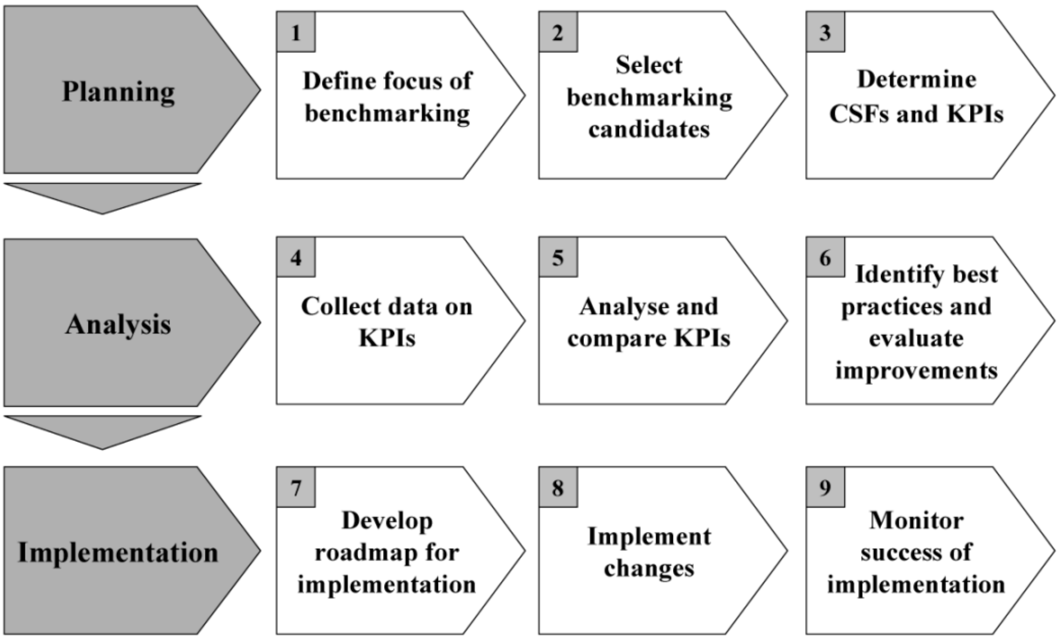

Figure 3.2: Internal benchmarking process - phases and steps (Durst and Binder, 2006)

External Benchmarking

External benchmarking goes beyond what internal benchmarking does by comparing your company with others in the industry. Keeping departments or locations competitive with each other is good for constant improvement. However, comparing your data with similar industries or businesses helps you understand how successful your company is and where it can grow.

The most used method for external benchmarking is found to be Data Envelopment Analysis (DEA) (Hogenboom, 2017). DEA would allow a particular warehouse to be compared to a large set of other warehouses. DEA would construct a hypothetical composite warehouse from the input and output data for all other warehouses, and this composite warehouse would be compared to the candidate warehouse (McGinnis et al., 2002).

Internal Versus External Benchmarking

CH Consulting Group (2021) compares internal and external benchmarking. The advantage of internal benchmarking is that it is typically easier to accomplish than external. This is primarily due to the greater accessibility of internal data within an organization, in contrast to the often limited or non-disclosable data available from external entities. Besides, for the DEA approach of external benchmarking to work efficiently, it requires many warehouses for comparison purposes. It is generally advised that the database should contain at least three to four times the number of warehouses as the number of individual inputs and outputs present in the DEA model. For example, if the model uses six input variables and four KPIs as output, the model should contain data from 24 to 30 warehouses. On the other hand, external benchmarking facilitates the identification of emerging trends and prevalent practices within a specific industry, offering insights that may be overlooked through solely internal benchmarking.

3.4 Statistical Analysis of the Performance Gap

When the opportunities for optimization are identified, this provides the input for selecting applicable optimization measures. Optimization measures are logically prioritized by their potential impact in terms of the improvement potential. The improvement potential theoretically is the largest, whereas the performance gaps are the largest.

Performance gaps are often quantified by absolute comparison between instances of analysis. For example, if an employee in Warehouse A can pick x products per hour, and an employee in Warehouse B picks $y = x - \delta$ products per hour, the performance gap of the employee in Warehouse B is δ picks per hour. This theoretical difference provides some insight into the opportunity for optimization. Still, it lacks insight into the relationship between the employee as the Independent Variable (IV)s and the picks per hour as the Dependent Variable (DV)s.

This is why, for example, Faber et al. (2017) and Johnson and McGinnis (2010) substantiate the relevance of performance gaps with statistical analysis. When the analyzed instances as IVs have a significant statistical relationship with the performance as DVs, the calculated performance gap is regarded as an opportunity for optimization. The term Statistical Significance refers to the extent to which the instance's value (the Independent Variable (IV)) influences the value of the analyzed performance indicator (the Dependent Variable (DV)) (i.e. how much an instance relates to the measured performance. This means certain opportunities for optimization are disregarded when the analyzed variables lack a statistically significant relationship with the performance. In other words, we want to answer the question: is the underperformance of the analyzed warehouse instance caused by that instance? Or is the underperformance mostly influenced by other variables?

We already distinguished the Dependent Variable (DV) and the Independent Variable (IV). The term Dependent Variable refers to a variable whose value and variation depend on that of another, here the variable used for performance measurement (e.g., productivity). The term Independent Variable (IV) refers to a variable whose value and variation do not depend on that of another, here used for the variable defining a profile (e.g., the client number or name of an employee).

The performance indicators of the different classifications stated in Section 3.2 are the DVs of the analysis, i.e., the measured performances are the outcomes. All the variables in our WMS-data that may influence this performance are the IVs, e.g., the type of product picker or the employee who picked it.

Since we deal with multiple Independent Variable (IV)s that influence the value of the Dependent Variable (DV)s, we have to use a *multivariate analysis*. According to Randolph and Myers (2013), the focus of multivariate analysis methods is on multiple variables. It is a collection of statistical techniques used to examine and make inferences about the relationships between variables.

Randolph and Myers (2013) describes three main methods of multivariate analysis: *multiple linear regression analysis*, *Analysis of Variance (ANOVA) and Analysis of Covariance (ANCOVA)*, and *path analysis*. Often these methods are used to support making inferences about causality between variables. ANOVA and ANCOVA, and path analysis are special types of multiple linear regression analysis. We analyze which method is most suitable for our model.

- *Multiple linear regression analysis* is a set of statistical procedures designed to examine relationships between multiple IVs and one DV. It is a form of correlation analysis. With the IVs we analyze, we can assess how much of the variance in the DV is explained by each of the different IVs. It is the most general form of multivariate regression analysis. However, it must still meet several assumptions to provide valuable results.
- *ANOVA* and *ANCOVA*, and multiple regression analysis operate under the presumption of a linear association between the IVs and the DV. However, these methodologies diverge in several significant aspects (Keith, 2006). Specifically, (multiple) linear regression models incorporate IVs measured across various levels (i.e. nominal, ordinal, interval, and ratio), whereas ANOVA primarily focuses on IVs at the nominal level. Moreover, multiple linear regression often entails evaluating the effects of multiple IVs, whereas the number of IVs in ANOVA is more constrained. Additionally, ANOVA is frequently employed in intervention studies to assess a particular treatment's effect on an outcome. In contrast, linear regression analysis is applicable in observational studies to describe the nature of existing relationships.
- *Path analysis* comprises a suite of statistical techniques that scrutinize linear and causal connections among variables. Defined by Bohrnstedt and Knoke (1994) as "a statistical approach that processes quantitative data to provide empirical estimations of variable influences within a presumed causal framework," it has much in common with multiple linear regression analysis, notably in its treatment of linearity within causal links. Serving as an expansion of multiple regression analysis, path modeling facilitates a more comprehensive exploration of the interrelations between IVs and the DV in a given model. A distinctive feature of path analysis is its capacity to examine not just direct effects but also total and indirect effects, thereby enhancing the legitimacy of causal assertions regarding the variables in question.

3.5 Scoping the Set of Optimization Measures

This research does not study the eventual decision of the optimization measure. However, it does study the last step between the target optimization area and the decision of the optimization measure, the determination of this scoped set of optimization measures.

When we identified a target optimization area, where the performance gap is statistically significant, it means the data shows optimization could be valuable. Warehouse Education and Research Council (WERC) (2008) states that after the quantitative analysis, this last step of scoping the set of optimization measures requires alignment with the client. Quantitative data provides interesting and relevant insights, but in the end, every case requires some qualitative analysis to confirm these insights.

This qualitative analysis is often done during a meeting with the client to assess the applicability of the set of optimization measures. The goal is to check the current implementation status of certain optimization measures and to determine whether some restrictions block the applicability of the proposed optimization measures.

This qualitative analysis is often in the form of asking questions to the client. 4Supplychain already has a list of 140 questions that check for the implementation status of optimization measures as explained in Section 2.2.2. This forms the theoretical basis for a narrow set of questions applied to each possible target optimization area.

3.6 Summary

Selecting the right KPIs is essential in warehouse optimization. Choosing drillable, simple, actionable, and accountable KPIs is important. When placed in a good framework, measuring these KPIs could identify performance gaps that support the identification of opportunities for optimization. KPI exploration can be approached manually, selectively, and predicatively. Selective exploration fits a semi-automatic approach based on existing classifications.

Extensive work has been done on developing classifications for warehouse performance indicators in the literature. Indicators are classified as direct versus indirect, by dimension, resources, and warehouse activity. Classification and indicator definitions are ambiguous in the literature, however, using them in a clearly defined way supports framing the performance optimization and increases stakeholder understandability.

Several methods exist to identify opportunities for optimization in warehousing. Activity profiling is a proven concept in literature for identifying operational patterns that may lead to opportunities for optimization. However, this is not directly linked with the indicator-based performance assessment. Benchmarking is used to assess performance, identify inefficiencies, and scope the set of optimization measures as well. It does so by identifying the best practice, calculating the performance gaps, determining improvement potentials, and selecting the target optimization areas.

Determining the target optimization area is usually done by prioritizing the performance gaps to find the greatest opportunities for optimization. However, the performance gaps are often only quantified absolutely. This absolute benchmarking can be extended by analyzing the influence of the Independent Variable (IV)s of a dataset on the Dependent Variable (DV)s. For internal benchmarking, this means identifying if the analyzed instances have a significant statistical relationship with the value of the performance indicators. A multivariate statistical analysis, multiple linear regression analysis, can fulfill this task.

The last step towards a narrow scope of optimization measures is qualitative. It consists of deploying questions based on the target optimization area. A theoretical basis for this is the list of 140 questions of warehouse performance analysis from 4Supplychain's.

In short, the challenges for this research are to:

1. apply semi-automatic KPI selection based on existing warehouse indicator classifications to determine the suitable KPIs for the operational-data-driven warehouse performance analysis model
2. combine the advantages like pattern recognition, level of detail, and structure of activity profiling with the advantages like quantification and comparability of the indicator-based performance analysis of benchmarking, supported by statistical analysis, to generate an automated identification of opportunities for optimization
3. match the opportunities for optimization to a specified set of follow-up questions that scope the set of promising optimization measures.

The completion of these challenges can contribute in both academic and practical terms. First, to the best of our knowledge, this KPI selection based on the scoped input data is unknown in academic literature. Second, combining the advantages of activity profiling with internal benchmarking and statistical relationship analysis to determine a narrow scope of optimization measures has not been automated before. This critical KPI-review and selection is an addition as a classification framework to the literature. The new performance analysis method aims to practically contribute to efficient warehouse optimization consulting.

Chapter 4

Solution Design

This chapter explains how the solution should be designed. The solution design is based on the combination of findings in the introduction in Chapter 1, the context analysis in Chapter 2, and the theoretical framework in Chapter 3.

The sections of this chapter follow the flow of the solution design. Section 4.1 describes the scope of the improvement in the warehouse optimization strategy. Section 4.2 discusses the decisions made in the process performance measurement (research objective 1). Section 4.3 explains the method to identify opportunities for optimization (research objective 2). Section 4.4 describes how we find the narrow scope of optimization measures (research objective 3).

4.1 Scope of the Improvement of the Strategy

This section explains the scope of the improvement in the warehouse optimization strategy. Section 4.1.1 explains which phase and steps of the whole warehouse optimization strategy are improved and which parts are covert by the automated operational-data-driven performance analysis model. Section 4.1.2 describes the scope of the standard warehouse suitable for the model.

4.1.1 Performance Analysis Focus

The introduction in Chapter 1 and the context analysis in Chapter 2 describe the issues of 4Supplychain regarding the first phase of the warehouse optimization strategy, the performance analysis phase. Since the current strategy does not fulfill the needs in this phase, the focus for improvement of the strategy is on this performance analysis phase.

Figure 4.1 shows how the steps of the current strategy are connected to the three objectives 4Supplychain wants to achieve in this performance analysis phase. The current connection between the steps and the objectives has no logical flow but is intertwined. This is why we propose a more chronological, eight-task flow of the new performance analysis phase, which fits the three objectives of 4Supplychain. These eight steps are the tasks to be carried out for a complete warehouse performance analysis.

Except for the first task, gathering operational data, and the last task, proposing the optimization measures, all tasks can be automated efficiently and standardized. This solves the issues that 4Supplychain encounters regarding wasted time with their current performance analysis part of the strategy. The rest of this chapter explains the exact methods chosen for these tasks with the performance analysis model.

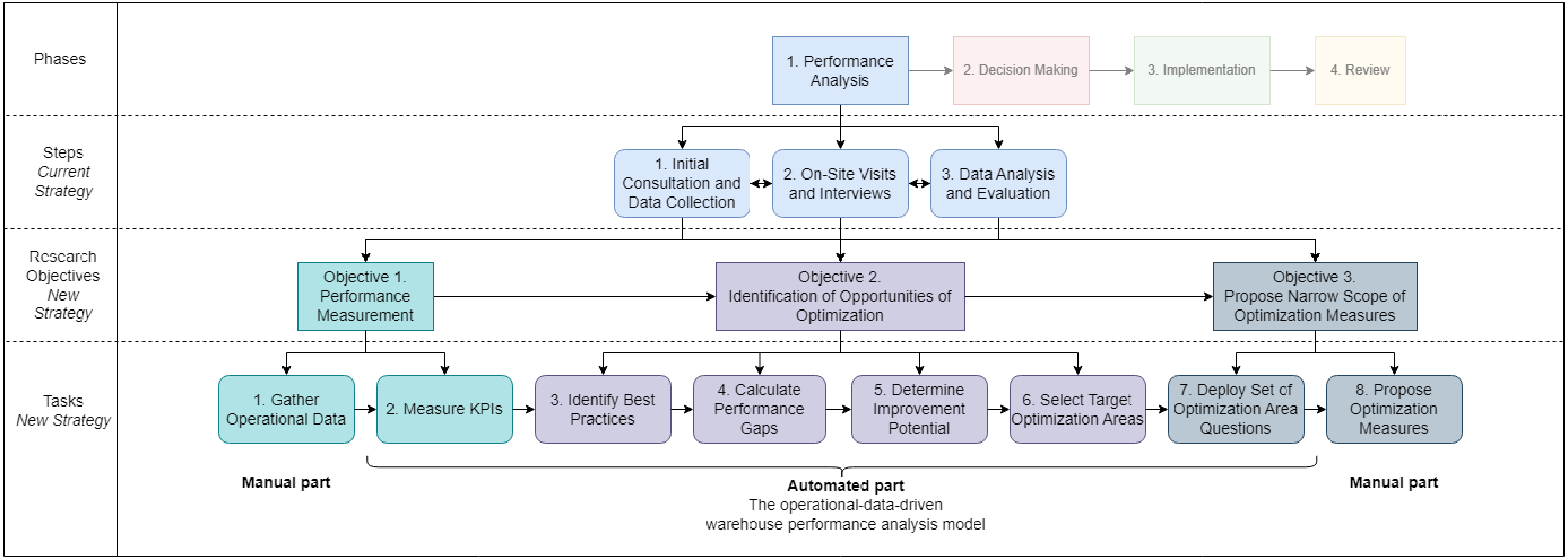

Figure 4.1: The improvement in the warehouse optimization strategy focuses on the performance analysis phase. Instead of three steps alternating in order and frequency, the new strategy consists of eight more specified chronological tasks, directly matching the research objectives.

4.1.2 The Standard Warehouse Characteristics

The goal is to standardize and automate the warehouse performance analysis with a model. However, warehouses can differ greatly, and not all exceptions fit into the standardized model. The performance analysis model only works for a warehouse with the standard characteristics described in this section. We consider the warehouse size, the product flow, the WMS-features and -data, the equipment, customers, units of handling, and storage strategies.

Warehouse Size

We disregard small-size facilities since these often lack the scale or the level of complexity that necessitates extensive data analysis. 4Supplychain seldom takes on projects regarding small-size facilities. This means our standard warehouse is medium to large-sized ($> 8,000m^2$).

Product Flow

We assume a standard flow of products in our warehouse that encompasses the main activities described in Appendix Section A.3. Figure 4.2 shows the standard warehouse flow and activities. The standard warehouse does not regard the cross-docking process, where products are shipped shortly after receipt, without storage. Besides, in the standard warehouse, the VAPs are not a significant part of the warehouse operations.

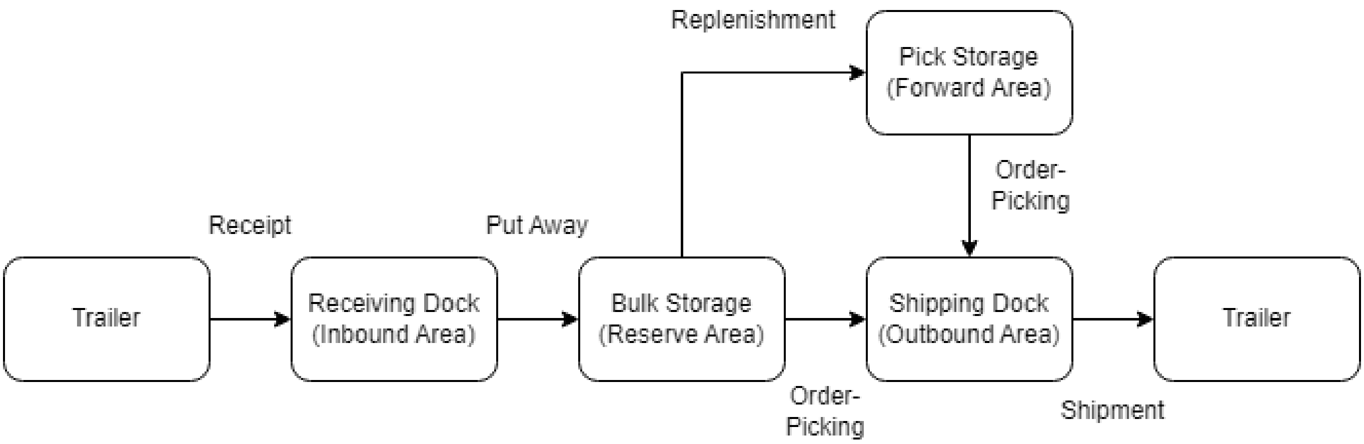

Figure 4.2: Standard warehouse flow and activities

WMS-Features and -Data

Last, the standard warehouse utilizes a WMS with at least the basic features displayed in Table A.1 in Appendix Section A.5.1. The application of these functions ensures the system creates the operational data necessary to use as the main input for the performance analysis model. Besides creating and utilizing this data, the system should be able to log and export it. Essential WMS-data types are:

- location master
- product master
- goods receipt
- shipments
- stock levels

- inventory adjustments

With these datatypes, the flow of products over time can be assessed in relationship with attributes of the activities, which is essential for performance analysis. Other datatypes like extra master data (equipment master, employee master, etc.), work data (picking tasks, put-away tasks, etc.), and configuration data (workflow settings, rules for order picking, etc.) could improve the level of performance analysis but are not essential to our standard warehouse.

Equipment

The standard warehouse may utilize different types of storage and handling equipment. Most types described in Appendix Section A.4 do not influence performance analysis. Only a high level of automation like a AS/RS or complex conveyor systems require a different approach, which is not within the scope of this research. The standard warehouse has a low to medium level of automation.

Customers, Units of Handling, Storage Strategies

Our standard warehouse may serve different types of customers, handle various handling units, and implement multiple storage strategies. These warehouse characteristics should not influence the application of the model. However, it is important to consider them when interpreting and comparing results across different warehouses.

4.2 The Performance Measurement

This section describes how the first two tasks of the improved strategy of Figure 4.1 are carried out to complete the performance measurement as the first objective. The first task, gathering the operational data, is simply a manual request to the client to provide WMS-exports for the essential data types stated in Section 4.1.2. The second task, measuring the KPIs, requires more research.

An important step in measuring the KPIs is the selection of the correct KPIs that fit the scope and goal of the model and define them clearly without room for different interpretations. Section 4.2.1 elaborately discusses which indicators classifications suit this research. Section 4.2.2 define all performance indicators measured by the model.

4.2.1 The Selected Performance Classifications

This section explains which classifications of KPIs are included in the KPI-selection. It assesses the relevance of each classification and the suitability to be included in the model. These classifications serve as the framework for the semi-automatic KPI-selection described in Section 4.2.2.

Each part of this section examines different types of classifications of performance indicators, which are stated in Section 3.2. First, we assess direct versus indirect classifications. Second, we evaluate the different dimensions of indicators. Third, we consider the resource classifications, and fourth, the activity classifications.

Direct versus Indirect Classifications - Selection of Direct-Indicators

This distinction between direct and indirect indicators is important to assess their suitability in the operational-data-based performance analysis model. Operational warehouse data, as described in Appendix Section A.5, is limited to quantifiable elements from which the direct indicators can be assessed. On the other hand, the indirect indicators often involve a certain qualitative assessment, which cannot easily be derived from the operational data files.

Besides, the equations for indirect indicators are often not available or too difficult to calculate (Staudt et al., 2015). Some examples are warehouse capability (Sohn et al., 2007), the supervisory coaching behavior (Ellinger et al., 2003), the customer perception (De Koster and Balk, 2008), etc. Because the intention of 4Supplychain is still to conduct a quick general performance assessment, the indirect indicators are regarded as unsuitable. This research will focus only on direct indicators and leave the indirect indicators out of scope.

Dimensions Classifications - Selection of Time, Productivity, and Utilization

From transaction, inventory, and work data of a WMS, it can be derived *when* and *where* activities are carried out. The master data encompasses the capacity of labor, space, and equipment. These data categories are directly related to time, productivity, and utilization performance measurement. For example, the receiving time can be measured between a truck's arrival and the last pallet unloaded. Order picking productivity can be measured in the number of picks per labor hour. Space utilization can be measured as the percentage of storage locations filled over time.

On the other hand, it is hard to assess the performance of the quality dimension based on operational WMS data. Transaction data shows all the jobs carried out in the warehouse but not the jobs that may have been requested by a customer. Work and inventory data only show the tasks or movements and how they are registered, but it does not show if different products have been picked than registered. Indicators like customer satisfaction or shipping accuracy cannot be derived from these sources.

The same goes for cost performance measurement. Most operational WMS data is not linked to financial data. Indicators like inventory, order processing, or labor costs cannot be assessed directly from the operational data. This could be explained by the affirmation of Gunasekaran and Kobu (2007) that the operational-level performance evaluation is mostly based on non-financial indicators.

4Supplychain is interested in the extent to which this operational 'data dump' can be quickly used for performance assessment. The performance dimensions that best fit this assessment form are time, productivity, and utilization. Although the quality and cost dimensions cannot be neglected, the focus of this research will be limited to the time, productivity, and utilization dimensions.

This focus can be further substantiated by the fact that productivity is the most popular performance dimension in warehousing (Frazelle, 2015). Staudt et al. (2015) also states that productivity (including utilization) is a relatively important performance dimension. Besides, Bartholdi and Hackman (2019) state that an initial focus on costs may complicate the productivity improvement process, while productivity improvement often eventually leads to cost improvement. This is because productivity improvements may require initial financial investments with a certain risk on eventual profit. From a cost perspective, this can create resistance, while a productivity perspective emphasizes efficiency gains.

Johnson and McGinnis (2010) distinguishes performance measurement into economic (revenue—and cost-related) and technical (productivity-related) measurements. They state that economic performance measurement is more difficult because warehouses often do not directly generate revenue because of their supportive function in a supply chain. Besides, costs may vary significantly across warehouses because of economic-geographical reasons, which makes comparison difficult. Technical measurements based on output generated and resources consumed tend to give a clearer picture of operational performance.

Additionally, costs do not have to be directly considered with performance indicators but can also be considered input parameters. We can relate this to labor hours and holding costs when we know possible savings in labor productivity or extra space utilization. This way, we can still express productivity and utilization improvements in terms of costs.

Although it may be argued that the cost dimension can be postponed in a first quick performance assessment, the quality dimension is of higher importance. Some researchers like Manzini (2012) suggest that performance of the time dimension can be regarded as part of quality performance, which is a good reason to include the time dimension. However, this does not regard the overall quality dimension.

The operational data-driven performance assessment model will focus on the dimensions of time, productivity, and utilization. The productivity and utilization dimensions are regarded as the most relevant, and all three dimensions are feasible to assess within the model scope. The quality and cost dimensions are also regarded as relevant; however, they are less feasible.

Resources Classifications - Selection of Labor and Space

As explained in Appendix Section A.5, the master data of a WMS could include the employee master, the location master, and the equipment master. Theoretically, the capacity of these resources can be derived from these files. In addition, it can be derived from inventory adjustment data *when* and *where* activities are carried out, but also *who* does it. This means the resource consumption is measurable as well.

