Design of an In-Plant Transport System: A Case Study at Tata Steel

Discrete-Event Simulation of the System Design with Automated Vehicles for a Steel Coil Manufacturing Plant

TIL5060: TIL Thesis

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TU Delft

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Design of an In-Plant Transport System: A Case Study at Tata Steel

Discrete-Event Simulation of the System Design with Automated Vehicles for a Steel Coil Manufacturing Plant

by

Joris Linders

To obtain the degree of Master of Science
At the Delft University of Technology
As part of the master Transport, Infrastructure & Logistics

To be defended publicly on: October 15th, 2024 at 13:00 PM.

Keywords— AGV, Block Layout, Flowpath, Forklift, In-Plant Transport, In-Process Inventory, Manufacturing, Scheduling, Steel Coil, Storage Location Assignment, System Design, Warehouse

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Project Duration:	February, 2024 - October, 2024	
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Abstract

Transport and storage operations in a steel coil manufacturing industry make up a large part of a factory's operating costs. With the advent of automated forklifts, unmanned transport and storage operations are becoming increasingly viable. Automated forklifts have the potential to lower operating costs, reduce the required number of employees, minimize transport damages and eliminate over-processing. Nonetheless, transitioning from manual forklifts to a fully operational automated transport and storage system requires addressing a range of complex decisions. These include the flow path layout, fleet sizing, vehicle dispatching, storage location assignment, and other relevant subjects.

This thesis presents an integrated approach to how the flow path layout design influences the material flow effectiveness, incorporating vehicle scheduling and storage location assignment policies. Based on a real-world case study, analyzed through Discrete-Event Simulation (DES) software, this study addresses the following research question: What in-plant system design facilitates effective material flow by implementing automated transport in a steel coil manufacturing plant?

First, applicable literature is investigated; thereafter, the system is analysed, and design alternatives are generated. The design alternatives vary in the use of manual and automated forklifts, and the flow path layout considers both conventional and zone-based flow approaches. The experiments test the influence of dispatching policies and fleet sizing on all alternatives. Furthermore, battery management, idle-vehicle positioning, unit-load selection and case-specific system constraints are integrated. The storage location assignment is based on the order identification number and the fill level of the storage parks.

By capturing the dynamic and variable nature of a stochastic production system, the DES evaluates the impact of different configurations on performance, costs, and other performance indicators. The cost-performance relations are plotted, resulting in a Pareto front consisting of a set of non-dominated system design configurations. A preferred automation alternative is selected from this set. Conclusions regarding the most effective transport system design and the integrated system design process are drawn.

Preface

This report presents my graduation research for obtaining the degree of Master of Science in Transport, Infrastructure, and Logistics at the Delft University of Technology. A case study was conducted at the Packaging factory of Tata Steel IJmuiden. Working on a project for a factory spanning over 1km wide was an invaluable experience. Analyzing the system by observing the transport operations inside the factory provided insights into the complexity of large-scale industrial processes.

I would like to thank Ir. Mark Duinkerken and Dr. Ir. Arjan van Binsbergen of the Delft University of Technology for their guidance and valuable feedback. Although I had no previous knowledge on discrete-event simulation studies, they supported me throughout the process.

Moreover, I would like to thank MSc. Ewald Veenboer, my daily supervisor at Tata Steel IJmuiden, for offering me this opportunity and for his support throughout the project. I would also like to extend my appreciation to all the employees of the Operational Development and Support department for their guidance and for giving me an understanding of the interesting projects they are working on. Additionally, I am grateful to MSc. Edwin Seldenthuis, a simulation expert, for helping me grasp the software tools essential to my research. Thank you to all my colleagues for making me feel like a valued member of the organization.

Furthermore, I would like to express my gratitude to MSc. Alexandru Rinciog from the startup SLAP-stack for adjusting his simulation software to model the case presented by Tata Steel. I greatly appreciated our conversations and his enthusiasm for supporting thesis projects.