From performance assessments in the literature, it becomes clear that the focus lies on labor and space productivity and utilization. Frazelle (2015) and Bartholdi and Hackman (2019) only state these two resources as the main resources of a warehouse. From the 43 articles analyzed by Staudt et al. (2015), no indicator regards the WMS as a resource. Only one indicator mentions one equipment-related indicator. 4Supplychain confirms the importance of the priority of labor and space resource performance assessment.

In addition, 4Supplychain mentions the lack of completeness of operational equipment data in practice. Where location (space-related) master data and user (labor-related) data use is common practice, this is not always the case for equipment. Using operational data, it can be complex to measure the consumption or capacity of equipment as a resource. Furthermore, the equipment master data is not always as available as the location and product master.

Besides, it is also complex to measure the performance of the WMS as a resource. The capacity and consumption are not easily quantifiable. Measuring this will include indirect indicators, which are unsuitable for the performance assessment model as explained in Section 3.2.1.

For resource classification, we use labor and space as separate classes. Capacity and consumption can be quantified from the operational data. Besides, one of the main warehouse management tasks is to divide resources among activities, which is why there is extra value in classifying these distinct resources.

Activity Classifications - Selection of Receiving, Put-Away, Storage, Replenishment, Order Picking and Shipping

Since an activity-based classification is widely used in literature and contributes to specifying the indicators' boundaries, it is also regarded as relevant. Besides, 4Supplychain's clients are very familiar with this activity-based thinking. When the performance assessment model uses indicators in the same classification, this will contribute to 4Supplychain's communication process with its clients.

We select all six main activities of the warehouse operations: receiving, put-away, storage, replenishment, order picking, and shipping. With this selection, there are four remarks worth mentioning in comparison with other activity-based classifications:

- The delivery process as an activity is disregarded in this classification. Although mentioned by several articles in the literature, we regard delivery (transport) as an external activity compared to the other warehousing activities. This activity is excluded because operational delivery data is often stored in a Transport Management System (TMS) rather than a WMS. Besides, the responsibility for delivery performance regularly lies (partially) with external parties, so it is not the main focus of warehouse management.
- The replenishment activity is added. While this activity is disregarded or covered by the order-picking activity in most literature, we examine it separately. According to Bartholdi and Hackman (2019), it is a typical warehouse activity that consumes significant resources like labor, space, and equipment. Separating this activity also contributes to setting clear boundaries for the order-picking indicators. In practice, replenishment strategies also differ from order-picking strategies.
- Typical activities that often occur but do not consume significant resources are placed under one of the main activities. For example, the checking activity before shipments can be part of the order picking or the shipping activity. This depends on practical applications in a warehouse and should be stated case by case.
- Activities that are not typical and do not often occur, like VAPs as alterations, repackaging, and assembling, should also be regarded case by case. The basic performance assessment model does not include them. Extensions of the model can be made where these activities could be added under one of the main activities or as a separate activity.

4.2.2 The Performance Indicator Selection and Definitions

This section defines all selected indicators that match the classifications determined in Section 4.2.1. First, it explains the units of measure applied to the indicators, which differ per activity. Second, the exact definitions of each category of indicators are stated. The term Category refers to a combination of several classifications, resulting in a specific type of performance indicator(s). The definitions for one or more indicators are stated if the category is assessed as relevant and applicable. Third, we state the Critical Success Factor (CSF) for each classification of performance indicators. The CSFs define the goals for the performance indicators.

Units Of Measure

Indicators can often be measured in several units of measure. To define the exact indicators used, it is important to determine which unit of measure is relevant for the different activities.

Activities all encompass the *output* of physical units of measure applied in a warehouse. According to Staudt et al. (2014), most activities in a typical warehouse can be measured in pallets. However, order picking is measured per order line, and shipping is measured per order line and order.

We state a few small adjustments to the units of measure proposed by Staudt et al. (2014). Since we take the operational data perspective and not the customer perspective, we change the order line into a pick line and separate the bulk-area picks (pallets) from forward-area picks. Furthermore, we do not measure the shipping per order but per trailer. For comparison reasons, we also add the trailer as a unit of measure for the receiving activity. The term Trailer refers to one truckload of products, which generally are up to 33 pallets. The final units of measure we distinguish per activity are:

- receiving: per pallet; per trailer
- put away: per pallet
- storage: per pallet
- replenishment: per pallet
- order picking: per pallet (bulk storage) & per pick-line; per item (forward area)
- shipping: per pallet; per trailer

Time

Time can simply be measured in the time passed between the start and end of an activity. According to Staudt et al. (2014), the standard unit of measure is in hours. The time dimensions can be measured for each activity. Definitions for these indicators are extensively studied. Table 4.1 provides the indicator definitions of ten indicators in six time-activity categories.

A CSF for improvement in efficiency is short lead times (Durst and Binder, 2006). Since all time indicators can be regarded as lead times of a sub-process of warehouse operations, the goal for all time indicators is minimization.

Table 4.1: The performance indicators for the time dimension

Category	Nr.	Definition	Source
Receiving time	1 2	Unloading time of a trailer Unloading time of a pallet	Gu et al. (2007); Matopoulos and Bourlakis (2010)
Put-away time	3	Lead time since a product has been unloaded to when it is stored	Mentzer and Konrad (1991); Koster et al. (2007); Yang and Chen (2012)
Storage time	4	Inventory time e.g. inventory coverage	Staudt et al. (2014)
Replenishment time	5	Lead time to transfers products from reserve storage area to forward pick area	Ramaa et al. (2012)
Order picking time	6 7 8	Lead time to pick a pallet Lead time to pick a pick-line Lead time to pick an item	Mentzer and Konrad (1991)
Shipping time	9 10	Loading time of a trailer Loading time of a pallet	Staudt et al. (2015)

Labor Productivity

Productivity is the ratio of *output to resource consumption* (Frazelle, 2015). The output is defined per activity in Section 4.2.2. The *resource consumption* for labor is defined as the *amount of item-handling labor hours* (Staudt et al., 2014). This encompasses the total time warehouse employees work on the ground, excluding breaks.

The labor productivity can be measured for almost all activities. Only storage does not consume labor, so storage labor productivity is omitted. Again, definitions for these indicators are extensively studied. Table 4.2 provides the indicator definitions of nine indicators in five labor-productivity-activity categories.

According to Durst and Binder (2006), high productivity is a CSF for an efficient warehouse. Frazelle (2015) also states "we always want to maximize productivity". This means the goal for all labor productivity indicators is maximization.

Table 4.2: The performance indicators for labor productivity

Category	Nr.	Definition	Source
Receiving lab. prod.	11	Trailers unloaded per labor hour in receiving activity	Mentzer and Konrad (1991)
	12	Pallets unloaded per labor hour in receiving activity	
Put-away lab. prod.	13	Pallets put away per labor hour in put-away activity	Staudt et al. (2014)
Replenishment lab. prod.	14	Pallets moved per labor hour in replenishment activity	Staudt et al. (2014)
Order picking lab. prod.	15	Pallets picked per labor hour in bulk-picking activity	Mentzer and Konrad (1991) Kiefer and Novack (1999) De Koster and Warffemius (2005)
	16	Order-lines picked per labor hour in forward-picking activity	
	17	Items picked per labor hour in forward-picking activity	
Shipping lab. prod.	18	Trailers shipped per labor hour in shipping activity	Staudt et al. (2015)
	19	Pallets shipped per labor hour in shipping activity	

Space Productivity

For space, productivity is still the ratio of output to resource consumption. The output defined per activity is the same. We define the resource consumption for space as the *the amount of hours locations are used*. This encompasses the locations with a unique address in WMS, both storage locations and transit locations.

Space productivity performance is not as extensively studied in literature as time and labor productivity performance. This means that a more conceptual analysis of definitions and expert opinions is required to determine relevant indicators and definitions. This analysis also regards the different warehouse activities.

Measuring the space consumption for each activity is complicated since not all activities consume a clearly defined set of locations/spaces for a certain time. We find relevant appointed locations in the literature for receiving, storage, and shipping activities. These are, respectively, the inbound docks (and staging area), storage locations, and outbound lanes (and docks) (Frazelle, 2015). However, the literature does not provide distinct locations for put-away, replenishment, and order-picking activities.

The latter activities typically only encompass the movement of products without any storage or temporary staging during the activity. There is no significant measurable time when a location like a hallway is used for that activity. Besides, all these activities use locations like hallways interchangeably and simultaneously.

Experts from 4Supplychain support the distinction between these types of activities when considering space productivity. They emphasize the relevance of inbound docks, storage locations, and outbound staging areas, as they often recognize these as areas suitable for productivity improvements.

Because of these reasons, we omit put-away, replenishment, and order picking for the space productivity assessment. Table 4.3 provides the definition of five indicators in the three remaining space-productivity-activity categories as supported by 4Supplychain management.

Still, with the same reasoning as the CSF for labor productivity indicators, the goal for the space productivity indicators is maximization.

Table 4.3: The performance indicators for space productivity

Category	**Nr.**	**Definition**	**Source**
Receiving spa. prod.	20	Trailers unloaded per occupied inbound dock hour	4Supplychain
	21	Pallets unloaded per occupied inbound dock hour	
Storage spa. prod.	22	Palles stored per occupied storage location hour	4Supplychain
Shipping spa. prod.	23	Trailers shipped per occupied outbound lane hour	4Supplychain
	24	Pallets shipped per occupied outbound lane hour	

Labor Utilization

Utilization is the ratio of *resource consumption to its capacity* (Frazelle, 2015). The labor productivity part already describes the resource consumption for labor per activity. The *resource capacity* for labor is defined as the *total available workforce hours* (Frazelle, 2002a). This encompasses the maximum amount of Full Time Employee (FTE), the sum of all permanent employees' hours plus the maximum use of flex workers.

Ideally, labor capacity is measured per activity, just like labor consumption. For example, we need the total available workforce hours for the receiving activity. This way, the labor utilization of all activities can be measured independently.

However, in practice, assigning unconsumed labor capacity to a specific activity is often impossible. For example, if a warehouse employee does not work to his full capacity, it is hard to say to which activity his unconsumed hours should be assigned. Since there is little literature about labor utilization indicators, we propose a new method to define these indicators.

We propose determining the labor utilization for each activity as the activity-based labor consumption against the total labor capacity. For example, the receiving labor utilization is the number of labor hours in the receiving activity as a ratio of the total available workforce hours. This provides more insight into the overall resource utilization and the division of labor among the activities.

Table 4.4 provides the indicator definitions of six indicators in five labor-utilization-activity categories. Note that the units of measure are omitted since utilization has nothing to do with activity output. The only category that has a second indicator is order picking since we still distinguish the bulk-area (*b)* and forward-area (*f*). Again, storage does not consume labor, so this activity is omitted.

For utilization indicators, the CSF is not as straightforward as with time and productivity indicators. Frazelle (2015) states that utilization should not be minimized or maximized, because ”there are appropriate control limits for utilization”. This is generally applicable for indicators like storage space utilization but not for labor utilization.

Appendix Section A.3 describes the average labor division over the activities based on an analysis of Frazelle (1996). While this analysis provides insights into a logical labor division, this relatively old research cannot be considered a benchmark. Effective labor division depends highly on the detailed characteristics of a warehouse. This is why we regard the labor-utilization indicators as supporting indicators that do provide interesting insights but cannot directly be used for performance analysis by themselves since they do not have clear CSFs

Table 4.4: The performance indicators for labor utilization

Category	**Nr.**	**Definition**	**Source**
Receiving lab. uti.	25	Ratio of labor hours in receiving activity of total workforce hours	4Supplychain
Put-away lab. uti.	26	Ratio of labor hours in put-away activity of total workforce hours	4Supplychain
Replenishment lab. uti.	27	Ratio of labor hours in replenishment activity of total workforce hours	4Supplychain
Order picking lab. uti.	28	Ratio of labor hours in bulk-picking activity of total workforce hours	4Supplychain
	29	Ratio of labor hours in forward-picking activity of total workforce hours	
Shipping lab. uti.	30	Ratio of labor hours in shipping activity of total workforce hours	4Supplychain

Space Utilization

For space utilization, there are two views on the definition:

- The *ratio of occupied locations to the available locations* (Frazelle, 2015). Since this is normally measured over time, an average of multiple measurements provides the ratio. This can be regarded as the ratio of time (hours) a location is occupied. This definition fits with the definition of resource consumption previously stated in space productivity. It provides insight into the extent to which locations are used to their maximum capacity.
- The *rate of total space occupied by locations destined for a certain activity*. It considers space consumption as the physical space a location consumes of the total space capacity rather than the hours a location is used to its location capacity. This definition is based on Ramaa et al. (2012) and provides more insight into space division among the activities.

Both definitions give different insights into the warehouse space performance, so we decided to use both. All activities that consume clear, distinct locations, i.e., receiving, storage, and shipping as explained at space productivity, are assessed on the *time occupation of their locations* and the *space occupation of the total warehouse space*.

Table 4.5 provides the indicator definitions of six indicators in three space-utilization-activity categories.

For the space utilization indicators, the CSF is again not straightforward because utilization should be controlled between certain limits for which the values differ per indicator. Only for the ratio of storage locations occupied to available storage locations should the value be between 70% and 90% according to Frazelle (2015). The literature does not provide values for good practice for the other indicators. Still, we measure these ratios to analyze the influence of different utilization values on other performance indicators like productivity. For example, we may find that a certain value for a receiving space utilization often relates to a high receiving space productivity, which means this can be identified as best practice.

Table 4.5: The performance indicators for space utilization

Category	Nr.	Definition	Source
Receiving spa. uti.	31	Ratio of inbound docks occupied to available inbound docks	4Supplychain
	32	Rate of receiving area m^2 of total warehouse m^2	
Storage spa. uti.	33	Ratio of storage locations occupied to available storage locations	Frazelle (2015)
	34	Rate of storage area m^2 of total warehouse m^2	Ramaa et al. (2012)
Shipping spa. uti.	35	Ratio of outbound lanes occupied to available outbound lanes	4Supplychain
	36	Rate of outbound area m^2 of total warehouse m^2	

Indicators over the Classifications

This section assessed the categories of the classification framework and their relevance and applicability. Most categories are assigned one or multiple indicators, including their definitions based on literature and conceptual analysis, in consultation with experts at 4Supplychain. In total, this leads to 36 performance indicators classified by the categories. Figure 4.3 shows the final performance indicators related to their categories.

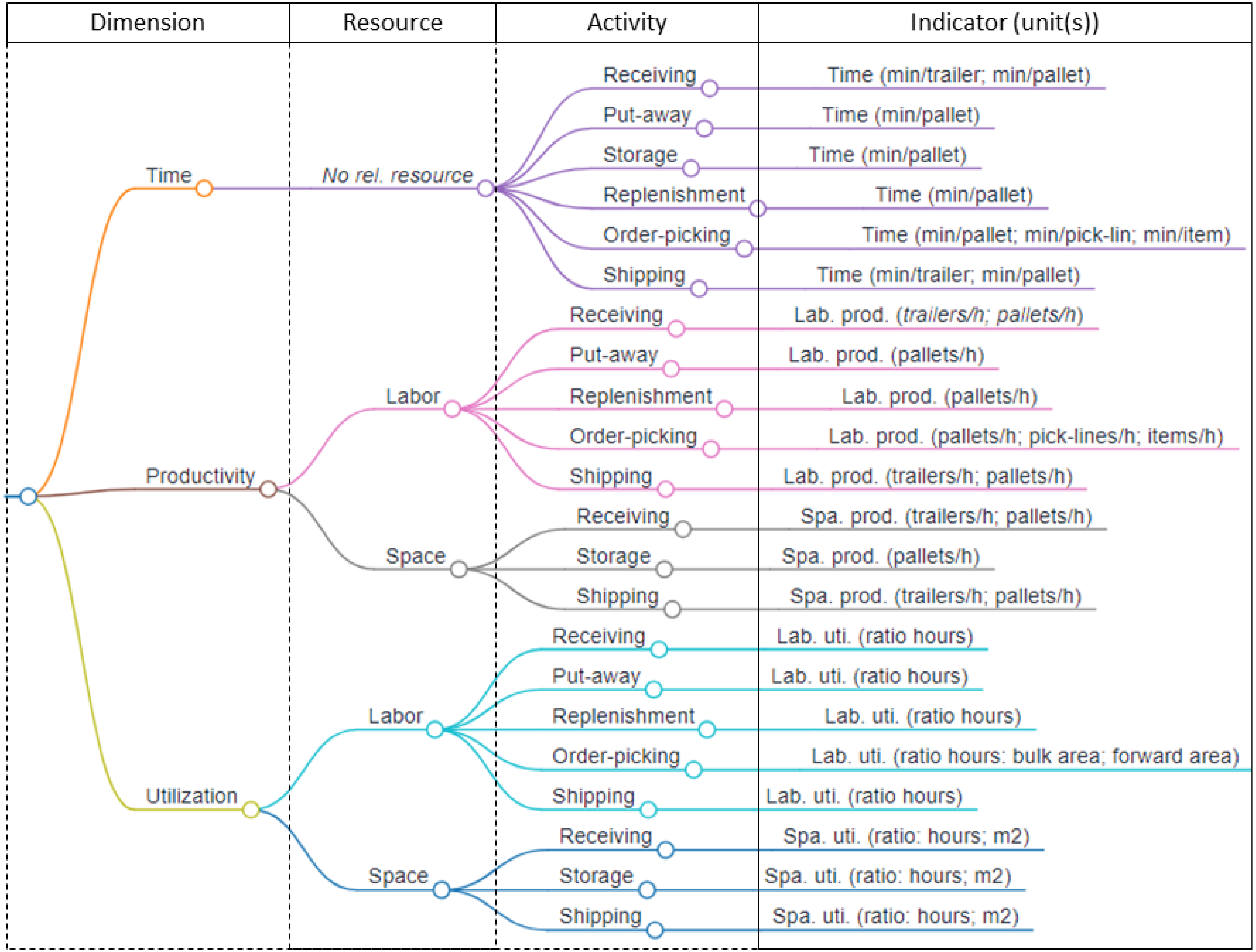

Figure 4.3: The 36 direct performance indicators classified by their categories

4.3 The Identification of Opportunities for Optimization

This section describes the method we apply to identify opportunities for optimization. First, Section 4.3.1 describes an addition to activity profiling, which forms a framework to structure the identification of opportunities for optimization. Next, Section 4.3.2 describes how benchmarking is applied to identify best practices and calculate performance gaps within this new structure. Last, Section 4.3.3 explains which statistical analysis method is applied to determine the significance of a performance gap and identify the target optimization areas.

4.3.1 Performance Based Activity Profiling

As described Section 3.2 and Section 4.2, extensive research is done in this indicator-based performance assessment by researchers like Staudt et al. (2015), Karim et al. (2020), and other authors stated in Section 3.2. The value of this approach is widely accepted, however, with these assessments, the focus lies on quantifying performance only. Its disadvantage is that it lacks a more detailed analysis of underlying patterns that lead to identifying opportunities for optimization.

Section 3.3.1 describes the method of activity profiling implemented by researchers like Frazelle (2015) and Bartholdi and Hackman (2019). The disadvantage is that there is no direct link with indicator-based performance assessment as described in Section 4.2.2. This makes it hard to asses which performance indicators can be improved, especially to which extent, based on these activity profiles only.

Since both activity profiling and indicator-based assessments have advantages and disadvantages, the question arises if using the best of both worlds is possible. To combine the advantages of activity profiling on the one hand and indicator-based assessment on the other hand, we propose a new perspective on activity profiling. Besides the two main categories of order profiles and item profiles shown in Figure 3.1, we propose to add the extra category of *performance based activity profiles*, or short *performance profiles*. The term Performance Profile refers to a scoped focus area for performance-indicator-based activity profiling.

The goal is to identify patterns of operations within different warehouse activities and link these patterns to indicator-based performance assessment. This extension of activity profiling contributes to quantifying the improvement potential of an optimization. With a quantified improvement potential, we can prioritize different optimization measures and support decision-making.

For example, the hour-of-day distribution in Section 3.3.1 only assesses the number of cases received per hour. With a performance profile, we may analyze which hour of the day has the highest receiving labor productivity. Based on this, we do not limit our optimization measure to divide labor over the workload. Instead, we can assess which combination of workload and labor achieves the highest performance and use this to organize the labor and the workload to accomplish the same at other hours.

Performance profiles aim to identify *instances* of a warehouse activity profile that underperform on a performance indicator. Each performance profile represents an Independent Variable (IV) in one warehouse activity, e.g., the names of the employees in the order-picking activity. The term Instance refers to the value an Independent Variable (IV) can take (e.g., Client A or Employee B).

In other words, performance profiles aim to distinguish certain warehouse aspects that are focus points for performance optimization. In an employee profile, we analyze performance variations between certain employees, in an item profile the variations between products, dock profile between dock doors, etc. The exact values of the employees, products, and docks are the respective *instances* of the performance profiles.

When the performances over the instances are measured with the same performance indicators, it helps to quantify the improvement potential. Examples of performance profiles are:

- A item profile as part of the order picking profiles: this profile could identify certain items with a relatively high number of pick-lines and a relatively high order picking time. This suggests inefficient locations or handling of these items.
- An order-picking-based employee profile: this profile could identify employees with a relatively low order-picking productivity. If significant, this could encourage the operational management to intervene.

With this new approach to the activity profiles, we need to establish which performance profiles are relevant, i.e., which Independent Variable (IV) may influence the performance of a warehouse we want to investigate. Current literature is not focused on the performance-based aspect but does provide interesting input of topics that we can link to the performance indicators of Section 3.2. The main source to determine the performance profiles is the consult of seven employees, regarded as experts' opinions from 4Supplychain.

The performance profiles for the performance assessment model were determined during two sessions with (part of) the experts. The sessions started with an explanation of the research design, previous conclusions of the research, and an introduction to warehouse activity profiling in the literature. The experts from 4Supplychain then provided input,, resulting in the different performance profiles.

We group the performance profiles by the six main warehouse activities. We chose this organization since this fits the lowest level classification organized in Figure 4.3. Second, the different performance indicators within one activity are often strongly related. For example, if the receiving time varies a lot between clients, it is more likely to vary between employees. Showing these related indicators together makes identifying the cause of lacking performance easier. Third, 4Supplychain believes an activity-based classification is often easier to grasp for warehouse management since other classifications, like dimensions, are not as commonly distinguished and used.

Three performance profiles are regarded as relevant for all activities by the 4Supplychain experts:

- A first relevant profile is the client profile since 4Supplychain consults a lot of 3PL providers. All items in a 3PL warehouse belong to one of the clients from receipt until shipment, and often, client requirements influence performance.
- A second general relevant profile is the item profile, which gives insights into how efficiently different items are handled throughout the activities.
- Third, the calendar clock profile can also always be applied to check seasonality impact on performance.

Besides these three general profiles for every activity besides storage, we propose:

- An employee profile which visualizes differences in employee functioning.

Furthermore, for receiving, put-away, order picking, and shipping, we propose:

- A dock profile which provides insights into how different dock locations influence the warehouse performance of activities that (partially) take place at a dock.

For put-away, storage, replenishment, and order picking, we propose:

- A storage location profile is relevant with the same reasoning as the dock profile.

Since the receiving and shipping activities often happen at the same part of a warehouse, we also propose:

- An inbound/outbound profile combines certain profiles of the receiving and shipping activities to analyze the influence on the performance of overlapping activities.

Last, it is important to note the differences between a client, supplier, and recipient for a warehouse. Although a client of a 3PL owns the items and has a strong influence on the process, it could be that this client works with different suppliers and customers for one warehouse. This is why we propose two extra profiles:

- For receiving and put-away, we develop a supplier profile to see if different suppliers influence the performance of the inbound process.
- For order picking and shipping, we develop a recipient profile to see if different customers influence the performance of the outbound process.

The selection of these performance profiles per activity results in the organization shown in Figure 4.4.

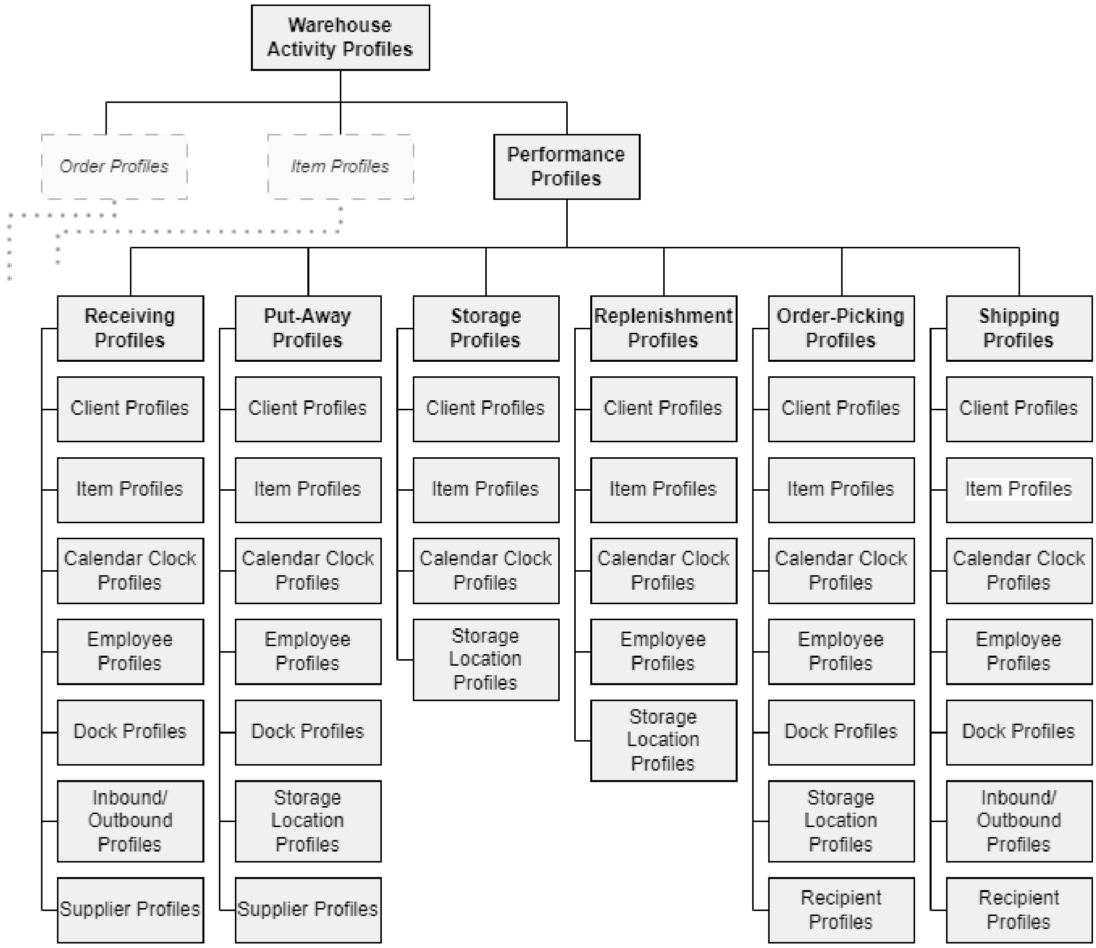

Figure 4.4: Organization of the performance profiles as an addition to the activity profiles by Frazelle (2015)

4.3.2 Benchmarking Within The Warehouse

While most internal benchmarking is applied to different business units (separate warehouses), we propose an even deeper-level internal perspective. We benchmark the performance of warehouse activities by comparing the different instances within the performance profiles of Section 4.3.1. This regards benchmarking performance within one single warehouse. This more deep-dive approach to benchmarking comes with some advantages and disadvantages to the general applied benchmarking approaches like internal benchmarking (across business units) and external benchmarking.

An advantage of benchmarking within a single warehouse is that it simplifies the performance comparison. First, it shortens the time-consuming data gathering, cleaning, and validating process. Second, the processes within one warehouse are likely more similar than those between different warehouses, which simplifies comparing performances. No extensive database and elaborate method like Data Envelopment Analysis (DEA) is necessary to compare performances within one warehouse.

On the other hand, a disadvantage of this approach is that performance is only compared to the best-performing instance within the analyzed warehouse. This means it does not regard best practices in the industry. When all warehouse instances are lacking, the identified performance gap will be smaller than theoretically possible compared to better-performing warehouses.

Table 4.6 shows the comparison between the general applied benchmarking approach and the benchmarking approach within a single warehouse comparison that we propose. Most of the differences logically follow from the differences in objects on which the comparison is made. For clarification, the main concepts of benchmarking in our approach are described in this section.

Table 4.6: Comparison of General and Single-Warehouse Benchmarking

Subject of Comparison	**General Benchmarking**	**Single-Warehouse Benchmarking**
Scope	Multiple warehouses	Single warehouse
Comparison On	Different warehouses	Instances of performance profiles
Method	Data Envelopment Analysis (DEA)	Absolute comparison and statistical significance analysis
Best Practice	Best performing (process of a) warehouse	Best performing instances
Performance Gap	Difference between analyzed (process of a) warehouse performance and best practice performance	Difference between analyzed instance performance and best practice performance
Improvement Potential	All (processes of) warehouses performing as best practice	All instances with statistical significant performance gaps performing as % of best practice
Target Optimization Area	The warehouse with the highest improvement potential	The performance profile with the highest improvement potential

Identify Best Practices

Since these analyses are performance-based, we can simply recognize the best practice as the best-performing instance in a profile. For example, we may analyze the client portfolio as part of the put-away portfolios. We may note that the pallets of one client are put away faster than the pallets of other clients. The client with the shortest put-away time is identified as best practice. The term Best Practice refers to the best-performing instance in a profile.

Calculate Performance Gap

When the best practice within a performance portfolio is identified, the next step is calculating the performance gap. The term Absolute Performance Gap refers to the absolute difference in performance indicator between an instance's performance and the best practice's performance within the same profile.

In the literature, benchmarking methods like DEA analyze many warehouses. The performance gap is then based on the extensive database and comparison method. The performance gap often remains as the 100% absolute difference in performance indicator values, implying that best practice performance is always achievable.

This cannot directly be applied to the benchmarking within a single warehouse since it would be unrealistic to state that all instances can achieve 100% of the level of the best practice. For example, we compare differences in order picking productivity between employees. An inexperienced employee may be trained and motivated to pick faster, but probably not soon be as quick as an employee with years of experience.

Here, we need another method to adjust the absolute performance gap and determine a more realistic adjusted performance gap. This is why we introduce the *performance threshold*. The performance threshold is a variable input parameter of the performance analysis model. The term Performance Threshold refers to an extent (%) of the best practice performance, which we believe is achievable for all instances in a specified profile. It can be set at this percentage.

Unless stated otherwise, the term performance gap refers to the Adjusted Performance Gap, the difference in performance indicator value between an instance's performance and the best practice's performance within the same profile, adjusted by the performance threshold.

Determine Improvement Potential

The improvement potential is determined by multiplying the performance gap with the workload. For example, if the performance gap is 100 seconds per pick-line and the workload is 1,000 pick-lines, the improvement potential is 100,000 seconds. However, this implies that all instances can completely fill the performance gap. Even though the performance gap is adjusted by the performance threshold, it is not clear if the improvement potential can be achieved for all instances.

We need an extra step to determine if the performance gap translates to an achievable improvement potential. We propose to evaluate the statistical significance of the relationship between the variables. More precisely, we check if the instances (the IVs) have a significant relationship to the measured performance (the DVs). If the best practice or analyzed instance does not significantly influence the performance, then focusing an optimization measure based on these differences is no use. For example, we might identify a performance gap between two employees in their order picking productivity. This could be caused by the fact that one employee works more efficiently than the other. However, it can also be caused by the fact that this employee only picks orders with products that are easy to grab. In the first case, we expect employees to have a significant statistical relationship with the performance. In the second case, we do not expect this.

The calculated performance gap can be translated into an improvement potential with the statistical analysis. The term Improvement Potential refers to the achievable performance gain based on the performance gap and the statistical significance of the relationship of the instance (IV) and the performance (DV). For some instances the improvement potential may be zero, for others, it may be the calculated performance gap, depending on the statistical relationship within the analyzed performance portfolios.

Select Target Optimization Area

When the performance analysis model has determined the improvement potential of all instance's overall performance profiles, the next step is to select the target optimization area. The term Target Optimization Areas refers to the most prioritized profiles for optimization based on the highest improvement potential. Logically, 4Supplychain wants to focus their optimization on areas of the warehouse where the most impact can be made.

We make the prioritization of performance profiles and, therefore, the selection of the target optimization areas based on the cumulative of all improvement potentials within one profile. For example, in order picking, there may be three employees, of which two have a determined improvement potential in productivity. They can both improve with 100 picks a day, the total improvement potential in the order picking employee profile is 200 picks a day. On the other hand, the order picking client profile shows that there are four clients, three of which have an improvement potential of 80 picks a day. The total improvement potential here is 240 picks a day. When only comparing these two profiles, the total improvement potential of the order-picking client profile is the highest, which means this becomes the target optimization area.

4.3.3 A Statistical Significant Target Optimization Area

This section describes the statistical method we apply to determine if a performance gap leads to a practical improvement potential. It considers the statistical method described in the theoretical framework in Section 3.4. Besides, it elaborates on the assumptions of the chosen method.

An advantage of ANOVA over multiple regression analysis is that the focus is on IVs at the nominal level. Most of the IVs we analyze are nominal, like employees, item types, and docks, which means it seems a good fit. However, we also analyze many IVs, whereas this number is constrained for ANOVA. Furthermore, ANOVA is not applicable for describing existing relationships. We conclude that multiple regression analysis is more suitable than ANOVA.

Also, the path analysis has an advantage over multiple regression analysis because it does provide a more comprehensive understanding of the relationships between the IVs and the DV. However, it requires extensive analysis work, including creating path diagrams for all variables. We only aim to conclude on the existence of the statistical significant relationship instead of the deeper understanding of the relationship. Besides, we assess dozens of DVs in a relationship with even more IVs. We conclude that the multiple regression analysis compile, which means we disregard the ANOVA and path analysis.

Multiple linear regression analysis is commonly used in fields like economics, social sciences, and natural sciences to predict outcomes and understand which factors are influential. For this research, the most important aspect is to understand which factors are influential. This means that we want to know which warehouse instances significantly influence performance.

According to Randolph and Myers (2013), the output of a multiple regression analysis typically includes regression coefficients, the R-squared, F-statistic and P-value. For this research, the P-value is one of the most important results. It indicates if the coefficient (and with that, the influence of the IV on the DV) is statistically significant. If this is the case, we can state that the identified performance gap of a warehouse instance is indeed caused by the influence of the analyzed instances in a profile. We can determine the improvement potential and prioritize the target optimization areas.

4.4 The Narrowed Scope of Optimization Measures

Now we have the target optimization area. As explained, this is the warehouse area where the data shows that performance optimization is achievable. The target optimization areas are prioritized on improvement potential.

This section describes how we get from this target optimization area to the narrowed scope of optimization measures. First, Section 4.4.1 describes which follow-up questions are deployed for which target optimization area and how they are derived. Section 4.4.2 then provides the set of optimization measures for each target optimization area and how a selection is proposed.

4.4.1 The Specified Set of Follow-Up Questions

Figure 4.4 in Section 4.3.1 shows the organization of the 39 performance profiles, one for each combination of activity and type of profile. All of these profiles could be identified as target optimization areas. As explained in Section 3.5, about scoping the optimization measures, we want to create a set of follow-up questions for each of these profiles. The term Follow-Up Questions refers to the set of questions for a specific target optimization area selected to identify and narrow the scope of optimization measures.

The main input for determining these specified sets of follow-up questions is the expert knowledge within 4Supplychain. First, the two managing consultants - with over ten years of experience in warehouse optimization - are engaged in three input and review sessions to assign questions to all 39 profiles. Second, as Section 3.5 explains, the other input is the list of 140 warehouse performance analysis questions of 4Supplychain's previous attempt for an improved warehouse optimization strategy.

The appendix Appendix C shows the derived dataset with sets of questions for each possible target optimization area. Per activity, it starts with general activity-related questions that apply to all the underlying areas. Then, specific questions are added to complete the set for every performance profile.

The general follow-up questions for all activities range between five and sixteen. The additional profile-specific questions range between one and twelve questions. The specified set of follow-up questions for a target optimization area ranges between six and twenty-eight.

4.4.2 The Proposed Optimization Measures

For every possible target optimization area, a set of possible optimization measures is also specified. It is determined using the same approach as the set of follow-up questions. The set of optimization measures is highly correlated with the follow-up questions since the follow-up questions aim to identify the implementation level and restrictions regarding possible optimization measures.

The appendix Appendix D shows the possible set of optimization measures for each target optimization area. Per activity, it starts with general activity-related optimization measures. Again, specific methods are added to complete the set for every performance profile.

For all activities, the number of general optimization measures range between five and ten. The additional profile-specific methods range between one and five. The specified set of optimization measures for a target optimization area ranges between six and ten.

The last step of the performance analysis is to propose certain optimization measures for these sets. This step is manual. It cannot be automated in the performance analysis model as easily as the more quantitative steps.

This step includes discussing the set of follow-up questions with warehouse management. During this discussion, the implementation level of optimization measures and restrictions regarding optimization measures can be identified. Based on this discussion, 4Supplychain should, in consultation with warehouse management, decide on the optimization measures from the set.

4.5 Model Description

Section 4.1 describes the scope of improving the warehouse optimization strategy. It shows that six tasks of the optimization strategy are automated with the model. The scope, method, and aim of each task are described in this chapter's previous sections.

Besides the model fulfilling the tasks, there are some relevant details about the requirements, assumptions, and functioning of the model, which are explained in this section. Section 4.5.1 describes the additional requirements of the warehouse performance analysis model. Section 4.5.2 describes the assumptions on which the model is based. Last, Section 4.5.3 gives an overview of the flow within the performance analysis model.

4.5.1 Model Requirements

The model requirements originate from two different sources. First, the lessons of the previous attempt of 4Supplychain to improve their warehouse optimization strategy described in Section 2.2.2 are re-evaluated. Second, the draft versions of the performance analysis model are discussed with 4Supplychain managing stakeholders and AG Logistic as the client stakeholder (also involved in the case implementation).

The first set of requirements includes:

1. minimize the number of committed users involved
2. minimize the workload for key-user
3. standardize metrics definition and scope
4. standardize measurement methods
5. limit the number of data sources
6. use standard available data sources
7. simplify comparability of metrics

Additionally, the second set of requirements contains:

8. exclude instances that do not meet minimum workload (e.g., an employee with two picks can be excluded)
9. enable adjustments in the confidence interval of the statistical analysis (i.e., check the influence of statistical uncertainty)
10. enable data filters on pick-moments (e.g., exclude first picks of a shift)
11. enable data filters on IVs (e.g., exclude certain clients or days of a week from analysis)
12. enable flexible output unit of measurement (e.g., number of pallets instead of pick-lines)
13. minimize runtime of complete analysis to a few hours maximum

14. use only one application (to reduce synchronizing problems and possible subscription costs)

These requirements are all taken into account during the development of the warehouse performance analysis model. Some were easily met, and some were harder to assess directly. The extent to which these requirements are met is evaluated after the case implementation in the case evaluation in Section 6.2 and the expert opinion validation in Section 6.3.

4.5.2 Model Assumptions

After reviewing the theory and discussing the model development with experts of 4Supplychain and a stakeholder of AG Logistics, we made several assumptions to simplify model flow. These assumptions are:

1. Performance levels that deviate more than two standard deviations from the mean performance are outliers and can be disregarded.
2. The performance of the first action of a new shift of an employee is always an outlier and therefore disregarded.
3. Inactive time of an employee of more than 30 minutes is considered break time and therefore disregarded from the working hours.
4. All employees constantly register under their own name only.
5. An instance with a statistically insignificant relationship with the performance can never be best practice.
6. An instance with a statistically insignificant relationship with the performance can never have an improvement potential.

4.5.3 Model Functioning

The automated performance analysis model is programmed in Python 3.9, using the Spyder integrated Development Environment (IDE). Besides basic data analysis functions with standard packages, noteworthy functions include the multiple linear regression with the statsmodel.api package and developing a Graphical User Interface (GUI) with the Tkinter package. Appendix E shows the model's graphical interface.

The model generally consists of four steps:

1. data file selection
2. data cleaning
3. performance analysis
4. performance visualization

The third step, the performance analysis is what the improved warehouse optimization strategy is about. Figure 4.5 gives a chronological overview of the model's tasks. It also shows the input and output for each task.

Besides the input of data files, the only other input parameter settings are used to identify the best practices, calculate the performance gaps, and determine the improvement potential. Additional input parameters are programmed to fulfill stakeholder requirements next to the performance threshold and the statistical confidence level. The options for the input parameters are discussed in Section 5.3 about the experimental settings.

The output per task summarizes the goal of every task of the model described in this chapter. It logically follows from the task to be fulfilled. More clarification of the output in terms of examples and visualizations follows in the case implementation in Section 6.1.

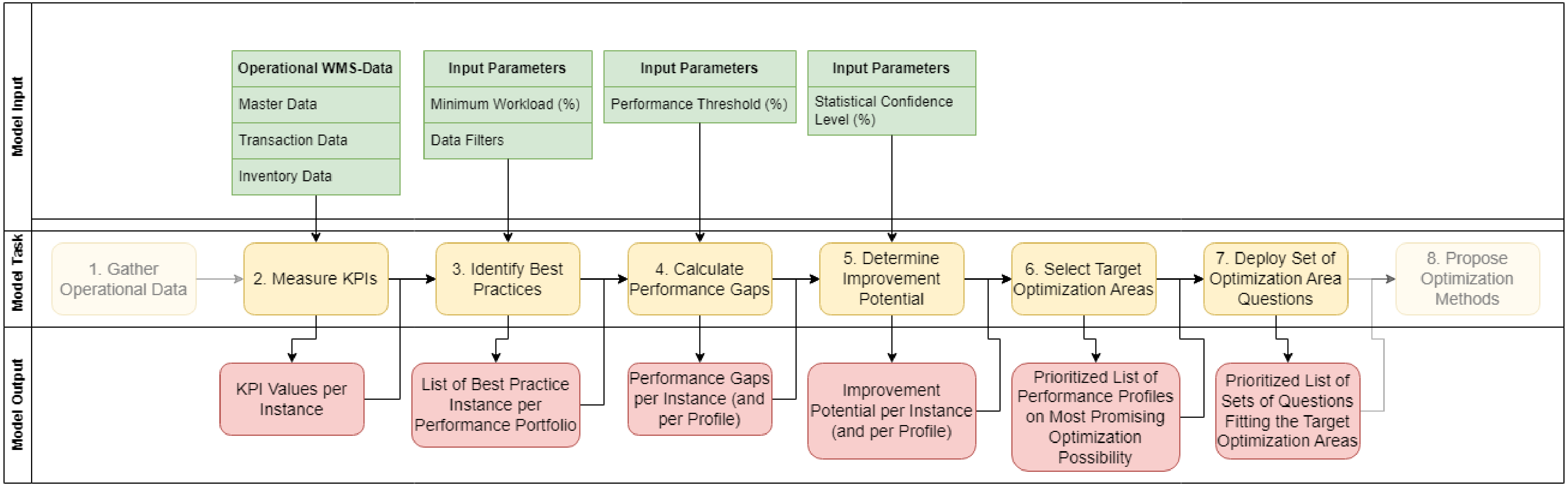

Figure 4.5: The input, tasks, and output of the warehouse performance analysis model

4.6 Summary

The solution design focuses on the performance analysis part of the warehouse optimization strategy. The solution design follows an eight-task plan to achieve the three objectives of performance analysis. The operational-data-driven warehouse performance analysis model can automate most of the tasks.

The performance analysis model's automation level can only be achieved if we scope the warehouse characteristics that fit a standard warehouse. This warehouse may work with different types of customers, units of handling, storage strategies, and equipment. Only this warehouse must be at least medium-sized, have a standard flow of products, not have a high level of automation, and store the essential WMS-data types.

Only certain classifications regarding performance indicators' directness, dimensions, resources, and activities fit the operational data-driven performance analysis model. Direct performance indicators are more suitable than indirect ones since they are less complex and only based on quantifiable data. The time, productivity, and utilization dimensions are best measurable within the goal and scope of the model. The relevant resource classes are labor and space. Last, six main activities are distinguished for performance analysis.

The performance analysis model should measure 36 different performance indicators. With the critical assessment and clearly defined definitions, they fit the standardized scope of the model. Figure 4.3 shows the relationships between the performance indicator definitions and the previously determined classifications.

We propose the concept of performance profiles as an additional performance analysis that combines pattern identification with indicator-based assessment. We organize the performance profiles per warehouse activity as shown in Figure 4.4. The chosen performance profiles differ per activity. This leads to 37 performance profiles, whose relevance is based on expert opinions from 4Supplychain.

We propose an internal benchmarking approach for different instances within a single warehouse. Although it limits identifying the industry's best practices, it has several advantages, such as limiting the time-consuming process of data gathering and preparation and enhancing comparability.

The internal benchmarking process consists of four steps:

- identifying the best practice
- calculating the performance gap
- determining the improvement potential
- selecting the target optimization area

The first two steps are simple direct comparisons of performance levels. The third step is executed with a multiple regression analysis to determine the statistical significance of the relationship between IVs and DVs. Additionally, it requires setting input parameters to re-evaluate the size of the improvement potential. The last step is again a simple prioritization of the performance profiles based on the size of the improvement potential to select the target optimization areas.

We determined a set of follow-up questions and optimization measures for each target optimization area. Both sets are determined based on 4Supplychain expert knowledge and experience. The specified follow-up questions should be discussed with warehouse management to propose the most promising optimization measures.

The automated warehouse performance analysis model is developed in Python. It follows the flow of tasks of the improved warehouse optimization strategy. Choices are made based on fourteen requirements from 4Supplychain and the client (AG Logistics). Six assumptions are made in the model development for simplification purposes.

Chapter 5

Case Description and Settings

This chapter describes the case for which the model, as described in the solution design in Chapter 4, is implemented. Section 5.1 provides general background information about the client of the case and the analyzed warehouse. Section 5.2 explains the scope of the case-implementation. Section 5.3 explains the experimental settings applied in the implementation.

5.1 Case Description

AG Logistics is a 3PL provider with five warehouses located in central parts of the Netherlands. Their sizes range from 13,000 to 64,000 m^2. The warehouse activities depend on the clients they serve. Mostly they serve retailers and e-commerce businesses, which means the warehouses share most characteristics with those types of warehouses. This section describes the warehouse with its main characteristics and the WMS-data it provides.

5.1.1 The Warehouse of AG Logistics

One of their main warehouses is located in the city of Ede. Unless specified otherwise, this warehouse is 'the warehouse' in this thesis report. This section briefly describes the standard characteristics of the warehouse. Appendix F gives a more elaborate description of AG Logistics and this main warehouse.

The warehouse fits the standard warehouse characteristics as described in Section 4.1.2:

- The warehouse size is 28,000 m^2 (large-size).
- Most products follow the standard flow described in Figure 4.2, where most storage is bulk, but there is also a dedicated forward area for picking. There is no cross-docking, and the VAP accounts for a relatively small part of the operational workload.
- The warehouse utilizes a WMS-system by Boltrics, based on Microsoft Dynamics 365 Business Central, specialized for 3PL-providers. It offers a wide range of basic and advanced features. It logs the necessary master, transaction, and inventory data.
- The warehouse uses mostly basic equipment. The only storage equipment is single-deep selective rack pallet storage. The Material Handling Equipment (MHE) is mostly human-controlled and consists of single-deep and double-deep pallet trucks, single-deep reach trucks, and single-deep lift trucks. However, the warehouse utilizes an automated, advanced Automatic Layer Picker (ALP).

- The customers are retailers with long-shelf-life foods and other consumer goods.
- The handling units range from full pallets to layers, cases, inner packs, and pieces.
- The warehouse applies a shared storage strategy to the bulk area and a combination of dedicated and shared storage for the forward area.

Besides these main characteristics, it is interesting to notice the limited level of performance analysis AG Logistics currently applies. They only measure the total number of pallets they receive and ship every month and the monthly profit. Although this does not directly imply a low performance, data-driven performance analysis can be very opportune for them.

5.1.2 The Available Case Data

As explained, the WMS-system of AG Logistics can provide all the necessary master, transaction, and inventory data for the model. In total, these are eight different data files. These files are:

- master data
  - product master
  - location master
- transaction data
  - booked inbounds
  - booked outbounds
  - booked movements
- inventory data
  - current stock level
  - pallets entered
  - pallets released
  - positive inventory adjustments
  - negative inventory adjustments
  - order picking inventory adjustments

AG Logistics provided these data files in November 2023. The master data and current stock levels are snapshots of when the data was collected. All other inventory and transaction data are logs covering the four months of July - October 2023.

The quality of the data varies for the different files. They are complete in covering all products, locations, logistical decisions, and inventory adjustments. However, not every row includes all the expected data. This means the files require data cleaning and preparation before the developed model can be applied.

5.2 The Scope of the Case

AG Logistics has provided WMS data from their main warehouse for a four-month period. Consequently, the scope of this implementation is confined to this single-warehouse, four-month timeframe.

The quality and quantity of the data files present certain challenges in data preparation. These challenges are addressed with extensive data checking, validating, cleaning, and formatting to ensure it is suitable for model programming and generalized, automatic purposes. Figure 5.1 shows the data preparation steps that are derived from addressing this challenge, which are expected to be generally reusable for other cases. Given that the primary objective of this case study is to explore the potential of using these types of data files (once prepared) for performance analysis, we have chosen to limit the number of data files utilized as input to the inventory adjustment data and the product master.