Finally, I would like to thank my family and friends. Their continuous support has been essential throughout all these years of study.

I hope you enjoy reading this thesis!

Joris Linders
Rotterdam, October 2024

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
ABSWP	Autonomous Block Stacking Warehouse Problem
AGV	Automated Guided Vehicle
AMR	Autonomous Mobile Robot
ARF	Deviating Route Form, coil that needs an adaptation (NL: Afwijkend Route Formulier)
BLITS	Production mainframe database for coils and plates of PAC (NL: Blik Informatie en Tracking Systeem)
CA	Continuous Annealing
CAPEX	Capital Expenditure
CB	Class-Based
COPL	Closest Open Pure Lane
DES	Discrete Event Simulation
DKG11	Double Colled Rolled 11 (NL: Dubbel Koud Gewalst 11)
DOE	Design Of Experiments
DW	Data Warehouse
EC	Electrolytic Chromed
ET/EV	Electrolytic Tinning Line (NL: Elektrolytische Vertinlijn)
FFBD	Functional Flow Block Diagram
FIFO	First-In First-Out
FTE	Full-Time Equivalent
HARA	Hazard Analysis and Risk Assessment
HW48	Hardening Roller 48 (NL: Hardingswals 48)
IB	Inspection Track (NL: Inspectie Baan)
IRR	Internal Rate of Return
KS	Kolmogorov-Smirnov
MASP	Minimum Available Storage Positions
(M)ILP	(Mixed) Integer Linear Programming
MOMS	Manufacturing Operations Management System
MSA	Measurement System Analysis
MWQ	Minimum Work-in-Queue
NEN-EN-ISO	NEderlandse Norm - European Norm - International Standardization Organization
NPV	Net Present Value
ODS	Operational Development and Support
OPEX	Operational Expenditure
OTP	On-Time Performance
PAC	Packaging
SCM	Supply Chain Management
SD	Shortest Distance
SKU	Stock Keeping Unit
SLAP	Storage Location Assignment Problem
TCO	Total Cost of Ownership
TIMWOODS	Transportation, Inventory, Motion, Waiting, Overproduction, Overprocessing, Defects, Skills Underutilized
TSP	Tata Steel Packaging

Abbreviation	Definition
ULSP	Unit-Load Selection Problem
ULRP	Unit-Load Relocation Problem
VDP	Vehicle Dispatching Problem
WACC	Weighted Average Cost of Capital
WMS	Warehouse Management System

Symbols

Symbol	Definition	Unit
m	Mass	[kg]
d	Distance	[mm]
t	Time	[s]
€	Euro (currency)	[€]
v	Velocity	[m/s]
μ	Mean	*Same as data*
σ	Standard deviation	*Same as data*
ρ	Density	[kg/m^3]

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1 Introduction

Manufacturing environments try to maintain their competitive position through lean operations and innovation. An in-plant transport system operates as a subsystem within a broader production system. The goal of any production system is 'the pursuance of greater delivery capability and reliability with the lowest possible logistic and production costs' (Nyhuis & Wiendahl, 2009, p. 762)[40]. The packaging factory (PAC) of Tata Steel IJmuiden wants to investigate the feasibility of implementing automated vehicles in a specific area of their factory. To meet the customer's expectations PAC uses lean manufacturing methodologies [29]. Several factors, such as the assignment of in-process inventory storage locations, automated vehicle scheduling, and the flow path layout design, influence an effective material flow.

Tata Steel IJmuiden has 9000 employees and produces over 7 million tonnes of steel yearly. Packaging Works IJmuiden produces around 16 kilotonnes per week in the form of coils and steel sheets. This steel is meant for various purposes and customers. The main purposes are food- and drinking cans, aerosols and lids. Tata Steel's customers manufacture and supply these products, particularly to the food industry. The department ODS provides support to the factory by working on feasibility analyses, among other things. Many modes of transport are moving through the factory, such as forklifts, narrow track wagons, trailers, cranes and golf carts. Due to the layout of the factory, the steel coils go back and forth through the factory several times. The transport process is complex and the assignment of storage locations is not data-driven, which causes additional transport movements.