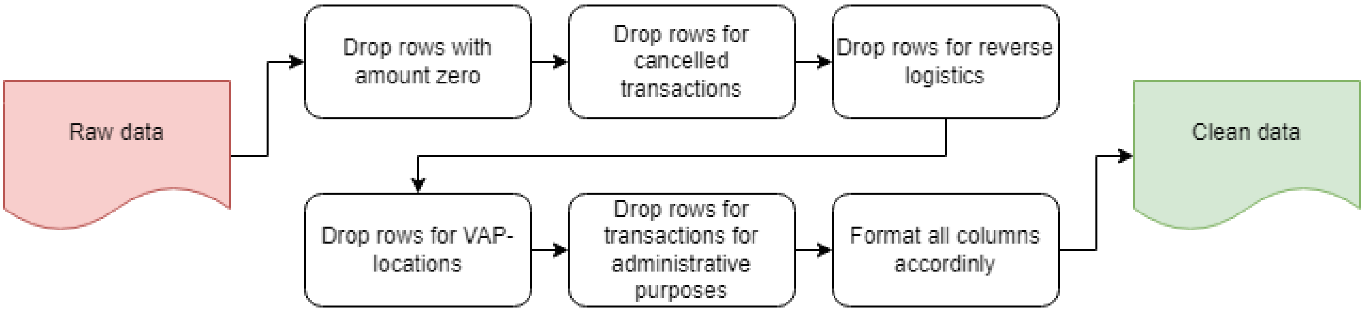

Figure 5.1: General data preparation steps

The output scope is also constrained in alignment with the limited input data. The proposed solution design, as detailed in Chapter 4, involves measuring 36 performance indicators across 37 different performance profiles.

Considering the goal of the case implementation, the intensive data preparation process, and extensive scope of output in the complete solution design, we have narrowed the focus of the case implementation to a specific part of the warehouse process. The chosen scope is the order-picking activity in the forward area.

Several factors substantiate this specific focus. First, order picking is typically the most resource-intensive activity, consuming significant operational costs and labor hours, as outlined in Appendix Section A.3 and corroborated by industry data from 4Supplychain. Second, AG Logistics has identified this activity as having the highest potential for performance optimization, which aligns with its operational improvement goals.

With this selection, the output is limited to five of the 36 performance indicators and seven types of performance profiles. However, since we do not analyze the other activities, we cannot measure labor utilization for order-picking since we do not know the overall amount of labor hours. This means four performance indicators remain for this limited case, which are:

- order picking time (sec/pick-line)
- order picking time (sec/item)
- order picking labor productivity (pick-lines/hour)
- order picking labor productivity (items/hour)

The model applies two units of measure: pick lines and items. The values on the different performance indicators are not easily comparable. In the case implementation in Section 6.1, a focus on one unit of measure is explained based on the first results.

Some types of performance profiles have certain sub-profiles, which brings the total number of performance profiles to ten. The remaining performance profiles for (forward-area) order picking are:

- client profiles
- item profiles
- calendar clock profiles
  - month/year profiles
  - day/week profiles
  - hour/day profiles
- employee profiles
- dock profiles
- storage location profiles
  - zone profiles
  - exact location profiles
- recipient profiles

For this selection of performance indicators and profiles, the whole flow of model tasks is applied as described in Figure 4.5 in Section 4.5.3. This means the model can be completely implemented and evaluated even with the limited scope. The flow of these tasks also generates the structure for Chapter 6. The tasks are:

1. measure KPIs
2. identify best practices
3. calculates performance gaps
4. determine improvement potential
5. select target optimization areas
6. deploy the set of optimization area questions

5.3 Experimental Settings

Now the WMS-data as input files and scope of the case are clear, the input parameters still need to be set for the experiment. Figure 4.5 in Section 4.5.3 shows the four input parameters that influence the model results. This section describes how these input parameters are set for the experiments. The four input parameters are:

- performance threshold (%)
- statistical confidence level (%)
- minimum workload (%)
- data filters

To determine the values of these input parameters, we use the literature sources when applicable and support this with conclusions from meetings with 4Supplychain and AG Logistics stakeholders. The goal is to set realistic parameter settings so the determined improvement potential is most realistically achievable.

Performance Threshold

The performance threshold is the extent (%) of the best practice performance, which we believe is achievable for all instances in a specified profile that are statistically significant. In benchmarking literature, this parameter is not commonly applied. Often the best practice performance is regarded as achievable, which implies this parameter is set at 100%.

Since it will be difficult to determine one realistic value for the performance threshold, we distinguish three scenarios: the best-case, base-case, and worst-case. In the best-case scenario, we set the threshold at a level applicable to very high achievable improvement potential. In the worst-case scenario, we set relatively low expectations of the improvement potential. In the base case, we try to approximate the average expected threshold as well as possible, so this should be the most realistic scenario.

Since the 100% performance threshold is the maximum, we consider this as the best-case scenario. In consultation with 4Supplychain and AG Logistics, we set the base-case at 90% and the worst-case at 80%.

Statistical Confidence Level

The statistical significance is the extent to which the instance's value - the Independent Variable (IV) - influences the value of the analyzed performance indicator - the Dependent Variable (DV) (i.e. how much an instance relates to the measured performance). The statistical confidence level is the extent to which we can say that we are sure that this statistically significant relationship indeed exists. The higher the level, the stronger the statistical relationship needs to be approved by the model to be used for an improvement potential.

The statistical significance level is often set at 95% in literature warehouse benchmarking (Johnson and McGinnis, 2010). This means that we regard the statistical relationship as significant if we are at least 95% sure this relationship exists.

Minimum Workload

The minimum workload percentage is the minimum part of the total workload an instance has to have done to be included in the analysis. This is an extra input parameter 4Supplychain and AG Logistics required for additional data analysis possibilities. Since this is not based on theoretical sources, we do not want this parameter to influence our case implementation results. This is why it is set to 0% for all scenarios.

Data Filters

The data filters are other additional input parameters that 4Supplychain and AG Logistics require. We can manually filter out certain pick moments and certain instances of certain profiles. The model automatically filters out the first pick-line of an employee's shift since this pick time is never representative. No other data filters are applied to the case implementation because of the same reasoning, which is that we do not want this to influence the results.

5.4 Summary

AG Logistics is a 3PL provider with their main warehouse in Ede. The large warehouse fits the basic warehouse regarding product flow, WMS, equipment, and other characteristics. They provide the necessary master, transaction, and inventory data logged for four months as input for the model.

The scope of the implementation case is reduced to the forward-area order-picking activity because this limits the extensive effort in data preparation and output generation. This ensures the feasibility of the implementation within the research time. The model is still implemented for all tasks it is developed for, however, it now focuses on four performance indicators and ten performance profiles only.

We created three scenarios for the setting of the performance threshold (%) for the case implementation:

- best-case: 100%
- base-case: 90%
- worst-case: 80%

The statistical confidence level is set at 90%. The minimum workload is set at 0%, and no data filters are applied, so these user requests do not influence the generic case implementation.

Chapter 6

Case Implementation, Evaluation, and Validation

This chapter provides a description of the implementation, evaluation, and validation of the performance analysis model as part of the improved warehouse optimization strategy described in Chapter 4 applied to the case of Chapter 5. Section 6.1 provides the step-by-step implementation including the results of the case. Section 6.2 evaluates the model's functioning for this case implementation. Section 6.3 describes how experts from 4Supplychain assess the model functioning and to which extent it meets the requirements stated in Section 4.5.1.

6.1 Case Implementation

This section provides the step-by-step implementation of the model. All model tasks are carried out. Section 6.1.1 describes the performance measurement and, therefore, the first task of the automated model: (1) measure KPIs. Section 6.1.2 describes the identification of opportunities for optimization and, therefore, the second to the fifth task of the automated model: (2) identify best practices, (3) calculate performance gaps, (4) determine improvement potential, and (5) select target optimization area. Last, Section 6.1.3 describes how the model narrows the scope of optimization measures and, therefore, the sixth task of the automated model: (6) deploy the set of optimization area questions.

Appendix G shows the graphs the model creates to visualize the results in this section. It shows the graphs of the client profile, which is the leading example profile in this section. All profiles follow the same steps and visualizations. This section provides the summarized results of all profiles.

6.1.1 Case Performance Measurement

The model measures the performance of the case on the four KPIs stated in Section 5.2. This section provides the overall performance and the performance of the client profile as an example profile and states the number of instances per profile. Besides, this section also provides the division of workload over the instances since we need the workload to calculate the KPI values, the improvement potential, and it provides interesting insights into workload spread.

1. Measure KPIs

Table 6.1 shows the overall performance of the main warehouse of the case, measured over the period July - October 2023. The total workload is over this four-month period. The performance indicator values are averages over this same period.

Table 6.1: Overall performance measurement of the case (main warehouse of AG Logistics, July - October 2024)

Total workload			Performance			
			Time		Productivity	
Pick-lines	Items	Labor hours	Seconds/ pick-line	Seconds/ item	Pick-lines/ hour	Items/ hour
26,757	316,762	1,601	226	20	16.7	197.9

Table 6.2 shows the example of the performance measurement in the client profile. The codes in the client column represent all the unique clients served in the order-picking forward area. There are three clients, i.e., three instances in the client profile. Internal coding is used so that AG Logistics clients can remain anonymous. Appendix Section G.1 in Appendix G shows the graphs of the workload and performance of the client profile.

Table 6.2: Performance measurement for the client profile

Client	Total workload			Time		Productivity	
	Pick-lines	Items	Labor hours	Seconds/ pick-line	Seconds/ item	Pick-lines/ hour	Items/ hour
K00020	21,274	234,982	1,317	234	22.4	16.2	178
K00035	3,730	23,203	171	172	28.8	21.8	136
K00038	1,753	58,597	112	247	7.9	15.7	523

Table 6.2 is just an example of one of the ten profiles analyzed in this implementation. This profile contains just three instances, which gives a clear overview. For the other profiles, there are many more instances.

Table 6.3 shows the number of instances per profile. The model measures the workload and performance of all these instances separately. The model provides all these extensive, detailed performance measurement results (like Table 6.2 and Appendix Section G.1) for all ten profiles. However, showing all the results to the users is not regarded as directly relevant to this research purpose.

6.1.2 Case Identification Opportunities for Optimization

This section describes the four steps toward the identification of opportunities for optimization. It starts with identifying best practices, followed by calculating performance gaps. Then, the improvement potential is determined, and target optimization areas are selected.

These steps rely on the performance levels' direct comparability. While all performance levels for the same indicator are easily comparable, there are still four different performance levels. This is why we select one main performance indicator for the following steps.

Since productivity strongly correlates with time (i.e., high labor productivity results in low order-picking times) and we can express both improvement potentials in hours, we can disregard one of the two performance dimensions. The main performance dimension in literature is productivity,

Table 6.3: Number of instances per profile

Profile	Number of Instances
Client	3
Items	443
Calendar Clock (Month/Year)	5
Calendar Clock (Day/Week)	5
Calendar Clock (Hour/Day)	20
Employee	30
Outbound Lane	43
Storage (Location)	754
Storage (Zone)	10
Recipient	224

as described in the theoretical framework in Chapter 3, so the focus lies on productivity and we disregard the time dimension.

Then, labor productivity in order-picking is measured in two units of measurement: pick-lines/hour and items/hour. According to Staudt et al. (2014), the most used unit of measurement for order-picking is pick-lines. Besides, preliminary model tests show that improvement potentials expressed from the pick-lines/hour indicators give more realistic results than those from the item/hour indicators. The applied unit of measurement is pick-lines/hour and we disregard items/hour.

In short, this section identifies opportunities for optimization based on the main performance indicator, *labor productivity in pick-lines/hour*.

2. Identify Best Practices

Table 6.4 shows the best practice instances. For every profile, the is one instance with the best performance in labor productivity in pick-lines/hour. The name and performance indicator value of those are stated.

Table 6.4: The best practice instances per profile, measured in pick-lines/hour

		Best practice	
Profile	**Number of Instances**	Instance	Pick-lines/ hour
Client	3	K00035	21.8
Items	443	A100035	61.0
Calendar Clock (Month/Year)	5	11 (November)	18.2
Calendar Clock (Day/Week)	5	2 (Tuesday)	18.6
Calendar Clock (Hour/Day)	20	13 (13:00 - 14:00)	27.4
Employee	30	THTHO	31.2
Outbound Lane	43	O185	26.0
Storage (Location)	754	2B-56-2-1	56.0
Storage (Zone)	10	EDE-PICKW0	21.8
Recipient	224	Supermarkt A	48.0

3. Calculate Performance Gaps

Table 6.5 shows the performance gaps per instance in the client profile. Appendix Section G.2 shows how the performance gaps for the client profile are visualized. These gaps are based on the instance performance, the best practice performance, and the performance threshold. The performances come from column Productivity, sub-column Pick-lines/hour in Table 6.2. The threshold differs for the scenarios, from (a) best case: 100%, (b) base case: 90%, and (c) worst case: 80% as explained in the experimental settings in Section 5.3. For example, for Client K00038 the calculations are:

- Best case: $100\% * 21.8 - 15.7 = 6.1$
- Base case: $90\% * 21.8 - 15.7 = 3.9$
- Worst case: $80\% * 21.8 - 15.7 = 1.7$

Table 6.5: The performance gaps per instance in the client profile, measured in productivity

	Performance Gaps (pick-lines/hour)		
Client	Best case	Base case	Worst case
K00020	5.9	3.4	1.2
K00035	0	0	0
K00038	6.1	3.9	1.7

Table 6.6 shows the total performance gap in terms of hours for all the instances in the client profile for the different scenarios. These total performance gaps are based on each instance's calculated performance gaps and workload. The last row describes the total performance gap of the whole client profile for each scenario for the four-month analysis period.

Table 6.6: The total performance gaps per instance in the client profile and the profile total (sum of all instances), measured in total hours

	Total performance gaps (hours)		
Client	Best case	Base case	Worst case
K00020	366.4	265.9	165.5
K00035	0	0	0
K00038	36.5	28.2	20
Total	402.9	294.1	185.5

Table 6.7 shows the total performance gaps for all ten profiles. This portfolio performance gap is the sum of all instances' individual performance gaps within that portfolio. This means the total time could be saved if all instances would achieve a performance that completely fills the gap. The experimental settings for the performance threshold described in Section 5.3 and applied at the client profile example are applied to all profiles.

4. Determine Improvement Potential

Table 6.8 shows the statistical test results for the client profile. The P-value represents the statistical significance of that instance (i.e., the client) to its performance and performance gap. With

Table 6.7: The total performance gaps per profile (sum of all instances per profile), measured in hours

	Total performance gap (hours)		
Profile	Best case	Base case	Worst case
Client	402.9	294.1	185.5
Items	1088.3	1030.9	982.1
Calendar Clock (Month/Year)	97.5	12.4	0.0
Calendar Clock (Day/Week)	182.9	82.2	36.0
Calendar Clock (Hour/Day)	542.6	435.9	322.9
Employee	759.9	674.5	582.2
Outbound Lane	771.2	683.7	588.4
Storage (Location)	1287.5	1241.7	1138.4
Storage (Zone)	440.4	324.4	217.6
Recipient	1167.0	1115.4	1055.1

a confidence level of 95%, the P-value needs to be lower than 0.05 (5%) to be regarded as statistically significant. Since client 'K00038' lacks a statistically significant relationship, its performance gap is not included in the improvement potential of this profile.

Table 6.8: The statistical test results for the client profile and the flow from performance gap to improvement potential (in the best-case scenario)

Client	**Performance Gap**	**P-value**	**Statistical Significant**	**Improvement Potential**
K00020	366.4	0.044	True	366.4
K00035	0	0.010	True	0
K00038	36.5	0.395	False	0
Total	402.9			366.4

Table 6.9 shows the improvement potentials per profile. This is the sum of all the *statistically relevant* performance gaps. Again, we apply the experimental settings of Section 5.3. Appendix Section G.3 shows the graph for determining the improvement potential of the client profile.

5. Select Target Optimization Area

The last step in identifying the opportunities for optimization is selecting the target optimization area. For this, we first calculate the average improvement potential of the different scenarios. Then we prioritize the portfolios with the highest improvement potential. Table 6.10 shows the prioritization of the different profiles. The top three target optimization areas in the forward area order picking are:

1. recipient profile
2. storage (location) profile
3. items profile

Table 6.9: The improvement potential per profile per scenario

Profile	Improvement potential (hours)		
	Best case	Base case	Worst case
Client	366.4	265.9	165.5
Items	819.2	446.6	360.5
Calendar Clock (Month/Year)	97.5	12.4	0.0
Calendar Clock (Day/Week)	182.9	48.1	21.4
Calendar Clock (Hour/Day)	402.4	140.2	112.3
Employee	701.1	308.2	260.0
Outbound Lane	429.6	256.0	0.0
Storage (Location)	992.3	601.1	558.1
Storage (Zone)	361.1	264.1	164.0
Recipient	985.1	662.3	578.8

Table 6.10: The average improvement potential per profile and target optimization area priorities

Profile	Average improvement potential (hours)	Target optimization area priority (#)
Recipient	797.3	1
Storage (Location)	587.3	2
Items	529.4	3
Employee	431.2	4
Outbound Lane	274.2	5
Calendar Clock (Hour/Day)	255.5	6
Client	252.7	7
Storage (Zone)	230.3	8
Calendar Clock (Day/Week)	123.0	9
Calendar Clock (Month/Year)	71.7	10

6.1.3 Case Narrowed Scope of Optimization Measures

This section provides the implementation after the opportunity for optimization is identified. This is the deployment of the follow-up questions. These questions relate to a narrow set of promising optimization measures. This section also quickly stated the set of promising optimization measures. Still, since our research focuses on narrowing the scope, we do not get into the decision of the optimization measure.

6. Deploy Set of Optimization Area Follow-Up Questions

As explained in Section 4.4, each possible target optimization area is directly linked to a set of follow-up questions. These questions are provided in Appendix C. From this set, we select the order-picking activity questions (since this is the only activity we analyze) with the standard activity questions plus the three sets of additional profile-specific questions. Appendix H shows the set of follow-up questions applied to the case based on the selected target optimization areas.

As explained in Section 4.4, each possible target optimization area is also directly linked to promising optimization measures. Appendix I shows this case's set of promising optimization measures. The extent to which these optimization measures are applicable and beneficial highly depends on the answers given to the follow-up questions. Since this is not within the scope of the research, we cannot determine the most promising optimization measures, so we can only provide the general set.

6.2 Case Evaluation

This section evaluates the implementation of the performance analysis model of Section 6.1. It assesses how well the model functioned as intended. Besides, it analyzes the influence of uncertainty in the choices in model development and experimental parameter settings. This analysis also assesses the model's value by interpreting the case implementation results.

1. Measure KPIs

Within the scope of the case, the performance measurement is carried out to a detailed, extensive extent. The model was able to measure the performance and the workload division of all instances of every profile on all determined KPIs. Also, the visualizations provide intuitive comparison possibilities to the user.

2. Identify Best Practices

The identification of best practices is easily applied to all profiles. This follows logically from the detailed and complete measurement of KPIs. Besides, using one main performance indicator simplifies the identification of one instance per profile.

3. Calculate Performance Gaps

The model is also able to calculate the performance gaps correctly. It calculates them for every instance and can also provide a portfolio's total performance gap.

The different scenarios for the performance threshold influence the size of the performance gap as expected. Table 6.11 shows the impact of the different scenarios on the total performance gap in hours and relative to the total workload hours. Based on the scenario settings, it shows the average performance gap of a portfolio can differ between 32% and 42% of the total workload.

Table 6.11: The differences in the average total performance gap and improvement potential for the three scenarios in total hours and relative to the workload

	Average Total Performance Gap		**Average Improvement Potential**	
Case	Hours	Relative to total workload hours	Hours	Relative to total workload hours
Best	674.02	42%	533.76	33%
Base	589.52	37%	300.49	19%
Worst	510.82	32%	222.06	14%

4. Determine Improvement Potential

The model also determines the improvement potential as expected. Because of the statistical test, some performance gaps are irrelevant, and these hours are not included in the improvement potential. Table 6.11 also shows the influence of this statistical test on the improvement potential and the differences across the three scenarios. Based on the scenario settings, it shows the average improvement potential of a portfolio can differ between 19% and 33% of the total workload.

According to 4Supplychain management, their general expectations at a productivity optimization project normally range between 10% and 20% for one cycle of their warehouse optimization strategy. This was also the aim of the previous strategy improvement attempt. This corresponds with the base-case (19%) and worst-case (14%) average improvement potential determined by the model. However, the aim is not to achieve an average optimization but to achieve a more effective optimization by focusing on the target optimization areas.

5. Select Target Optimization Area

In the case implementation, we select the target optimization area based on the highest improvement potential as the average over all scenarios. This is the recipient profile. However, if we select the target optimization area based on a certain scenario, we may select another one.

Table 6.12 shows the different target optimization areas selected in these scenarios. It shows that in all options, we select either the storage (location) profile or the recipient profile, which are also the number one and two prioritized target optimization areas. This shows that, for this case, the uncertainty in the performance gaps and improvement potentials because of different performance thresholds eventually does not lead to a high fluctuation in the selected target optimization area.

Table 6.12: The selection of the target optimization area for different scenarios

	Target optimization area selection			
Priority (#)	Best case	Base case	Worst case	Average
1	Storage (Location)	Recipient	Recipient	Recipient
2	Recipient	Storage (Location)	Storage (Location)	Storage (Location)
3	Items	Items	Items	Items

6. Deploy Set of Optimization Area Follow-Up Questions

The model directly links the target optimization area to the set of follow-up questions, as shown in Appendix H. The number of follow-up questions for the three top-priority target optimization areas ranges between 18 and 27. This is way less than the original 140 questions that 4Supplychain deployed for their previous warehouse optimization strategy. Although assessing the level and value of these follow-up questions is hard, it shows that a substantial reduction in the questions has succeeded.

Furthermore, the implementation provides the narrow scope of promising optimization measures in Appendix I. Again it is hard to assess the value of these optimization measures, but they provide an interesting scoped view of possibilities.

6.3 Expert Opinion Validation

This section presents an expert opinion validation of the performance analysis model's value. The validation process assesses the extent to which the research objectives are achieved, evaluates the fulfillment of the model requirements, and reflects on the model's overall practical value and relevance.

The expert consulted is a managing consultant at 4Supplychain Consulting, with approximately twenty years of experience in supply chain optimization, particularly in warehousing. He has collaborated with numerous multinational retailers, 3PL-providers, and other medium to large warehouse-operating entities. Unlike the case implementation and evaluation, this expert opinion validation offers a business perspective, focusing on practical value for the supply chain consultancy industry.

Appendix J contains the form presented to the expert from 4Supplychain to structure his expert opinion validation of the model. In addition to this form, the expert was provided with a demonstration of the model, the thesis report, and was specifically asked to review the case implementation (Section 6.1) and case evaluation (Section 6.2).

6.3.1 Achievement of the Objectives

This section explores how well the model contributes to achieving the research objectives set by 4Supplychain: (a) performance measurement, (b) identification of optimization opportunities, and (c) proposing targeted optimization measures.

Performance Measurement

The expert expressed high praise for the model's performance measurement capabilities. He noted that about 80% of medium or larger warehouses lack this level of detailed performance measurement. This innovative approach is a significant contribution to most warehouses.

Additionally, the business model of 3PL-providers often relies on estimated pricing per warehouse movement. This model offers substantial support in determining these logistics parties' pricing. The next development step should link these time/productivity indicators to costs.

The activity-based approach was also deemed highly applicable. 4Supplychain is interested in extending the measurement to all activities. However, they prioritize order-picking and find the measurement very complete within its current scope. Expanding to other dimensions of KPIs would be valuable but secondary to productivity measurement.

In summary, the expert commends the level of performance measurement and considers it a valuable service for future clients of 4Supplychain.

Identification of Optimization Opportunities

The expert believes that identifying best practices is beneficial for establishing benchmarks. Clients often seek such benchmarks, making this a valuable communication tool.

While the performance gap calculation provides a good indication of theoretical performance gains, the expert notes that the lack of historical benchmark data introduces uncertainty. He emphasizes the need to calibrate parameters through iterative testing with additional cases. Although the current approach is a good starting point, the exact numbers require further refinement.

Despite this, the expert sees value in the relative comparison of performance metrics for selecting target optimization areas. Although the exact figures may not yet be realistic, they serve as a solid foundation for identifying optimization opportunities.

In summary, the expert supports the approach to identifying optimization opportunities. While the initial figures need refinement, the relative comparison already offers valuable insights into potential improvements.

Proposing a Narrow Scope of Optimization Measures

The expert evaluates the sets of follow-up questions and proposed optimization measures together. He notes that the current level lacks certain details, which should be refined based on practical experiences when applying the model. The current descriptions of optimization measures are somewhat general and vague.

He attributes this to the case-specific nature of optimizations. Hence, he emphasizes the importance of follow-up questions. The current 'optimization measures' provide a direction rather than a defined solution. He concludes that providing a complete solution would require extensive research on its own.

In summary, the expert sees value in the follow-up questions and the direction provided by the optimization measures. Practical experiences will enhance the quality of these questions over time.

6.3.2 Model Requirements Assessment

In this section, the expert evaluates the extent to which the requirements outlined in Section 4.5.1 are met. This assessment involves a semi-structured review of the requirement list, with brief explanations for each rating.

The expert was asked to rate all the requirements from 1 (requirement is not met at all) to 5 (requirement is completely met) and provide brief descriptions for each rating.

The first set of requirements: Lessons from the previous attempt of 4Supplychain to improve their warehouse optimization strategy (the Logresult tool). The model can:

1. Minimize the number of committed users involved: 4
   - Only one person is involved in data provision until the follow-up questions phase, which can be managed by a single logistic manager.
2. Minimize the workload for the key user: 5
   - The performance measurement effort is entirely automated, significantly reducing user workload.
3. Standardize metrics definition and scope: 4
   - Definitions are clearly stated within the current scope and can be extended in future versions.
4. Standardize measurement methods: 5
   - Measurement methods are fully standardized and automated.
5. Limit the number of data sources: 5
   - Only a few WMS exports are needed.
6. Use standard available data sources: 3
   - Usage of WMS and storage of these data files is common practice but cannot be guaranteed for all potential clients.
7. Simplify comparability of metrics: 3

- Measurements are conducted using the same method, enhancing comparability. However, additional second-level metrics could support or refute the comparability of the same metrics, which would be useful to add.

The second set of requirements: Derived during intermediate feedback sessions during model development. The model can:

8. Exclude instances that do not meet minimum workload: 2
   - Applying this threshold is useful. It is included in the latest model version but has not been thoroughly tested.
9. Enable adjustments in the confidence level of the statistical analysis: 4
   - Included in case implementation, but its influence remains unclear. While not most relevant for this version, it may be important for future iterations.
10. Enable data filters on pick-moments: 2
    - Applying this threshold is useful. It is included in the latest model version but requires further testing.
11. Enable data filters on certain instance-variables: 2
    - Applying this threshold is useful. It is included in the latest model version but needs further testing.
12. Enable flexible output unit of measurement: 3
    - Tested for two units of measurement, but more are relevant.
13. Minimize runtime of complete analysis to a few hours maximum: 3
    - Pre-calculation may take a few hours (completed in minutes). However, switching between analyses should be done within seconds (currently takes minutes).
14. Use only one application: 4
    - The current model is robust with one application. Future requirements should consider client needs, such as using Power-BI for quick visualization switching.

The third set of requirements: Added during the validation phase.

15. Minimize the subjective input by users: 3
    - The performance measurement is entirely objective. However, the calibration of input parameters for determining improvement potential remains subjective and should be objective.
16. Minimize application-, IT-, and processing costs: 5
    - The current application runs in a free programming environment, which is a significant advantage.

6.3.3 General Value of the Model

The expert generally assesses the performance analysis model as a valuable enhancement to 4Supplychain's warehouse optimization strategy. In the growing warehousing market, where profit margins are thin, every optimization in productivity can mean the difference between profit and loss.

Given the current challenges with personnel shortages in warehouses, saving labor hours is particularly relevant. The expert highlights that most warehouses focus on large, risky investments in robotization, while simpler operational productivity optimizations can yield 10% to 15% improvements. The detailed 'heavy data analysis' provided by the developed model is a unique contribution, pinpointing exactly where these improvements can be made.

6.4 Summary

The model has been successfully implemented as intended for all tasks within the limited scope of the order-picking activity. It measures performance at a detailed level, identifies opportunities for optimization by highlighting best practices, calculates performance gaps, determines improvement potentials, and selects target optimization areas. Finally, it connects these areas to follow-up questions and promising optimization measures.

For the AG Logistics case, the prioritized target optimization areas are the recipient profile, the storage (location) profile, and the item profile. The calculated average improvement potential is 797.3 hours, representing a 50% improvement in total labor hours for this activity.

The performance measurement process is clear and detailed. However, the quantification of performance gaps and improvement potential is somewhat ambiguous. The application of different performance thresholds affects these analyses as expected. It is not yet clear what the most realistic value for this input parameter is. Future case implementations should include the execution of optimization measures to accurately measure the improvement potential. These measurements will enhance the accuracy of performance thresholds, thereby reducing the ambiguity of the improvement potential.

For selecting the target optimization area, relative comparisons are more critical than exact values, ensuring the applicability of this step. The follow-up questions and promising optimization measures can also be deployed as intended.

A 4Supplychain expert in warehouse optimization has assessed the model as highly valuable for the supply chain consultancy industry. The detailed performance measurement focusing on productivity provides insightful and applicable innovations for approximately 80% of 4Supplychain's potential clients. The identification of opportunities and optimization measures represents a robust approach and a solid starting point. These steps should be refined over time through trial and error and new experiences gained from practical applications.

Chapter 7

Conclusions and Recommendations

This chapter explains the main conclusions from this research and provides recommendations for 4Supplychain, AG Logistics, and future research.

7.1 Conclusions

This section provides the overarching conclusions from this research. The research focused on developing a performance analysis model to improve the warehouse optimization strategy of 4Supplychain Consulting. The main research question answered is:

> *To what extent can operational warehouse data be used to automatically (i) measure warehouse performance, (ii) identify opportunities for optimization, and (iii) narrow the scope of optimization measures?*

The main conclusions are:

- WMS-exports as operational warehouse data are very suitable sources to measure direct performance indicators in the dimensions of time, productivity, and utilization, regarding the resources space and labor and all main warehouse activities.
- The developed model measures the performance within its scope on a very detailed and complete level, which, according to 4Supplychain experts, provides unique insights into productivity optimizations.
- The process of identification of opportunities for optimization can be automated based on the operational warehouse data. The approach combines internal benchmarking principles with an activity profiling structure and is supported by statistical analysis. The four steps followed are (a) identifying best practices, (b) calculating performance gaps, (c) determining improvement potential, and (d) selecting the target optimization area.
- The current level of the model in quantifying performance gaps and improvement potentials is still low, which means it is impossible to derive realistic numbers for this. The approach, however, provides opportunities to be finetuned during future implementations. Furthermore, the selection of target optimization areas is relative, so an achievable improvement potential is not essential to continue the performance analysis.
- It is possible to automatically provide a narrow scope of follow-up questions and promising optimization measures when opportunities for optimization are identified. Despite not providing a pre-determined optimization plan, these scoped lists provide promising directions for optimization. This saves significant time for supply chain consultants.

- The model identifies the recipient portfolio, the storage (location) portfolio, and the item portfolio as target optimization areas. The determined improvement potential is 50% of the total labor hours in forward-area order picking. While we cannot conclude that this number is realistic, the average improvement potential of all portfolios between 14% (worst-case) and 33% (best-case) provides a more realistic quantification.
- The model has a high practical value. It is useful for warehouses lacking productivity in certain parts of their operational flow. Furthermore, it saves time and effort for supply chain consultants, which may result in acquiring more projects and a bigger market share. Besides, another practical function is that it could aid 3PL-providers in pricing their services.
- Applying the model to multiple warehouses would increase the value in several aspects. First of all, the parameter values can be fine-tuned to get more realistic improvement potential values. Second, best practice identification is not limited to one warehouse but can be extended to certain industries.

7.2 Recommendations 4Supplychain

Based on the research conclusions and discussions and validation with 4Supplychain experts, we recommend the following:

- Continue model development by extending it to all activities.
- Add financial parameters to the analysis to convince clients of the value.
- Implement the model at several additional try-out clients for warehouse productivity optimization.
- Implement the model at a try-out 3PL-provider to assist in pricing their services.
- Keep updating the input parameters and sets of follow-up questions and optimization measures based on experiences.

7.3 Recommendations AG Logistics

For AG Logistics, the client of the case implementation, we recommend the following:

- Answer the follow-up questions for the recipient profile, the storage (location) profile, and the item profile to determine which optimization measure best applies for performance improvement.
- Regularly apply the performance analysis model to identify more optimization opportunities and improve performance.
- Remain cooperative with 4Supplychain to enhance the model en mutually provide from the improvements.

7.4 Recommendations for Future Research

Although the value of this research can be regarded mostly as a practical contribution to the supply chain consultancy industry, there are a few recommendations we make for future academic research:

- A significant amount of literature exists on warehouse benchmarking and calculating performance gaps. Besides, there are a lot of possible optimization measures and ways to identify when they are applicable. However, it is still very hard to realistically quantify an improvement potential. We recommend researchers in warehouse optimization to conduct research on the quantified improvement of finished warehousing optimization projects and how they relate to the preceding expected improvement potential. These insights can contribute to setting more realistic expectations of improvement potentials in future warehouse optimization projects.
- Investigate more in the consideration between robotization and (operational) productivity optimizations to solve the employee shortage problems in warehousing. Currently, the shift towards robotization may be an unnecessarily costly step for warehouses.

Appendix A

Warehousing Concepts and Terminology

This chapter provides context descriptions of warehouse functioning. It explains fundamental concepts and terminology. It illustrates the role of warehouses, basic characteristics, typical activities, and equipment used. Besides, it explains the functions of a WMS and the operational data it can use, create, and store, on which the model is based.

A.1 Warehouses in a Supply Chain

From a lean perspective, the purpose of a warehouse does not make sense directly. Warehouses consume time and space, which are considered wastes that should be reduced. Still, there are good reasons to utilize a warehouse within supply chain management.

Warehouses are used to match supply with demand better. Because demand often changes quicker than supply, it is necessary to have a stock to respond to these fluctuations in demand. Seasonality, marketing campaigns, or other internal and external events can cause these fluctuations.

Another function of warehouses is to reduce transportation costs. Because of fixed costs per transport, it is important to use full carrier capacity. Warehouses can combine products from several suppliers to use this capacity.

Warehouses offer a strategic avenue for product differentiation by facilitating the customization of generic products near the end customer. This capability extends to tasks such as applying specialized labeling on packaging or customizing specific product attributes.

A.2 Warehouse Types

Warehouses can be categorized in many different ways. They can be categorized by size, the customers they serve, the units they handle, the storage types they use, and other characteristics stated in Section 2.1. This section explains a few different ways to categorize warehouses. This supports identifying which types of warehouses are suitable for operational data-driven productivity improvement for this research.

There are more types of warehouses than described in this section, but it gives an overview of the most common types. The distinction can be made based on other characteristics as well, such as inventory characteristics, throughput and service requirements, footprint and capital cost of equipment, and labor costs.

Still, it is important to know the characteristics of common types of warehouses to ensure the general applicability of the model. Besides, excluding warehouses with extraordinary characteristics that might not fit within the concept of the common types described in this section gives insight into the scope of the model.

A.2.1 Building Size

A general distinction made by Onstein et al. (2021) in the "typology of distribution center facilities" is about the building size. They state seven categories of building size, ranging from XXS ($< 200m^2$) to XXL ($> 40,000m^2$).

Interesting conclusions from the typology regard the relevance of larger-size warehouses for the Dutch logistic market. The share of large (L) facilities ($> 20,000m^2$) is relatively small (19%), but they represent almost half (47%) of the total 42,1 million m^2 of logistics facility in The Netherlands. Besides, at least a medium (M) size ($> 8,000m^2$ is needed to serve parcels as well as pallets and bulk.

A.2.2 Warehouses and their Customers

Bartholdi and Hackman (2019) makes general distinctions between the following types of warehouses based on the customers they serve:

- A *retail distribution center* serves retail giants like Walmart and Target, providing scheduled shipments to retail stores. Orders are typically substantial in volume, serving hundreds or thousands of items. Advance order information allows for effective planning, with some products being dispatched to stores to support marketing campaigns.
- A *service parts distribution center* manages spare parts for expensive capital equipment, such as automobiles and medical devices. They stock a vast inventory of parts, including high-value items. While overall activity is statistically predictable, individual part demand is uncertain, necessitating the maintenance of substantial safety stock. This can result in increased space requirements and longer order-picking distances. Service parts warehouses handle two primary orders: stock orders for replenishing dealer inventories and emergency orders for critical equipment repairs.
- A *catalog fulfillment or e-commerce center* receives small orders from individual customers via various channels. Orders are typically small but numerous, requiring prompt fulfillment and shipment
- A *3PL warehouse* offers outsourced warehousing services to multiple clients, achieving economies of scale and serving as overflow facilities during demand surges. This type of warehouse can have characteristics of other types depending on the customer(s) they serve.
- A *perishables warehouse* specializes in perishable items requiring refrigeration, such as food and vaccines. These warehouses prioritize space efficiency and strict temperature control. They follow inventory management principles like First-In, First-Out (FIFO) and First-Expired, First-Out (FEFO) and adhere to handling restrictions. Different temperature zones are maintained for various products.

A.2.3 Units of Handling

An important characteristic of every warehouse is the different units of handling. The units of handling of a warehouse are the units of measure that are applied. In general, the largest unit tracked in a warehouse is a pallet. The smallest unit tracked of a product is a Stock Keeping Unit (SKU). In between, the handling units are (large to small) a pallet tier/layer, a case/carton/box, and an inner pack. Often, products arrive in a warehouse packed in high volume in a large unit and they are shipped packed in low volume in a smaller unit.

A.2.4 Storage Strategies

Each location in a warehouse has a unique address in a WMS. The term Location refers to a unique, specific, designated place within the warehouse where goods are stored, or specific activities take place. This applies to storage locations such as bulk storage and transit locations like an inbound dock. All these locations consume space, which is a main resource, which means it needs to be used as efficiently as possible.

There are two main storage strategies: dedicated and shared. Dedicated means each storage location is assigned to a specific product. Shared means that products can be stored in multiple storage locations, and one storage location can contain different products over time. Figure A.1 by Bartholdi and Hackman (2019) shows the typical use of the two main strategies.

The shared storage strategy maximizes space utilization but increases management complexity. It is typically used for bulk storage areas where most volume is held on pallets, as is the case for most 4Supplychain clients.

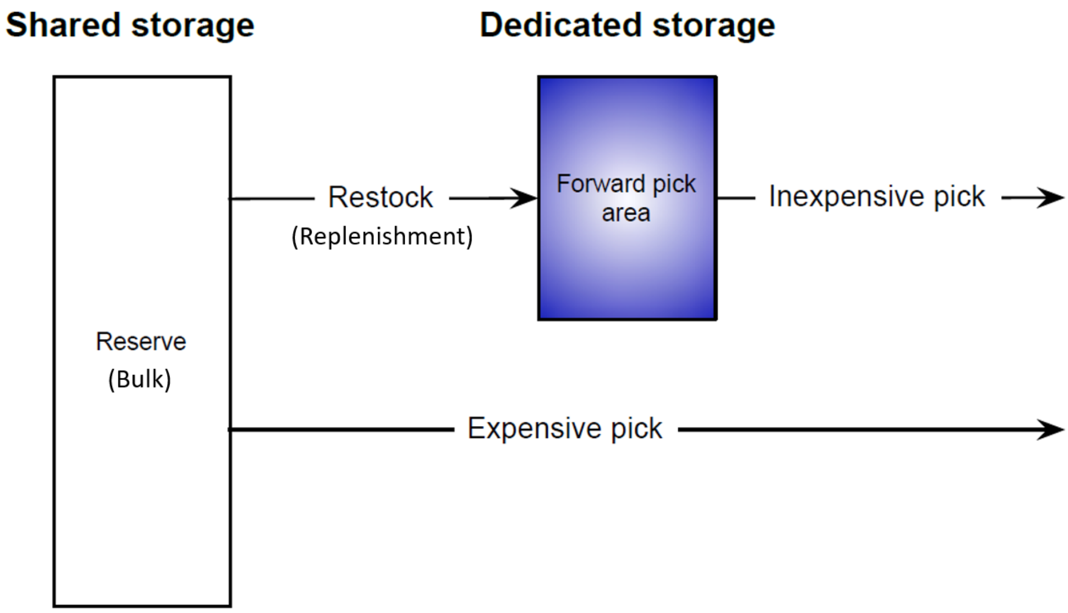

Figure A.1: Typical use of the two main storage strategies (Bartholdi and Hackman, 2019)

A.3 Warehouse Activities

Figure 1.1 shows the five steps that describe the general operations of a warehouse. From these steps, the general warehouse activities follow. The term Activity refers to any operation or process that takes place within a warehouse to manage the storage, handling, and distribution of goods. This section provides more insight into these activities. It describes the different methods and challenges per activity. Frazelle (1996) analyzed the division of labor and operating costs over the activities for a typical warehouse. Typically, most products follow the flow from receipt to bulk to forward area to shipment, and all activities are carried out manually with the help of human-controlled equipment.

A.3.1 Receiving

Efficient receiving starts with an advance notification of the arrival of products. On arrival, the product is unloaded and possibly staged for put away. Normally it is scanned for register in the WMS and inspected. Typically, receiving is not very labor intensive and only accounts for about 10% of the operating costs in a typical distribution center (Frazelle, 1996).

A.3.2 Put-away

The put-away activity starts with determining a storage location. Since this has a large impact on the efficiency of the subsequent activities, this is very important. When the location is determined, the product can be put away and scanned to record it in the WMS. Put-away typically requires about 15% of the warehouse operating expenses (Frazelle, 1996).

A.3.3 Order Picking

Order picking starts with the receipt of a customer order. The WMS then executes several tasks. It checks the availability of inventory. Then it produces a pick list. It produces necessary shipping documentation. Last, it plans the order picking and shipping.

Typically, order picking accounts for about 55% of warehouse operating costs, which means it consumes a large part of the resources. This activity can be further divided into traveling (55% of order picking time), searching (15%), extracting (10%), and paperwork and other activities (20%) (Frazelle, 1996).

A.3.4 Replenishment

To facilitate order picking, the products that are first stored in large units of measure (bulk) like pallets, must become available in small units of measure fit for picks. This is generally not done by the order pickers but by restockers. They extract the products from their bulk location, prepare them by removing shrink-wrap or opening boxes, and place them at the pick location. This activity is called replenishment.

Since restockers move large units of measure compared to order pickers, they can move more units at the same time. In general, a warehouse needs one restocker for every five pickers, however, this depends a lot on the patterns of flow (Bartholdi and Hackman, 2019). Combining the analysis of Frazelle (1996) and Bartholdi and Hackman (2019), we derive that replenishment accounts for about one-fifth of 55%, so roughly about 10% of the operating costs of a warehouse.

A.3.5 Checking and Packing

Orders have to be checked and packed before they are ready for shipment. Often when products are ordered in small units of measure, they need to be packed in cartons and/or pallets. If orders already exist out of full pallet loads, extra packing is not always necessary. When the products are packed, they are checked and scanned.

Packing and checking are labor-intensive. However, there is little traveling. It is hard to assign a typical part of the operational costs to packing and checking since the workload of this activity differs significantly based on warehouse type and customer needs. Also, this activity is often analyzed together with order picking (or sometimes shipping).

A.3.6 Shipping

Shipping is the last activity in warehousing. It may include some traveling if products are staged before shipment. This is often the case when products have to be delivered in reverse order of delivery or if it takes too long to fill a trailer. These freights have to be double-handles, which takes more time. Before shipping, the truck is often scanned to register departure and update the customers. In general, since shipping handles large units of measure, shipping is not very labor intensive. It accounts for a relatively small part of the operational costs.

A.3.7 Other Activities

Frazelle (2015) notes the evolution of warehouses from storage locations, to fulfillment centers. These modern warehouses often carry out several extra activities, the Value-Adding Processes (VAP). There are a few VAP that are commonly applied in modern warehouses. Typical examples are:

- ticketing or labeling
- alterations (like letter marks on clothing)
- repackaging (which adds more design value compared to packing)
- kitting (repackaging to form a new item)
- postponement of final assembly
- invoicing

The application of these extra services differs a lot per warehouse depending on their capabilities and customer needs. With this also the workload and operational costs of these activities are highly variable. For a total analysis of productivity performance, it is often important to analyze these extra VAP cases individually.

A.4 Storage and Handling Equipment

Many types of special equipment have been designed to increase warehouse productivity. The type of equipment used and the region of storage determine the *storage mode*. The storage mode is a way of storing for which the costs to pick are approximately equal within that mode.

Most storage equipment is one of the following types: pallet storage (large units), lift truck, shelving (small units), or conveyors. Some of them reduce labor costs, by increasing pick density, facilitating picking/restocking, or moving products. Other equipment increases space utilization by partitioning space into subregions for similarly-sized SKUs, or by enabling high storage (where space is inexpensive). This section explains the most common types of equipment as described by Bartholdi and Hackman (2019).

A.4.1 Pallet Storage

Pallets are generally the largest unit of measure handled in a warehouse. Although there are six standard sizes of pallets, the way storage and movement can typically be generalized as well. Since most products are often stored on pallets most of the time, efficient storage is very important. Five different common types of pallet rack storage are:

- *Selective rack* stores pallets one deep.

- *Double-deep rack* consists of two single-deep racks placed behind each other.
- *Push-back rack* extends double-deep rack to 3–5 pallet positions per lane.
- *Drive-in/drive-through rack* allows lift trucks to access interior loads, supporting FIFO policies.
- *Pallet flow rack* uses slanted shelving with rollers, facilitating gravity-driven movement of pallets and put-away from the back.

A.4.2 Lift Trucks

For put-away and retrieval of the pallets in these pallet racks, some type of *lift truck* is required. Sometimes specialized trucks are necessary to operate in special racks. The most common types of lift trucks are:

- *(Counterbalance) lift truck*: a versatile type with sit-down and stand-up versions.
- *Pallet truck* or *pump truck*: a specific type only suitable for transport at floor level.
- *Reach lift truck*: equipped with a reach mechanism for pallet handling at greater heights.
- *Turret Truck*: utilizes a turning turret for handling loads, enabling a narrow aisle.
- *Stacker Crane*: part of an Automated Storage-and-Restrievel Systems (AS/RS) designed for handling tall loads.

Most of these lift trucks also exist in versions with a double-deep forklift to carry (stacks of) pallets two-deep at a time.

A.4.3 Shelving

Shelving is used for the storage of small units of measure, typically cases or smaller. There are different kinds of equipment for this as well. The most common types of shelving are:

- *Bin-shelving/static rack* is the most basic mode. These are shallow shelves on which the product is picked from the same side as it is restocked.
- *Gravity flow rack* is a type with tilted shelves with rollers. Shelves can be restocked from the back. Different versions are *vertical frame*, *layback frame*, and *front-tilted layback frame*.

A.4.4 Conveyors

Conveyors can automate traveling and reduce labor costs, however, they come with some issues regarding the suitability of products for conveyors and the restriction of movement of workers. A special type of conveyor is the *sorting equipment*. These systems are installed downstream from picking, to simplify the order picking and sorting afterward for efficiency.

A.5 Warehouse Management System

Section 1.2 emphasizes the complexity of the coordination of large warehouses. This is why almost all these complex warehouses use a Warehouse Management System (WMS). These systems are complex software packages that help manage inventory, storage locations, and the workforce, to ensure that customer orders are picked quickly, packed, and shipped (Bartholdi and Hackman, 2019).

A.5.1 Functions of a WMS

A WMS has several basic functions. The most basic functions are recording the inbound and outbound shipments. Another standard function is that of a *stock locater system*, which manages the inventory of products and the inventory of storage locations. This supports the directed put-away and order picking. For this, the WMS needs to be able to work in real-time by updating simultaneously from multiple sources (receiving, picking, shipping, etc.).

Besides its basic features, a WMS often includes multiple high-end features and sometimes even advanced features. Table A.1 shows the processes that can be supported with these features, according to Bartholdi and Hackman (2019). Over time, WMSs are becoming more and more advanced by including more of these features, slowly evolving to more complete supply chain execution systems.

Table A.1: Processes that can be supported with WMS-features according to Bartholdi and Hackman (2019)

Basic Features	**High-end Features**	**Advanced Features**
Appointment scheduling	RF-directed operation	Multi-DC view
Receiving	Cycle counting	Sku slotting
Quality assurance	Carton manifesting	Broken-case flow
Put-away	Replenishment	EDI capability
Location tracking	Value-added services	Parcel shipping
Work-order management	Vendor/carrier compliance	Impact analysis
Picking	Trailer manifesting	Traffic management
Packing and consolidation	Configurability	Import/export management
Shipping	Returns	ASP capability
	Pick/put to light	
	Yard management	
	Wave management	
	Labor management	
	Task interleaving	
	Flow-through processing	

A.5.2 WMS-Data

In a WMS, data is typically organized into several categories to ensure efficient warehouse operations. All these categories are interconnected and influence the others. Although categorization can vary between different systems, common categories as described by Murray (2012) are:

- *Master Data* refers to the core, foundational data that remains relatively static over time and provides a consistent reference point for various transactions and operations within the warehouse. Several key examples are *location master*, *item master*, *client master*, but there are many more.

- *Transaction Data* encompasses all the data generated from various transactions occurring in the warehouse. These are the higher-level logistical decisions, mostly relevant for the inbound, outbound, and transfer orders. Important data files include *goods receipts* or *inbound data*, *shipments* or *outbound data*, and *transfers*.

- *Inventory Data* pertains to the real-time status and movement of items within the warehouse. Elements include *current stock levels* and *inventory adjustments and movements*.

- *Work data* revolves around the tasks and activities assigned to warehouse personnel. These include *picking tasks*, *put-away tasks*, *replenishment tasks*, and *packing tasks*.
- *Configuration data* or *control data* relates to how the WMS is set up and customized for specific operational needs. This type of data can be regarded as settings that can be adjusted to improve warehouse productivity performance. It includes *workflow settings*, *rules for order picking*, *put-away strategies*, and *alert and notification configurations*.

Other categories that are sometimes part of the WMS data are *reporting and analytics data*, *document data*, and *historical data*.

Appendix B

Classifications Warehouse Performance Indicators In Literature

Table B.1: Direct warehouse performance indicators classified by dimension, derived from a literature study by Staudt et al. (2015) examining 43 articles

Dimensions	Indicator Name	NPA
Time	Order Lead Time	9
	Receiving Time	5
	Order Picking Time	4
	Delivery Lead Time	3
	Queuing Time	2
	Putaway Time	2
	Shipping Time	2
	Dock-to-stock Time	2
	Equipment Downtime	1
Quality	On-time Delivery	10
	Customer Satisfaction	8
	Order Fill Rate	5
	Physical Inventory Accuracy	5
	Stock-out Rate	4
	Storage Accuracy	4
	Picking Accuracy	3
	Shipping Accuracy	2
	Delivery Accuracy	2
	Perfect Orders	2
	Scrap Rate	2
	Orders Shipped on Time	1
	Cargo Damage Rate	1
Cost	Inventory Cost	7
	Order Processing Cost	3
	Cost as a % of Sales	3
	Labor Cost	2
	Distribution Cost	2
	Maintenance Cost	2
Productivity	Labor Productivity	11
	Throughput	10
	Shipping Productivity	7
	Transport Utilisation	5
	Warehouse Utilisation	4
	Picking Productivity	3
	Inventory Space Utilisation	3
	Outbound Space Utilisation	3
	Receiving Productivity	2
	Turnover	2

Table B.2: Warehouse performance indicators classified by warehouse activity (and dimension) by Frazelle (2002a)

	Financial	Productivity	Utilization	Quality	Cycle Time
Receiving	Receiving cost per line	Receipts per man-hour	% Dock door utilization	% Receipts processed accurately	Receipt processing time per receipts
Putaway	Putaway cost per line	Putaways per man-hour	% Utilization of putaway labor and equipment	% Perfect putaways	Putaways cycle time (per putaway)
Storage	Storage space cost per item	Inventory per square foot	% Locations and cube occupied	% Locations without inventory discrepancies	Inventory days on hand
Order Picking	Picking cost per order line	Order lines picked per man-hour	% Utilization of picking labor and equipment	% Perfect picking lines	Order picking cycle time (per order)
Shipping	Shipping cost per customer order	Orders prepared for shipment per man-hour	% Utilization of shipping docks	% Perfect shipments	Warehouse order cycle time

Table B.3: Productivity indicators for different warehouse activities, according to Frazelle (2002a)

Activity	**Productivity indicator**
Receiving	Receipts per man-hour
Putaway	Putaway per man-hour
Storage	Inventory per square foot
Order picking	Order lines picked per man-hour
Shipping	Orders prepared for shipment per man-hour

Table B.4: Warehouse productivity indicator definitions, according to (Staudt et al., 2015)

Indicator	**Definition**
Labor productivity	Ratio of the total number of items managed to the amount of item-handling working hours
Throughput	Items/hour leaving the warehouse (or items/m^2 per day)
Shipping productivity	Total number of products shipped per time period
Transport utilization	Vehicle fill rate
Warehouse utilization	The average amount of warehouse capacity used over a specific amount of time
Picking productivity	Rate of space occupied by storage
Inventory space utilization	Utilization of the area inside the warehouse used for retrieving, order picking, packing, and shipping
Outbound space utilization	Total number of products picked per labor hours in picking activity
Receiving productivity	Number of vehicles unloaded per labor hour
Turnover	Ratio between the cost of goods sold and the average inventory

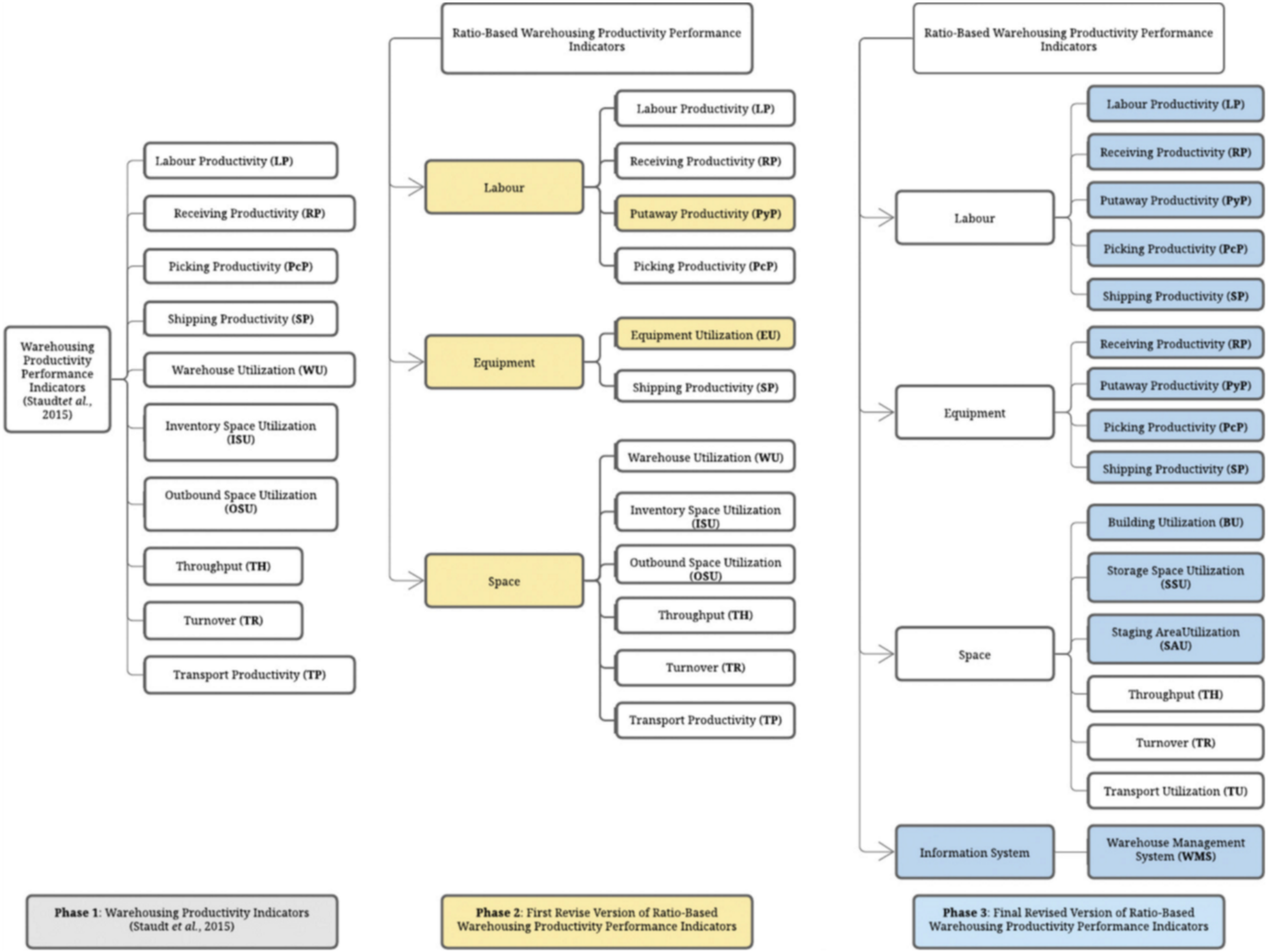

Figure B.1: The revised ratio-based warehousing productivity performance indicators, according to Karim et al. (2020)

Appendix C

The Sets of Follow-Up Questions

CONFIDENTIAL APPENDIX

Appendix D

The Sets of Optimization Measures

CONFIDENTIAL APPENDIX

Appendix E

Model Interface

Figure E.1 shows a snapshot of the graphical interface of the model showing the input parameters, portfolios and steps of the benchmarking process to identify opportunities for optimization.

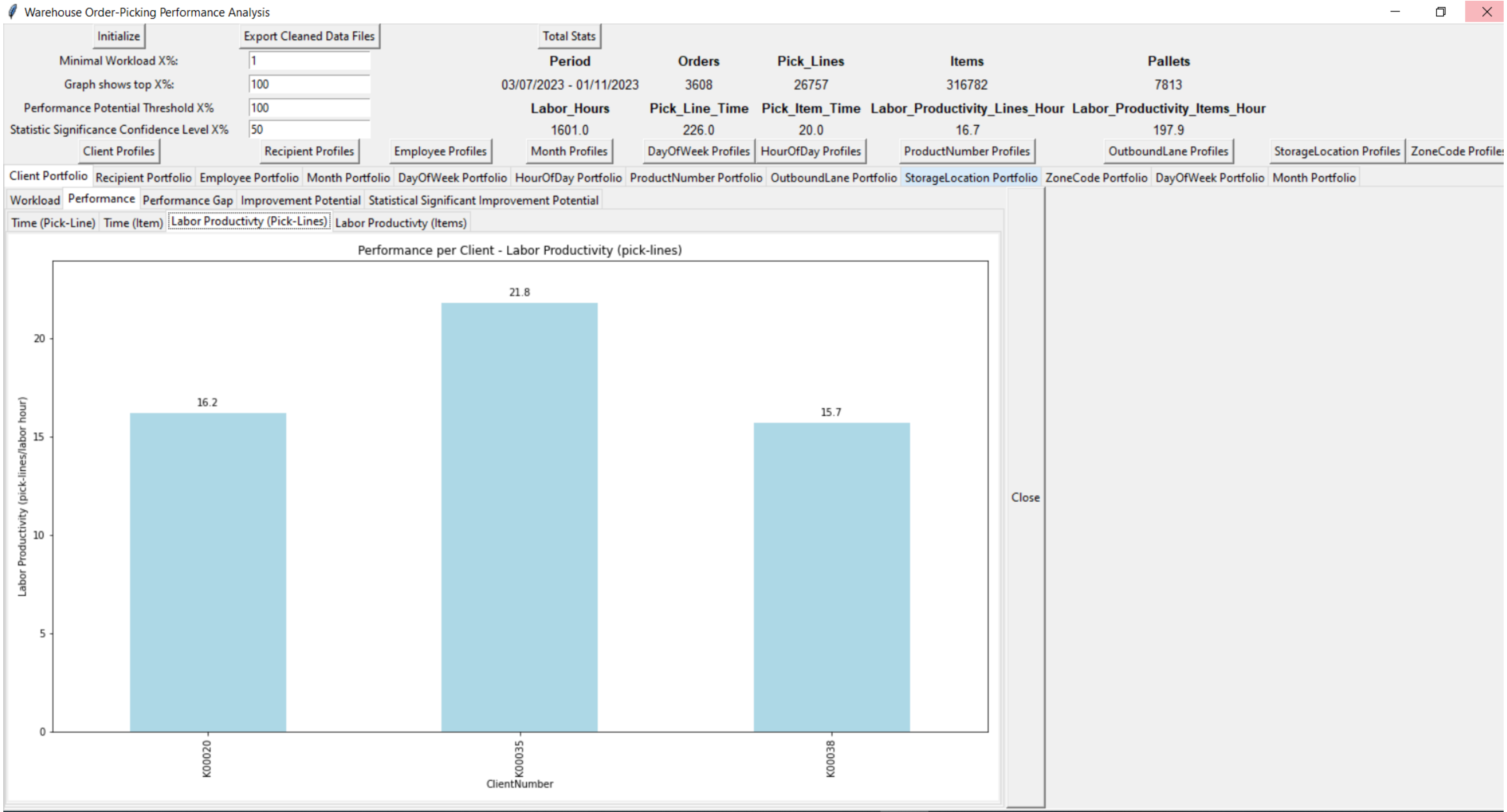

Figure E.1: A snapshot of the graphical interface of the model showing the input parameters, portfolios and steps of the benchmarking process to identify opportunities for optimization

Appendix F

Extended description of AG Logistic Case

This appendix provides an elaborate description of the AG Logistics case, the analyzed warehouses and its characteristics. It provides background information on the context of the case. Besides, the description could support the interpretation of the model results.

AG Logistics is a 3PL provider with five warehouses located in central parts of the Netherlands. Their sizes range from 13,000 to 64,000 m^2. The warehouse activities depend on the clients they serve. Mostly they serve retailers and e-commerce businesses, which means the warehouses share most characteristics with those types of warehouses. This section describes the warehouse type, activities, equipment, WMS and current status of performance analysis of AG Logistics to provide context to the case.

F.1 Warehouse Type AG Logistics

One of their main warehouses, located in the city of Ede, serves several retailers with long-shelf-life foods and other consumer goods. They serve about twenty different clients, from which one main client accounts for more than 75% of the workload. The warehouse covers 28,000 m^2. Unless specified otherwise, this warehouse is 'the warehouse' in this thesis report.

As with most warehouses, this warehouse receives a high volume of large units of handling. This regards full-pallet loads with occasional pallet layers. The warehouse ships both large units of handling as well as smaller units of handling. Besides full pallets and pallet layers, they also ship cases, inner packs, and (occasionally) pieces.

For most clients, the only type of storage is bulk storage, the pallets reserve. However, for the main client, accountable for over 75% of the workload, and a few other clients, there also is a dedicated forward area. This forward area is used for less-than-pallet orders, so the order picking of small units of handling. The general storage strategy applied to bulk locations is shared storage, whereas the storage strategy applied to forward locations is dedicated storage.

F.2 Warehouse Activities AG Logistics

Figure F.1 shows the flow of products in a typical warehouse. This can be regarded as a simplified version of the warehouse flow of AG Logistics. It shows the chronological movement of products from area to area, as well as the different activities that are carried out in between. The warehouse activities include all the standard activities described in Appendix Section A.3.

Important to notice is that in practice at AG Logistics there is no distinction between inbound and outbound docks. However, the inbound and outbound products are staged at different locations per dock. They are either at a receiving dock location or an outbound lane location, which are segregated by a pathway.

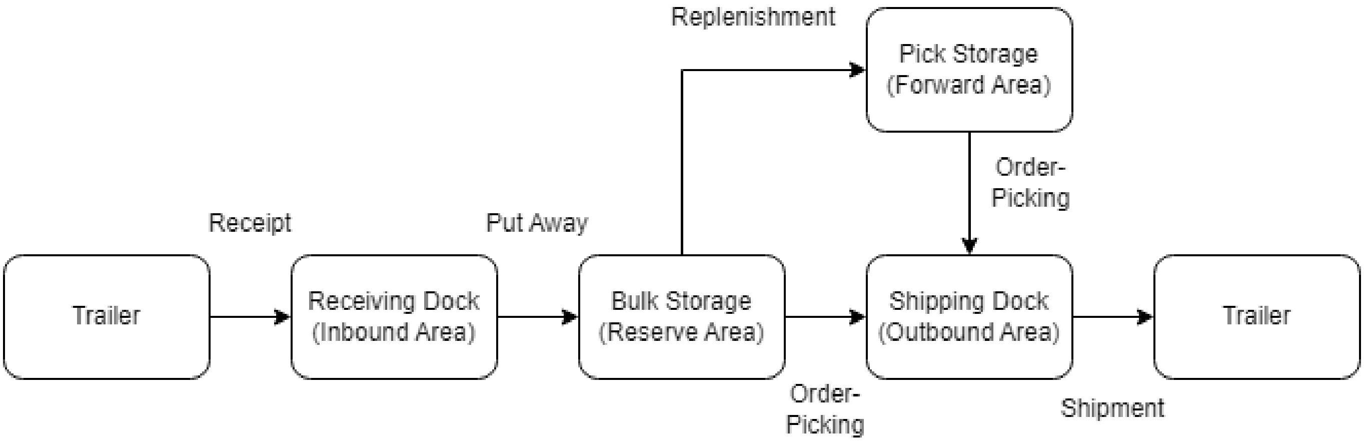

Figure F.1: Simplified warehouse flow and activities

The simplified warehouse flow excludes the level of detail of the different steps within an area of the warehouse. Furthermore, the warehouse carries out a few VAP that are not part of the standard activities. These extra steps complicate the warehouse flow.

Figure F.2 shows the overall warehouse flow in the warehouse. It becomes clear that in practice there are a few extra steps, with extra locations and movements that are not commonly discussed in the standardized activities in theory.

Figure F.2 also shows the size of the units of handling that flow from location to location. Commonly two to four full pallets are moved at the same time, however, all the flows from and to the bulk storage contain just one full pallet. In the forward area, most movements contain single or low-quantity cases, inner packs, or pieces. Appendix Section F.3 explains more about these differences in relation to the warehouse equipment.

The warehouse executes three VAP:

- At the Repack Station ('Vetipack') products are taken out of their original packaging material and repacked in new material. It is often used for design purposes of the customers. It is an inbound controlled VAP, which means the activity is set at the arrival of the product.
- The Automatic Layer Picker (ALP) is used to fulfill order requests where pallet layers are ordered instead of full pallets. The machine separates layers of pallets to later combine these on a new pallet to fit the requested orders. Because this is based on orders, this VAP is outbound controlled.
- The Alterations ('Activitysquare') location carries out customers' requests to restack products on different pallets or have other special requests. It is also an outbound controlled VAP.

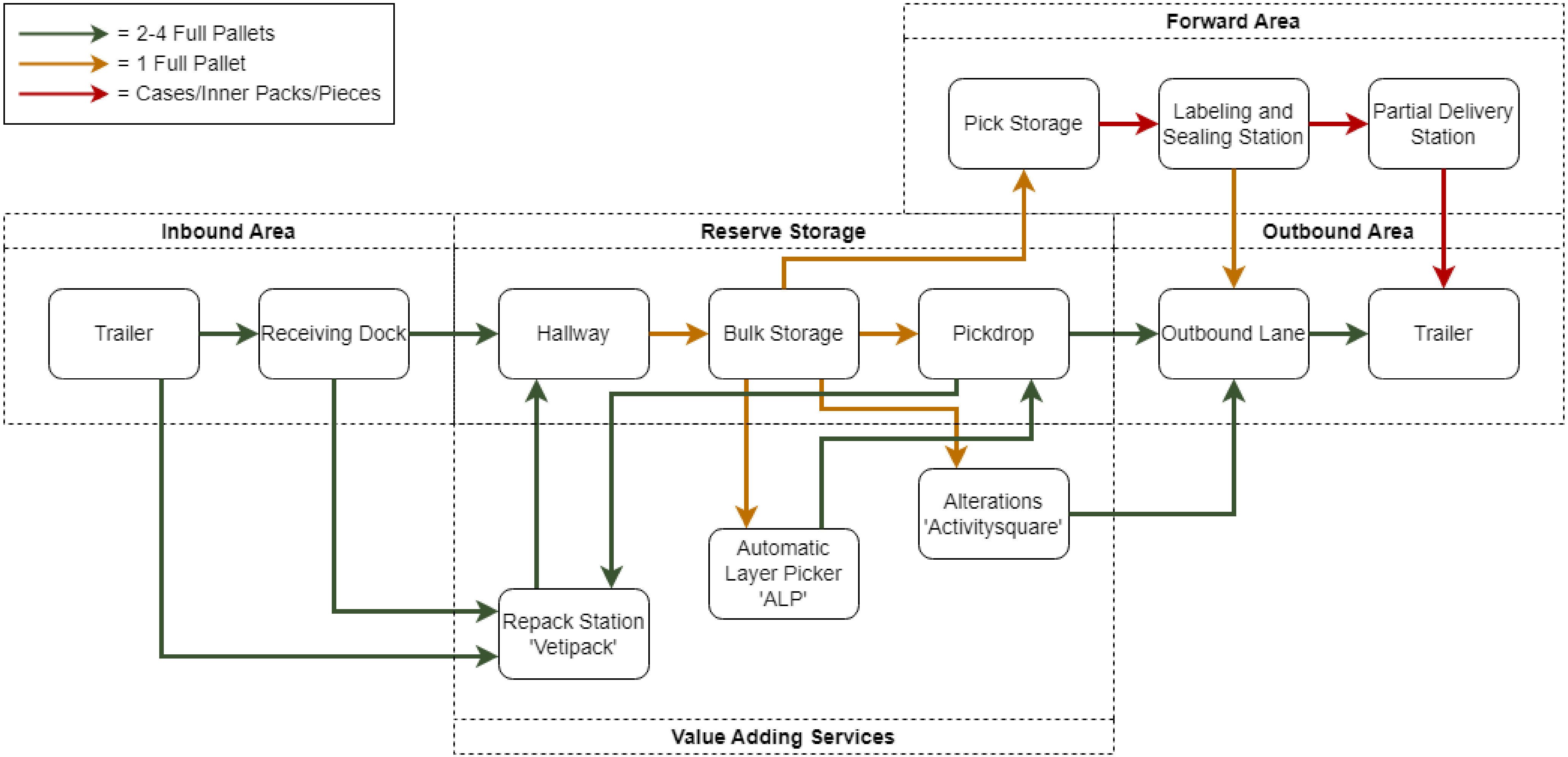

Figure F.2: Overall warehouse flow

F.3 Equipment AG Logistics

Currently, over 95% of the storage locations of AG Logistics are destined for pallet storage (bulk storage). Only a few percent is reserved for picking less-than-full pallets. The MHE used differs for different activities.

F.3.1 Pallet Storage AG Logistics

The only type of pallet storage used is the selective rack (single-deep) storage. This common type of pallet storage provides freedom and does not require complicated management strategies.

Other warehouses of AG Logistics use and have used double-deep racks to increase storage capacity. However, this storage type was regarded as inconvenient for the client portfolio AG Logistics serves. Most products of AG Logistics clients have expiration dates. The requirements per customer of a client differ in terms of remaining shelf life, shelf life compared to previous deliveries, and batch number differences.

In practice, it occurs that one type of product can be stored and divided into six different batches with different expiration dates. Depending on customer requirements and orders, all these different batches may need to be accessible. Double-deep racks and even drive-in/drive-through racks and pallet flow racks do not support this. This is why it is very convenient to ensure the freedom of direct accessibility of the one-deep selective rack.

F.3.2 Lift Trucks AG Logistics

AG Logistics utilizes four different types of lift trucks:

- Single-deep pallet trucks, which are used only for the order picking of less-than-full pallets. All cases, inner-packs, and pieces are manually placed on the single pallet carried by these pallet trucks. AG Logistics owns eight of these.
- Double-deep pallet trucks, which are used for all the movements visualized by the green arrows in Figure F.2. They can move pallets up to two-deep and two-stacked at the same time, so four pallets in total. AG Logistics owns eleven of these.
- Single-deep reach trucks, which are used for all the movements visualized by the orange arrows in Figure F.2. This is always one pallet at a time. AG Logistics owns twelve of these.
- Single-deep (basic) lift trucks, which can carry up to two (stacked) pallets at a time. These are only used for a low number of movements regarding the VAP. AG Logistics owns two of these.

AG Logistics has used a special type of autonomous pallet truck that follows the order picker during the order picking activity. With this machine, the employee does not have to step up and down the truck every time to drive it. However, since it frequently happens that an order picker has to lift a whole remainder of a pallet, means he still has to get up the truck often. The time saving was very small and it complicates the activity, which is why they stopped using it.

F.3.3 Other Equipment Types AG Logistics

AG Logistics does not use any type of shelving to facilitate the order picking of less-than-full pallet-sized units of measure. Currently, the cases, inner-packs, and pieces are taken off pallets by the order pickers manually for each pick.

Shelving would not suit this order picking activity, since most of this order picking regards several cases of the same product at a time. If an order picker takes ten of the same cases per order, the throughput of cases is very high. Shelf replenishment will be very time-consuming. Besides, in these quantities, it frequently happens that whole pallet remains are picked with several cases. This is more efficient than taking several cases from shelves.

The general storage and order picking process does not use conveyors. Since a lot of the workload considers heavy full pallets, most conveyors cannot facilitate the capacity. The only conveyors used are at the ALP.

F.4 WMS AG Logistics

F.4.1 The WMS-system of AG Logistics

AG Logistics uses a WMS by Boltrics. Boltrics is a company that specializes in providing software solutions for 3PL. They have developed their solutions based on Microsoft Dynamics 365 Business Central, which ensures that users benefit from a future-proof platform.

The Boltrics WMS is designed to optimize warehouse processes and help companies work more efficiently. According to Boltrics (2023) they have a wide range of functionalities including all the basic features stated in Table A.1. It also covers almost all high-end features as well, despite yard and labor management. Furthermore, certain advanced features like SKU slotting, Electronic Data Interchange (EDI) capability, parcel shipping, and import/export management are included in the system as well. Common strengths of this WMS are integration with other systems, customization, future-proofness, and user-friendliness.

Experiences within 4Supplychain confirm the view on Boltrics as an advanced WMS that is very suitable for a 3PL provider like AG Logistics.

F.4.2 The WMS-data availability of AG Logistics

At the moment, AG Logistics uses their WMS mostly for operational task coordination. Rarely, the WMS data is used for operational productivity optimization purposes, let alone tactical or strategic productivity optimization interventions. However, most WMSs, including the system of AG Logistics stores a lot of operational data. 4Supplychain believes this can be used for optimization purposes.

The data that can be extracted from the WMS of AG Logistics does not include all the general types of data. AG Logistics WMS data contains:

- master data: including all typical subcategories
- transaction data: goods receipts, shipments, and transfers data
- inventory data: (current) stock levels and inventory adjustments data
- configuration data: The priority rules for order pick sequence

Unfortunately, the work data is not logged, so pick lists, put-away tasks, and replenishment tasks cannot be extracted as assigned to the workers. The configuration data is limited as well because most of the control decisions are based on the common sense of the warehouse employees or ad hoc instructions from the logistic coordinator or team leader on the ground.

However, all the movements of products can be tracked by looking into the inventory adjustments data. This data contains all the registered mutations of inventory levels at any location in the warehouse for any product. By tracking negative and positive mutations of unique pallets on the warehouse locations over time, it's path and duration of different activities can be mapped.

F.5 Performance Analysis AG Logistics

At AG Logistics the extent of performance analysis is very limited. Their whole performance analysis is limited to the number of pallets they receive and ship every week and the fact that they make a profit every month.

This does not directly imply that performance is at a low level. 4Supplychain has encountered cases where performance analysis and optimization were lacking, but the common sense of operational managers ensured a decent-performing warehouse. Still, data-driven performance analysis is of interest for AG Logistics, because it can either confirm the current operational strategy or suggest optimization measures.

Appendix G

Graphs Warehouse Performance Analysis Model

This appendix provides the graphs generated by the performance analysis model. It shows these visualizations for the client portfolio as example portfolio. First it shows the performance measurement graphs, then the graphs for identification of opportunities for optimization.

G.1 Measure KPIs

The section shows the workload and performance measurement for all instances in the client portfolio.

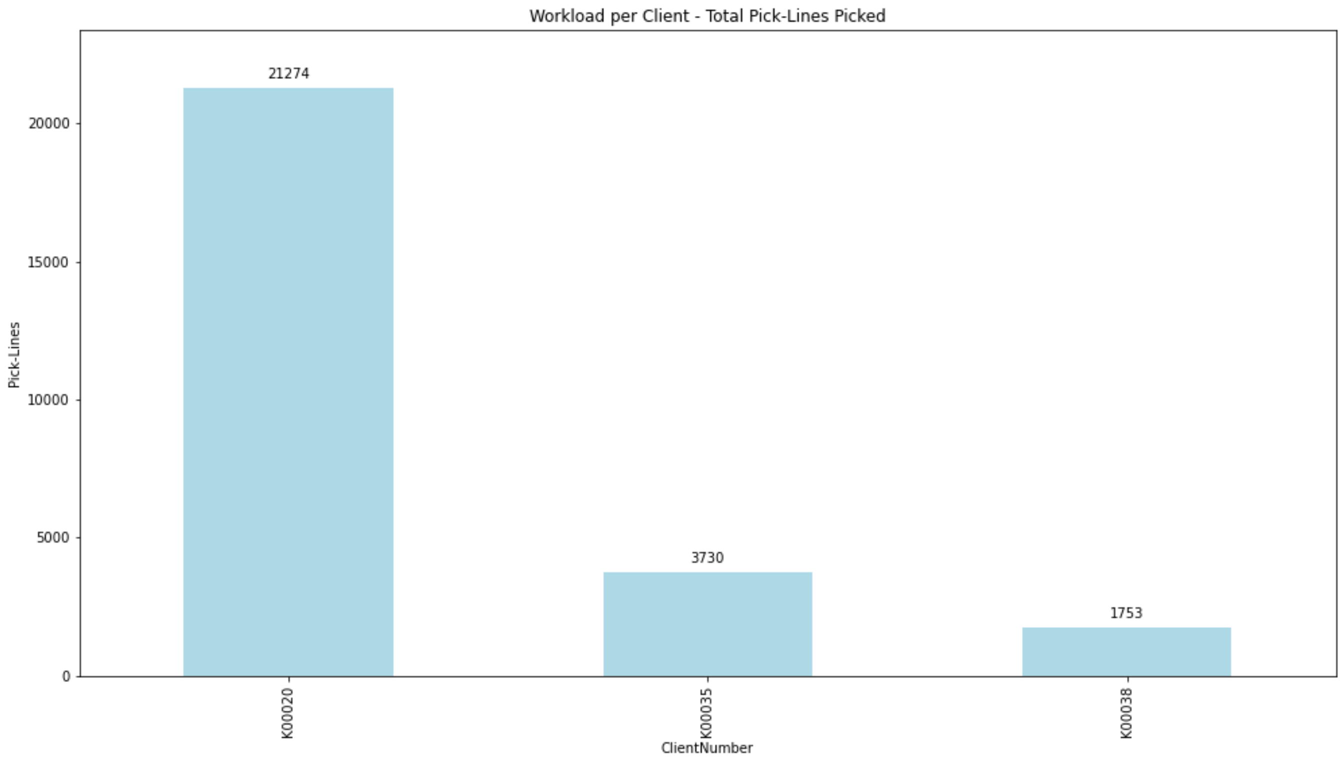

Figure G.1: Client Profile - Workload - Pick-Lines

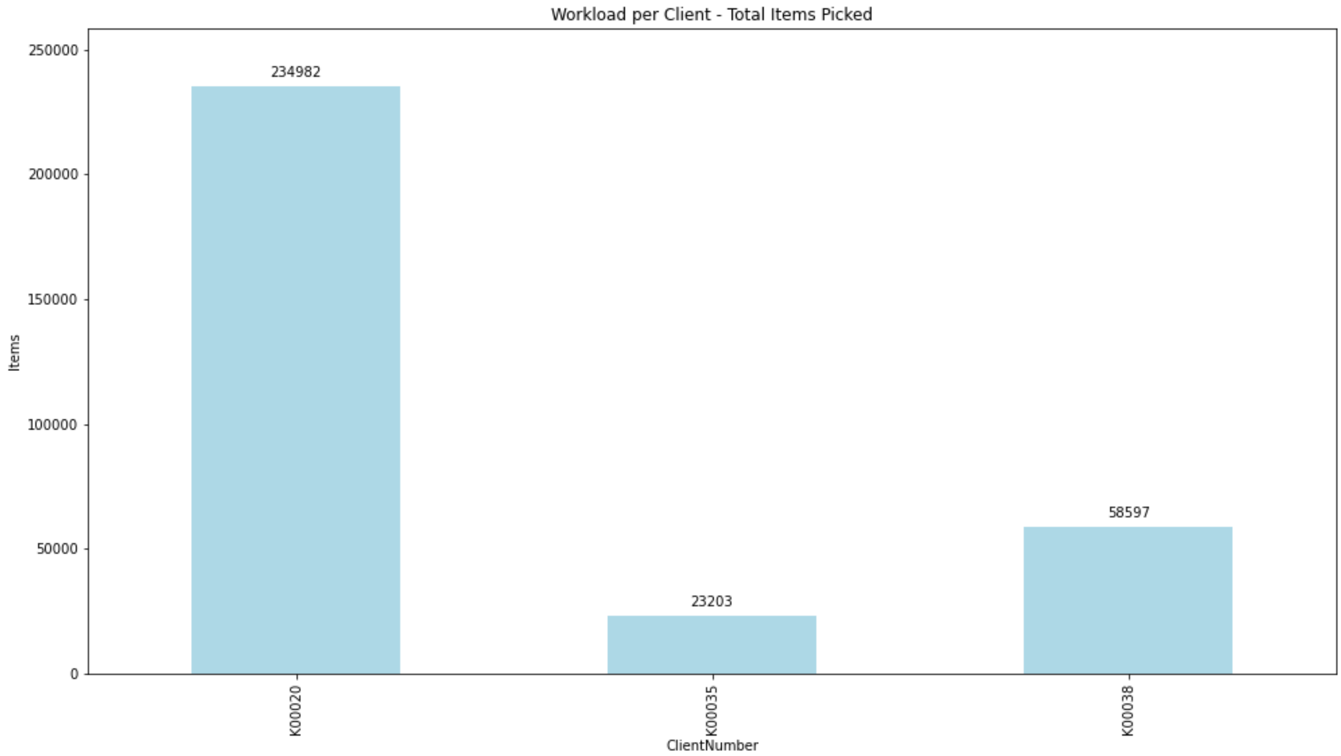

Figure G.2: Client Profile - Workload - Items

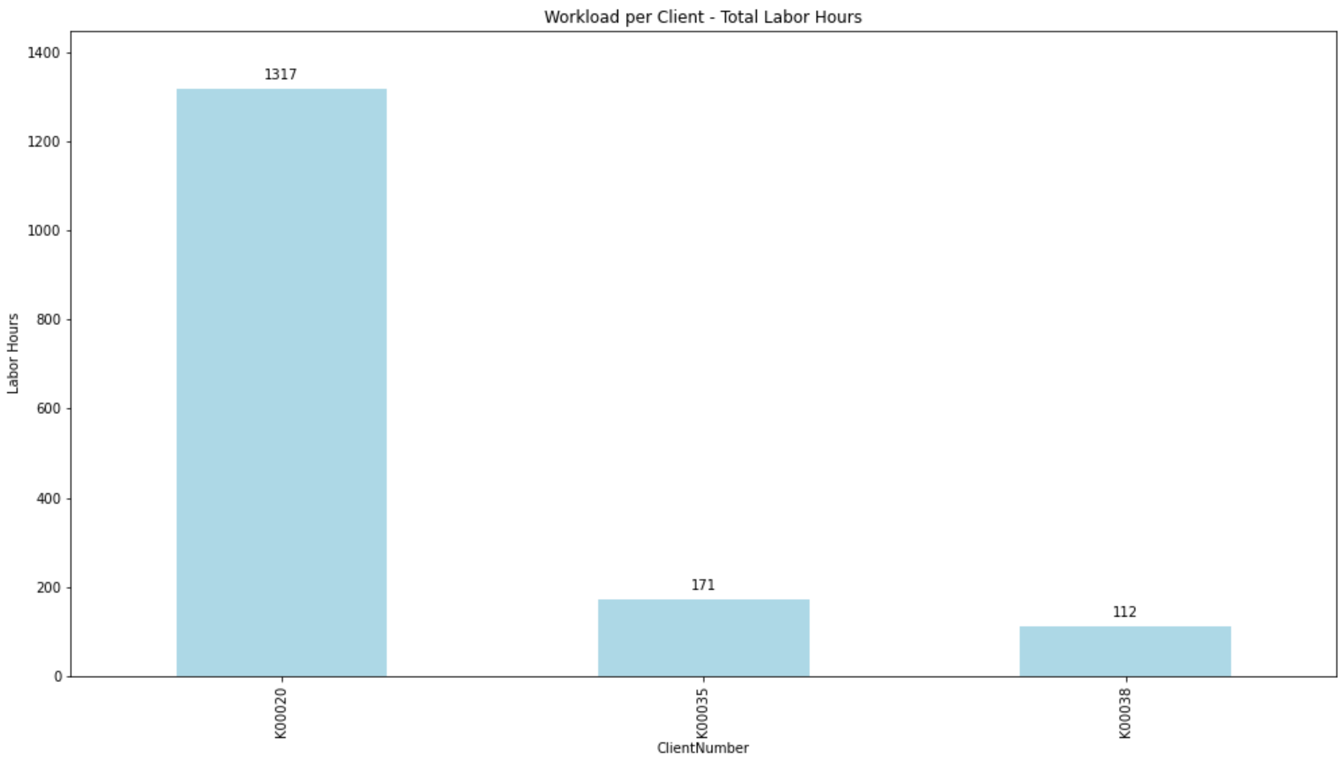

Figure G.3: Client Profile - Workload - Labor Hours

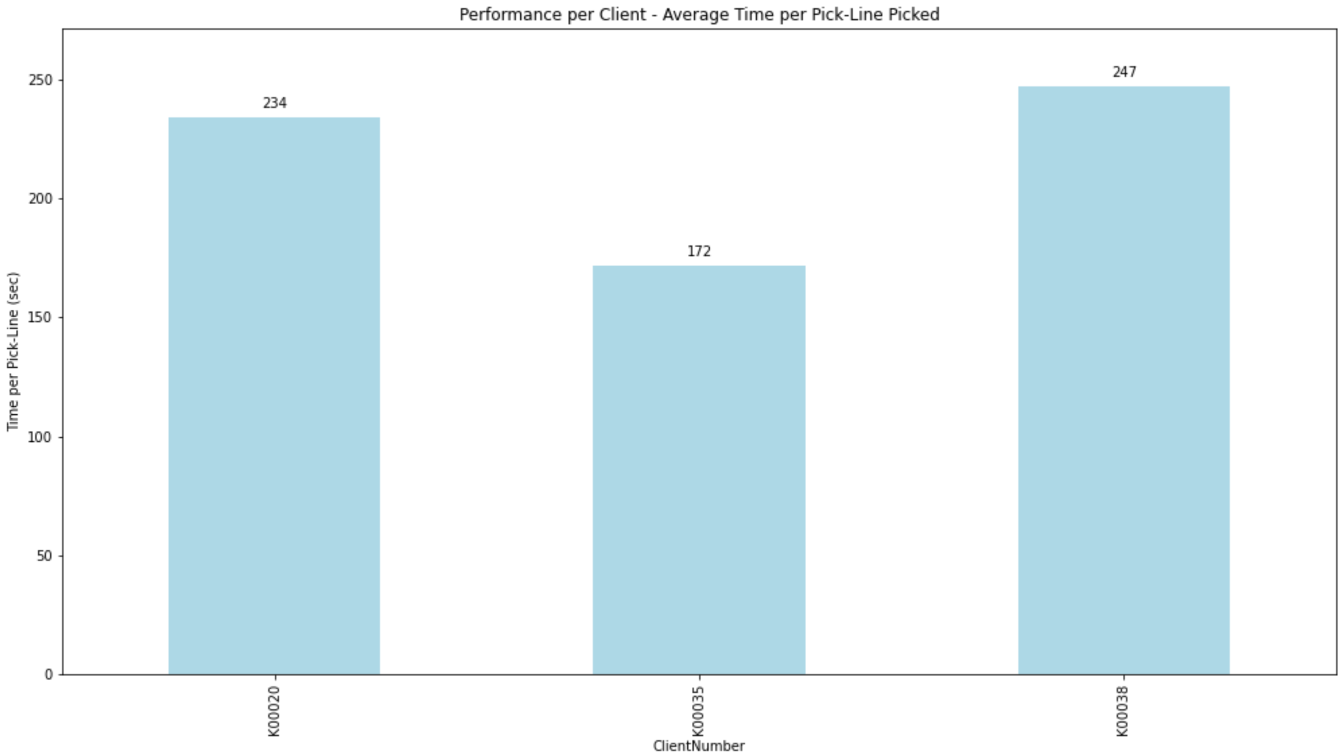

Figure G.4: Client Profile - Performance - Time (Pick-Line)

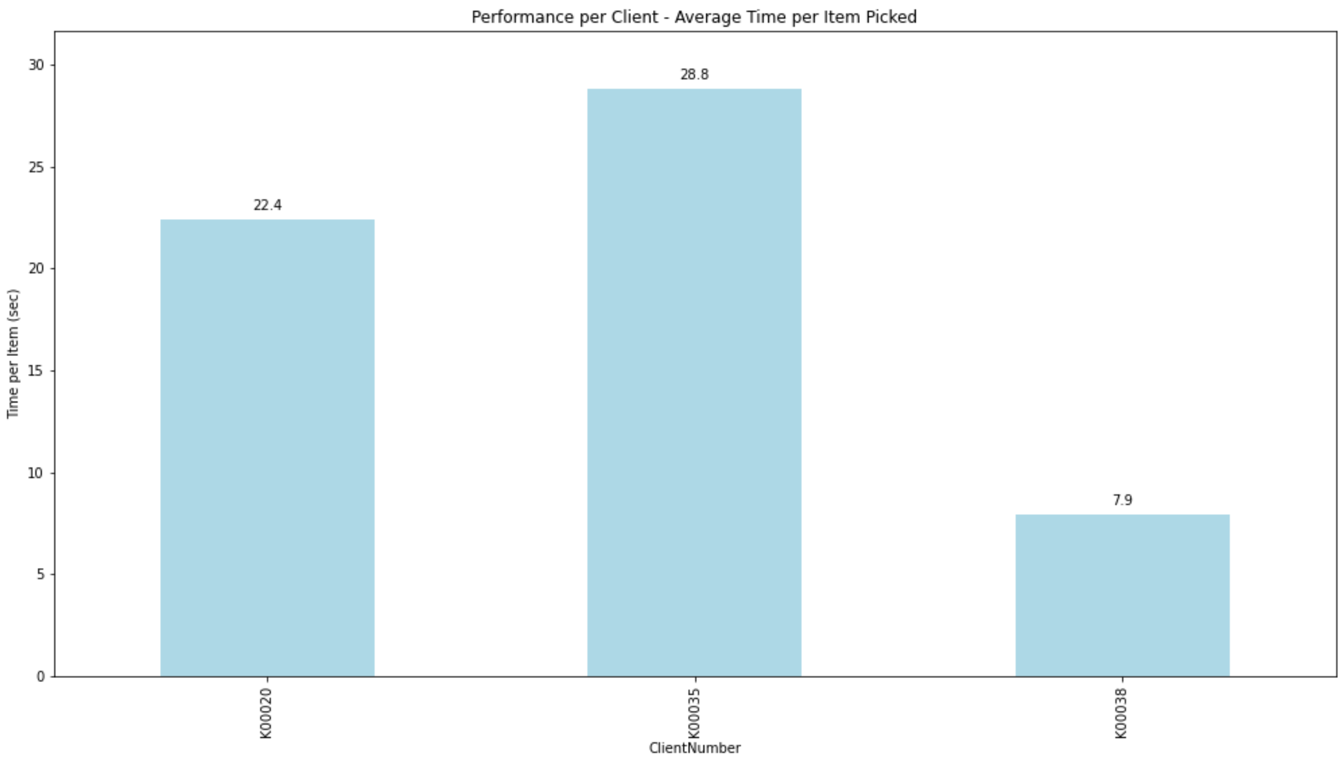

Figure G.5: Client Profile - Performance - Time (Item)

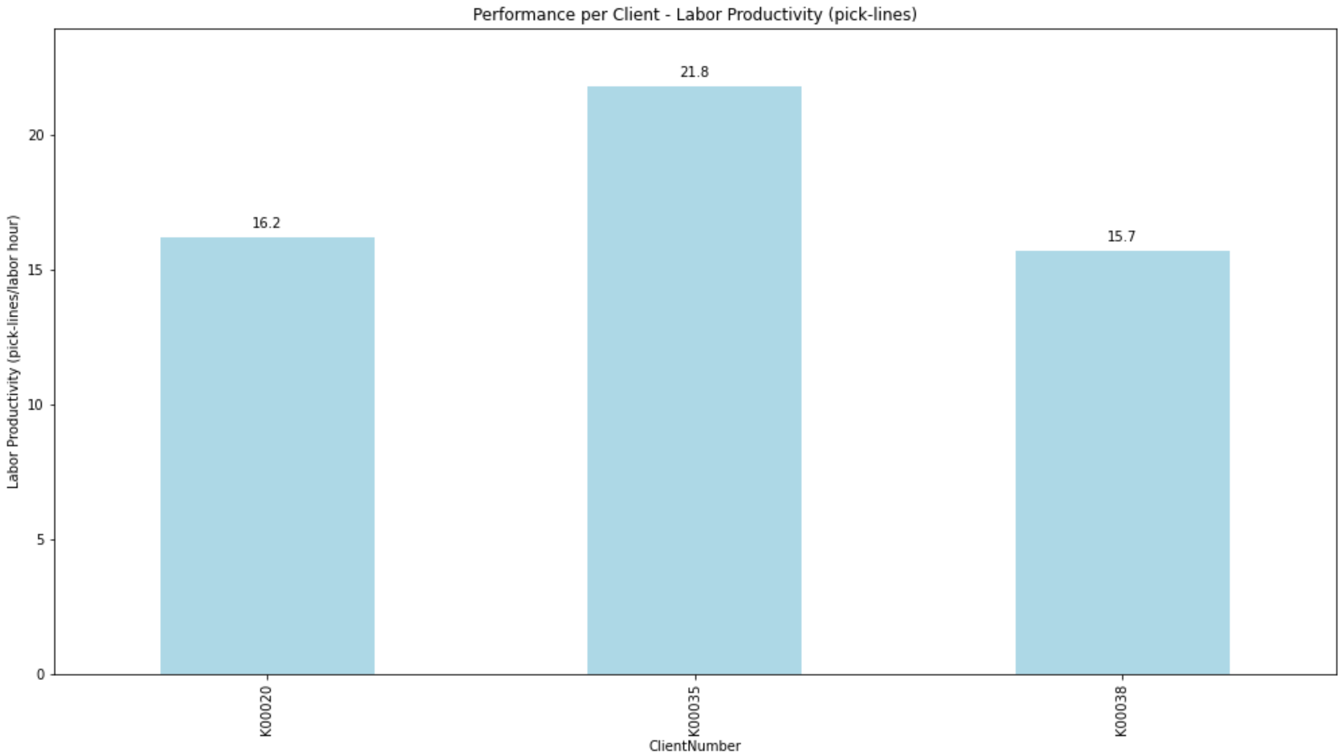

Figure G.6: Client Profile - Performance - Labor Productivity (Pick-Lines)

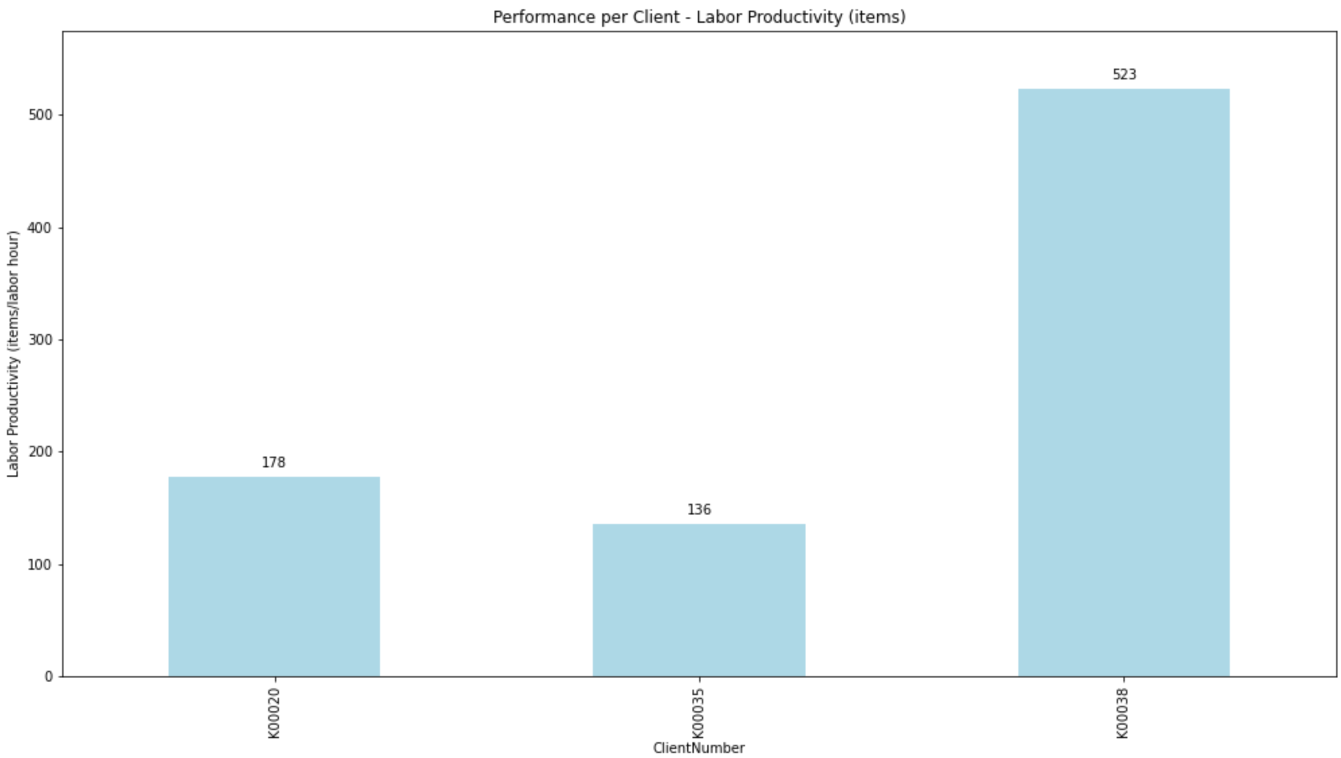

Figure G.7: Client Profile - Performance - Labor Productivity (Items)

G.2 Calculate Performance Gaps

The section shows the performance gaps for all instances in the client portfolio.

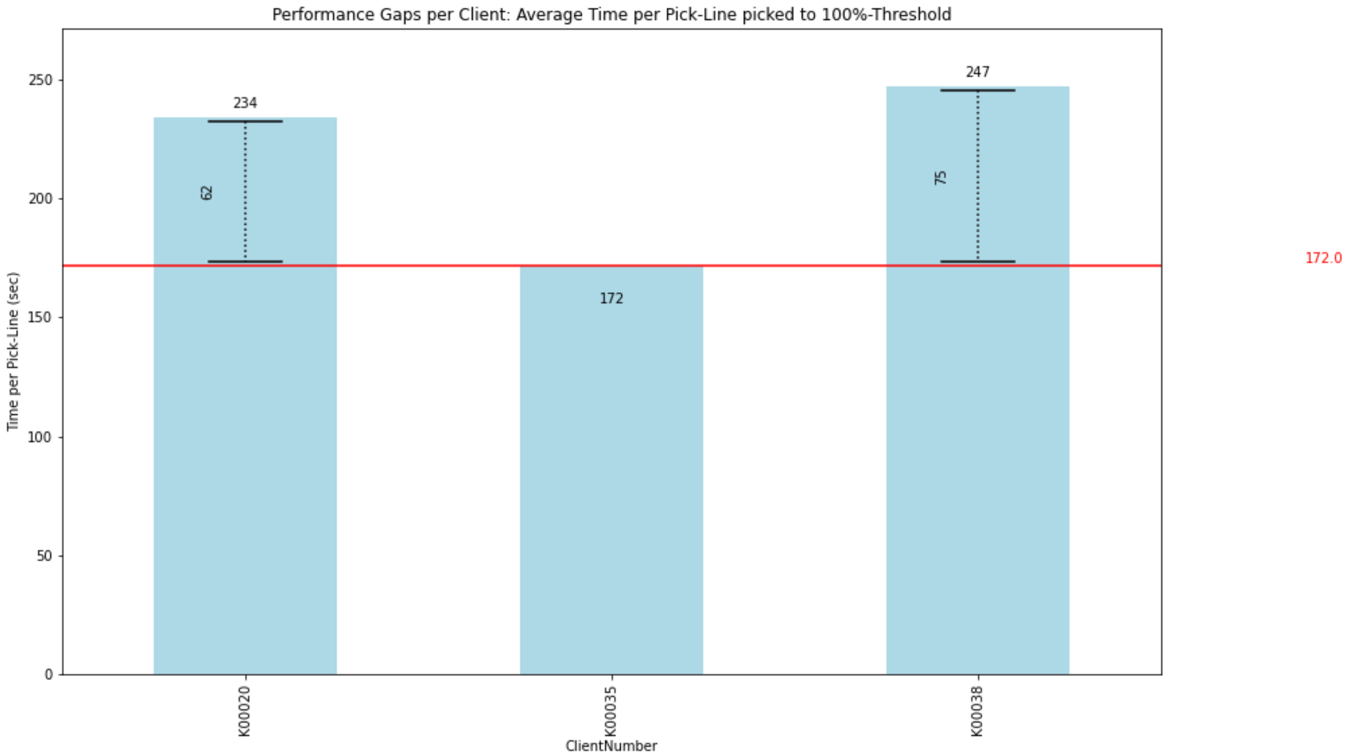

Figure G.8: Client Profile - Performance Gap - Time (Pick-Line)

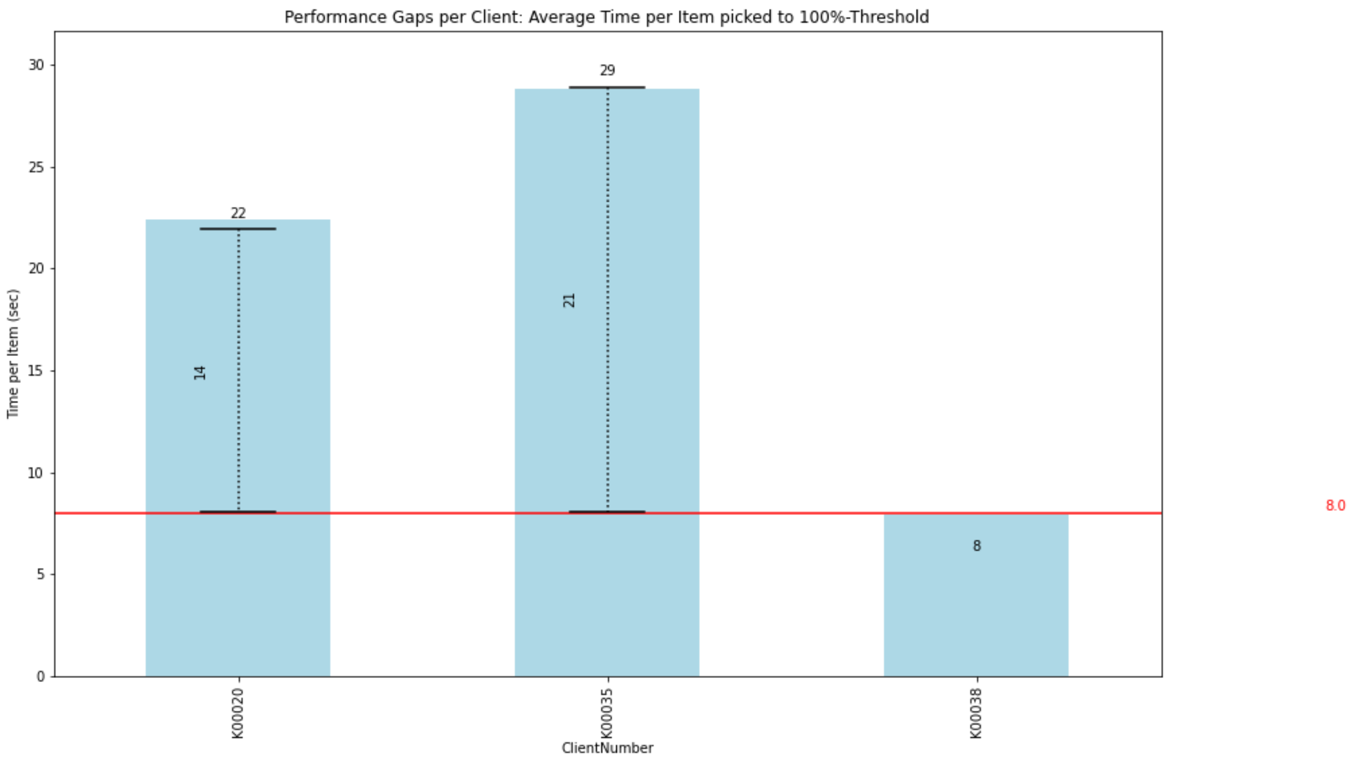

Figure G.9: Client Profile - Performance Gap - Time (Item)

G.3 Determine Improvement Potential

The section shows the improvement potential for all instances in the client portfolio, including the total improvement potential.

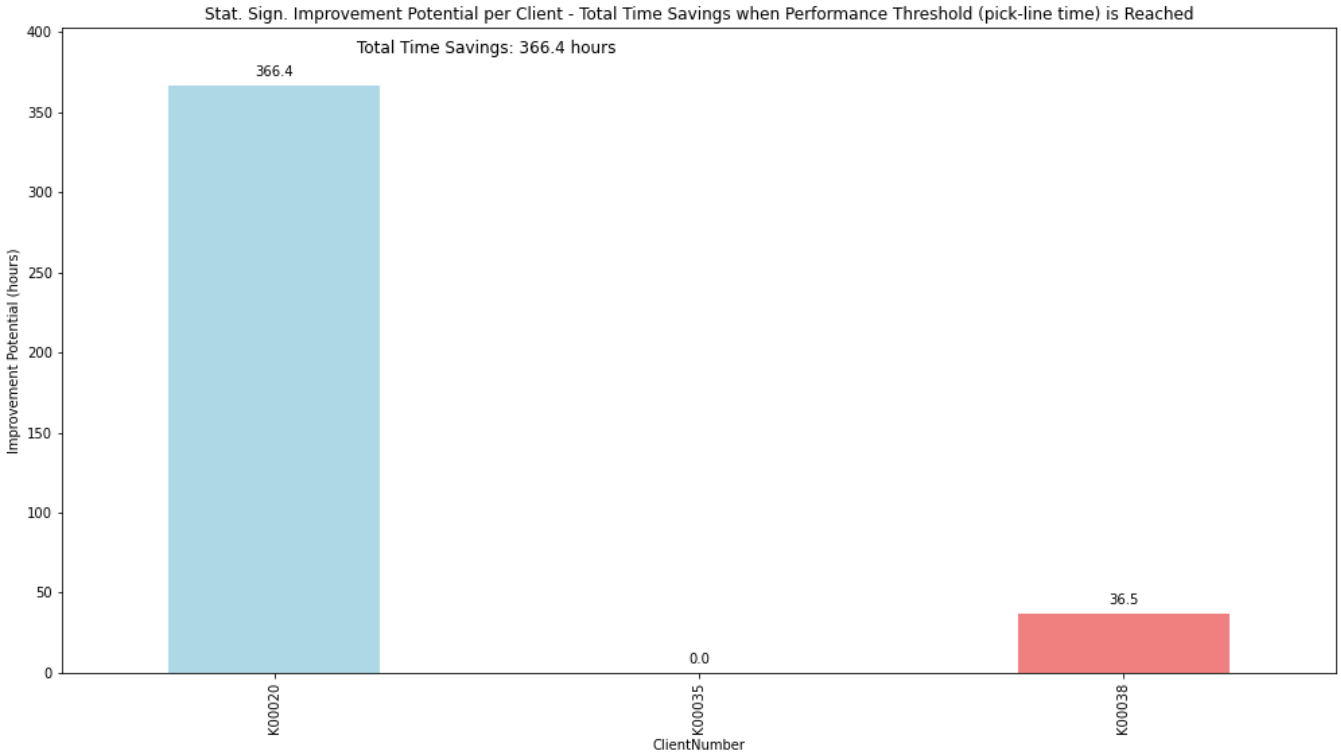

Figure G.10: Client Profile - Stat. Sig. Improvement Potential - Pick-Line Threshold

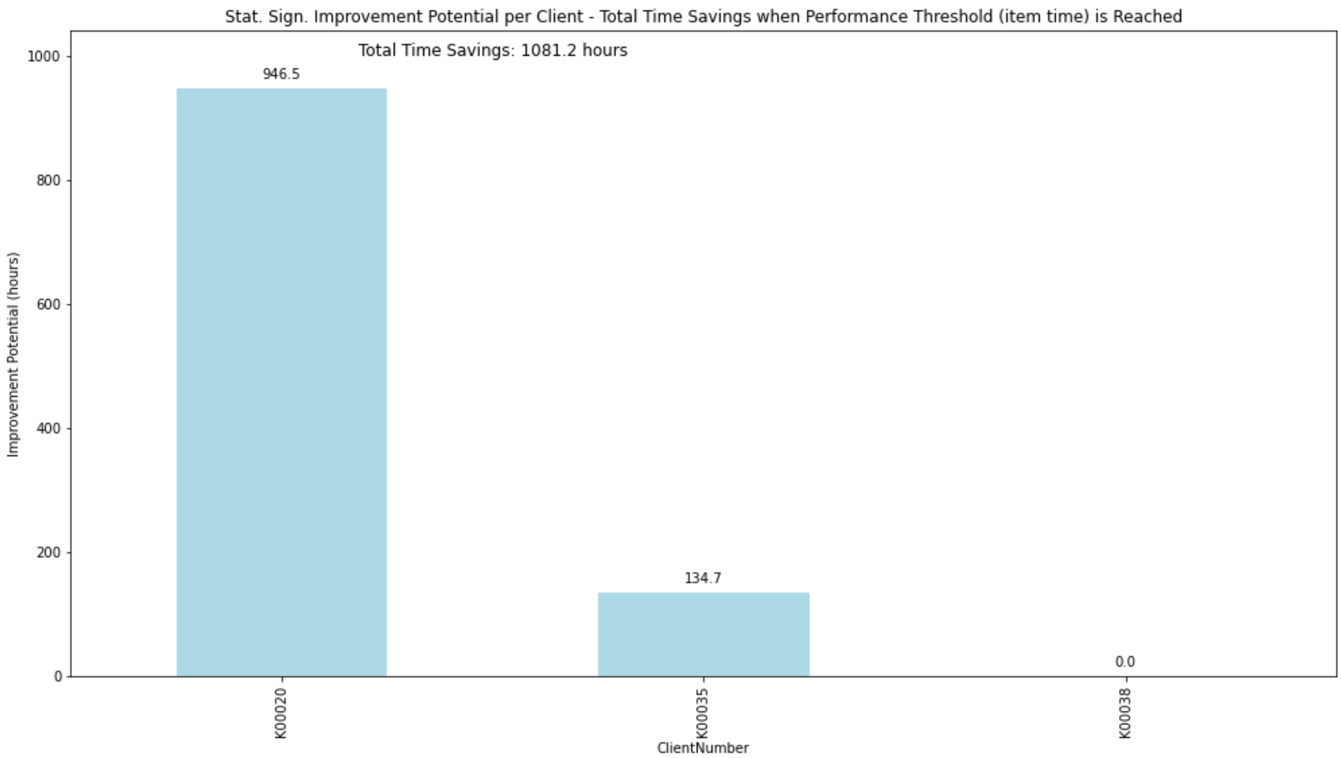

Figure G.11: Client Profile - Stat. Sig. Improvement Potential - Item Threshold

Appendix H

Set of Follow-Up Questions for the Case

CONFIDENTIAL APPENDIX

Appendix I

Set of Promising Optimization Measures for the Case

CONFIDENTIAL APPENDIX

Appendix J

Design Expert Opinion Validation Form

The form below shows the form which is presented to the expert of 4Supplychain to structure his expert opinion validation of the model. Next to this form, the expert is shown a demonstration of the model. Furthermore, he is provided with the thesis report and specifically requested to read the case implementation (Section 6.1) and case evaluation (Section 6.2).

Introduction

The aim of this form is to acquire an assessment on the value of the warehouse performance analysis model as part of improving the warehouse optimization strategy of 4Supplychain Consulting. This validation consists of three parts:

1. open assessment on the extent to which the research objectives as perceived by 4Supplychain are achieved
2. semi-structured assessment of the extent to which the model requirements are met
3. open assessment of the practical value of the model

1. Research Objectives

The original model's objective can be divided into three sub-objectives to which the research should contribute:

1. The model can assess the current warehouse performance based on indicators that can be measured with operational data.
2. The model can identify opportunities for optimization based on the performance assessment and patterns in the operational data.
3. The model narrows the scope for optimization measures based on the opportunities for optimization.

Please provide an open assessment of the extent to which each of the research objectives are achieved. Base your assessment on the model demonstration and the report sections about the implementation and the evaluation of the model.

2. Requirements

Please rate all the requirements stated below on to which extent they are achieved with the model as part of the warehouse the optimization strategy. Per requirement provide a numerical rating from 1 (requirement is not met at all) to 5 (requirement is completely met) and shortly describe why this rating is given.

The model is able to:

1. minimize the number of committed users involved
2. minimize the workload for key-user
3. standardize metrics definition and scope
4. standardize measurement methods
5. limit the number of data sources
6. use standard available data sources
7. simplify comparability of metrics
8. exclude instances that do not meet minimum workload (e.g., an employee with two picks can be excluded)
9. enable adjustments in the confidence interval of the statistical analysis (i.e., check the influence of statistical uncertainty)
10. enable data filters on pick-moments (e.g., exclude first picks of a shift)
11. enable data filters on IVs (e.g., exclude certain clients or days of a week from analysis)
12. enable flexible output unit of measurement (e.g., number of pallets instead of pick-lines)
13. minimize runtime of complete analysis to a few hours maximum
14. use only one application (to reduce synchronizing problems and possible subscription costs)

If there are any additional requirements not stated above, please supplement the list including a rating and explanation.

3. Practical Value

Please provide an open assessment on the general practical value of the model in context of warehouse optimization and the supply chain consultancy business. If you have any additional remarks on the model, please also state these here.

Bibliography

Adedu, A., Maladzhi, R., Katumba, M. G. K.-K., and Daniyan, I. (2023). Development of an improvement framework for warehouse processes using lean six sigma (dmaic) approach. a case of third party logistics (3pl) services. *Heliyon*, 9(e14915).

Badawy, M., El-Aziz, A. A., Idress, A. M., Hefny, H., and Hossam, S. (2016). A survey on exploring key performance indicators. *Future Computing and Informatics Journal*, 1:47–52. Available online 11 April 2016.

Bartholdi, J. J. and Hackman, S. T. (2019). *Warehouse & Distribution Science*. Georgia Institute of Technology, 0.98.1 ed. edition.

Bohrnstedt, G. W. and Knoke, D. (1994). *Statistics for social data analysis*. F. E. Peacock, Itasca, IL, 3 edition.

Boltrics (2023). Wms warehouse management software. `https://www.boltrics.com/nl/oplossingen/wms-warehouse-management-software/`. Accessed: 2023-04-15.

Buonamico, N., Muller, L., and Camargo, M. (2017). A new fuzzy logic-based metric to measure lean warehousing performance. *Supply Chain Forum: An International Journal*, 18(2):96–111. HAL Id: hal-01837935.

Cagliano, A. C., DeMarco, A., Rafele, C., and Volpe, S. (2011). Using system dynamics in warehouse management: A fast-fashion case study. *Journal of Manufacturing Technology Management*, 22(2):171–188.

CH Consulting Group (2021). What are the differences between external and internal benchmarking? `https://chconsultinggroup.com/what-are-the-differences-between-external-and-internal-benchmarking/`. Accessed: 2024-01-08.

Chow, G., Heaver, T. D., and Henriksson, L. E. (1994). Logistics performance: Definition and measurement. *International Journal of Physical Distribution & Logistics Management*, 24(1):17–28.

Cormier, G. and Gunn, E. A. (1992). A review of warehouse models. *European Journal of Operational Research*, 58(1):3–13.

De Koster, M. B. M. and Balk, B. M. (2008). Benchmarking and monitoring international warehouse operations in europe. *Production and Operations Management*, 17(2):175–183.

De Koster, M. B. M. and Warffemius, P. M. J. (2005). American, asian and third-party international warehouse operations in europe – a performance comparison. *International Journal of Operations & Production Management*, 25(7–8):762–780.

Diamantini, C., Genga, L., Potena, D., and Storti, E. (2014). Design of performance monitoring systems: Sebd. In *Proceedings of the design of performance monitoring systems*.

Dotoli, M., Fanti, M. P., Iacobellis, G., Stecco, G., and Ukovich, W. (2009). Performance analysis and management of an automated distribution center. In *2009 35th Annual Conference of IEEE Industrial Electronics*, pages 4371–4376, Porto. IEEE.

Durst, S. M. and Binder, M. (2006). Improving efficiency through internal benchmarking. *Int. J. Business Performance Management*, 8(4):290–306.

Eckerson, W. W. (2009). Performance management strategies. *Bus Intell J*, 14(1):24–27.

Ellinger, A. D., Ellinger, A. F., and Keller, S. B. (2003). Supervisory coaching behavior, employee satisfaction, and warehouse employee performance: A dyadic perspective in the distribution industry. *Human Resource Development Quarterly*, 14(4):435–458.

Faber, N., De Koster, R. B., and Smidts, A. (2017). Survival of the fittest: the impact of fit between warehouse management structure and warehouse context on warehouse performance. *International Journal of Production Research*, 55(21):6339–6353.

Frazelle, E. (2002a). *Supply Chain Strategy: The Logistics of Supply Chain Management*. McGraw-Hill, New York.

Frazelle, E. (2002b). *World-Class Warehousing and Material Handling*. McGraw-Hill Companies, Inc.

Frazelle, E. H. (1996). *World-Class Warehousing*. Logistics Resources International.

Frazelle, E. H. (2015). *World-Class Warehousing and Material Handling*. McGraw-Hill Education, 0.98.1 ed. edition.

Fugate, B. S., Mentzer, J. T., and Stank, T. P. (2010). Logistics performance: Efficiency, effectiveness, and differentiation. *Journal of Business Logistics*, 31(1):43–63.

Gallmann, F. and Belvedere, V. (2011). Linking service level, inventory management and warehousing practices: A case-based managerial analysis. *Operations Management Research*, 4(1–2):28–38.

Gu, J., Goetschalckx, M., and McGinnis, L. F. (2007). Research on warehouse operation: A comprehensive review. *European Journal of Operational Research*, 177(1):1–21.

Gu, J. X., Goetschalckx, M., and McGinnis, L. F. (2010). Research on warehouse design and performance evaluation: A comprehensive review. *European Journal of Operational Research*, 203(3):539–549.

Gunasekaran, A. and Kobu, B. (2007). Performance measures and metrics in logistics and supply chain management: a review of recent literature (1995-2004) for research and applications. *International Journal of Production Research*, 45(12):2819–2840.

Gunasekaran, A., Marri, H. B., and Menci, F. (1999). Improving the effectiveness of warehousing operations: A case study. *Industrial Management & Data Systems*, 99(8):328–339.

Hackman, S. T., Frazelle, E. H., Griffin, P. M., Griffin, S. O., and Vlasta, D. A. (2001). Benchmarking warehousing and distribution operations: An input-output approach. *Journal of Productivity Analysis*, 16(1):79–100.

Heerkens, H. and Winden, A. V. (2021). *Solving Managerial Problems Systematically*. Noordhoff Uitgevers, 1st ed. edition.

Hogenboom, T. (2017). Operational efficiency in warehousing. M.sc. thesis, Delft University of Technology, Delft, The Netherlands. Supervised by dr.ir. Y. Pang.

Johnson, A. and McGinnis, L. (2010). Performance measurement in the warehousing industry. *IIE Transactions*, 43(3):220–230.

Karagiannaki, A., Papakiriakopoulos, D., and Bardaki, C. (2011). Warehouse contextual factors affecting the impact of rfid. *Industrial Management and Data Systems*, 111(5):714–734.

Karim, N. H., Abdul Rahman, N. S. F., Hanafiah, R. M., Abdul Hamid, S., Ismail, A., Kader, A. S. A., and Muda, M. S. (2020). Revising the warehouse productivity measurement indicators: ratio-based benchmark. *Maritime Business Review*, pages 49–?

Karim, N. H. and Shaiful Fitri, A. R. N. (2018). Warehousing productivity assessment on logistics service sector. In *Proceedings of the GROSTLOG 2018*. Available online at proceedings.itltrisakti.ac.id.

Keith, T. Z. (2006). *Multiple regression and beyond*. Allyn & Bacon, Boston.

Kiefer, A. W. and Novack, R. A. (1999). An empirical analysis of warehouse measurement systems in the context of supply chain implementation. *Transportation Journal*, 38(3):18–27.

Koster, D., Le-Duc, T., and Roodbergen, K. J. (2007). Design and control of warehouse order picking: A literature review. *European Journal of Operational Research*, 182(2):481–501.

Lao, S. I., Choy, K. L., Ho, G. T. S., Tsim, Y. C., Poon, T. C., and Cheng, C. K. (2012). A real-time food safety management system for receiving operations in distribution centers. *Expert Systems with Applications*, 39(3):2532–2548.

Lu, C.-S. and Yang, C.-C. (2010). Logistics service capabilities and firm performance of international distribution center operators. *The Service Industries Journal*, 30(2):281–298.

Manikas, I. and Terry, L. A. (2010). A case study assessment of the operational performance of a multiple fresh produce distribution centre in the uk. *British Food Journal*, 112(6):653–667.

Manzini, R., editor (2012). *Warehousing in the Global Supply Chain: Advanced Models, Tools and Applications for Storage Systems*. Springer, London. Department of Industrial and Mechanical Plants, University of Bologna.

Matopoulos, A. and Bourlakis, M. (2010). Sustainability practices and indicators in food retail logistics: Findings from an exploratory study. *Journal on Chain and Network Science*, 10(3):207–218.

McGinnis, L. F., Chen, W.-C., Griffin, P., Sharp, G., Govindaraj, T., and Bodner, D. (2002). Benchmarking warehouse performance: Initial results for internet-based data envelopment analysis for warehousing (ideas-w 1.0). Technical report, Georgia Institute of Technology, Atlanta, GA. W. M. Keck Virtual Factory Lab, School of Industrial & Systems Engineering.

Mentzer, J. T. and Konrad, B. P. (1991). An efficiency/effectiveness approach to logistics performance analysis. *Journal of Business Logistics*, 12(1):33–61.

Murray, M. (2012). *Warehouse Management with SAP ERP: Functionality and Technical Configuration*. Galileo Press, Boston, MA, 2 edition.

Onstein, A. T., Bharadwaj, I., Tavasszy, L. A., el Makhloufi, A., and van Damme, D. A. (2021). From xxs to xxl: Towards a typology of distribution centre facilities. *Journal of Transport Geography*, Issue number if available:Page range if available.

Parmenter, D. (2010). *Key performance indicators: developing, implementing, and using winning KPIs*. John Wiley & Sons.

Ramaa, A., Subramanya, K. N., and Rangaswamy, T. M. (2012). Impact of warehouse management system in a supply chain. *International Journal of Computer Applications*, 54(1):14–20.

Randolph, K. A. and Myers, L. L. (2013). *Basic Statistics in Multivariate Analysis*. Pocket Guides to Social Work Research Methods. Oxford University Press, New York.

Rimiene, K. (2008). The design and operation of warehouse. *Economics and Management*, 13:136–137.

Sellitto, M. A., Borchardt, M., Pereira, G. M., and Gomes, L. P. (2011). Environmental performance assessment in transportation and warehousing operations by means of categorical indicators and multicriteria preference. *Chemical Engineering Transactions*, 25:291–296.

Sohn, S., Han, H., and Jeon, H. (2007). Development of an air force warehouse logistics index to continuously improve logistics capabilities. *European Journal of Operational Research*, 183(1):148–161.

Staudt, F. H., Alpan, G., Di Mascolo, M., and Taboada Rodriguez, C. M. (2015). Warehouse performance measurement: a literature review. *International Journal of Production Research*.

Staudt, F. H., Di Mascolo, M., Alpan, G., and Taboada Rodriguez, C. M. (2014). Warehouse performance measurement: classification and mathematical expressions of indicators. In *ILS 2014 - 5th International Conference on Information Systems, Logistics and Supply Chain*, pages 1–9, Breda, Netherlands. HAL Id: hal-01242034.

van den Berg, J. P. and Zijm, W. H. M. (1999). Models for warehouse management: Classification and examples. *International Journal of Production Economics*, 59(1–3):519–528.

Warehouse Education and Research Council (WERC) (2008). Standard definitions. `http://www.werc.org/assets/1/workflow_staging/Publications/742.PDF`. Accessed April 1, 2015.

Wieringa, R. J. (2014). *Design Science Methodology for Information Systems and Software Engineering*. Springer.

Wu, Y.-J. and Hou, J.-L. (2009). A model for employee performance trend analysis of distribution centers. *Human Factors and Ergonomics in Manufacturing*, 19(5):413–437.

Yang, L.-r. and Chen, J.-h. (2012). Information systems utilization to improve distribution center performance: From the perspective of task characteristics and customers. *Advances in Information Sciences and Service Sciences*, 4(1):230–238.