Automated vehicles dispatch goods from one location to another with greater ease. Many decisions must be made when automated vehicles are being implemented in a manufacturing environment. Decisions must be addressed at the strategic, tactical, and operational levels. Strategic decisions include the guide path design for forklift AGVs, type of forklift AGVs and fleet size, maintenance strategy and integration with data systems. Tactical decisions are battery management, maintenance scheduling, warehouse configuration, scheduling & dispatching, vehicle positioning & parking, and zoning. On the tactical level, vehicle routing decisions, conflict/ deadlock resolution decisions, order processing decisions, and the storage location assignment problem must be addressed. This report explores how automated transport can be effectively implemented in an in-plant transport system by addressing some of these key decisions. Through a discrete-event simulation model, several designs are assessed. The designs primarily focus on the flow path layout and scheduling policies.

1.1. Problem Statement

Packaging Works IJmuiden (PAC) is one of the many factories on the Tata Steel IJmuiden site. Steel coils are received from the hot rolling mill and processed by the packaging-steel production lines, making them suitable for applications such as food or aerosol cans. In the production lines, the steel is pickled, cold-rolled and heated so that the material becomes softer and more malleable [60]. Hereafter, the temper rolling production lines increase the strength of the steel and provide the required surface quality. Finally, a tin coating layer is applied to the thin steel plate material to prevent corrosion. After the tin coating is applied, the coils may be coated with a layer of Protact® polymer, or they are packed up and shipped to the customer directly.

There are many production lines within Packaging. Over the years, the facility expanded its operations, with new installations placed wherever space was available or new production halls constructed alongside the existing factory. This expansion resulted in an inefficient factory layout.

When a coil is processed by one of the production lines, it is transported to an in-process inventory. In this in-process inventory, the coils are stored in a deep-lane storage configuration to save space and cannot be stacked to avoid potential damage. From there, it is moved to the next production line, continuing through the various stages until all processes are complete. This system, combined with the inefficient layout, generates a high demand for transport operations. Currently, these operations are carried out using manual forklifts. Due to the challenges and inefficiencies, the client seeks to explore the feasibility of implementing automated transport. This research examines the feasibility of automated transport between the temper rolling and electrolytic tin-plating production lines. The scope is described in section 1.5. Several topics are driving the research into automated transport:

- It is challenging to find qualified employees to operate forklifts.
- The wages of forklift operators make up a large part of the facility's operating cost.
- Current operations result in transport damages to the manual forklifts, infrastructure and steel coils. Automating the transport process can greatly reduce this risk by ensuring more controlled and precise movements.
- Automated transport needs to be scheduled and controlled by a Warehouse Management System (WMS). This allows to overcome the following inefficiencies:
  - The combination of a high workload and a labour-intensive method of recording the location of steel coils in the data system causes steel coils to get lost. An automated vehicle integrated with a WMS can automatically track and store this data, resolving the issue.
  - Coil storage locations are recorded by scanning a barcode on each coil and assigning its location. However, moving between closely spaced, sharp-edged coils increases the risk of safety-related incidents.
  - Forklift operators determine the storage position of the coils in the in-process inventory themselves. This increases the chance of an inefficient storage location assignment process and the chance of sorting operations in the storage park to retrieve the targeted coil. Implementing a storage location assignment policy within the WMS can optimize this process and improve overall efficiency.

Implementing automated transport systems offers a solution to many challenges and inefficiencies in current operations. However, its implementation brings several challenges, including lower operating speeds, longer pick-up and drop-off durations, and adherence to strict regulations. Additionally, the presence of other transport modes in the same area complicates the integration of automated transport systems. An effective material flow should be established by automated vehicles, ensuring the desired level of logistical performance while minimizing resource-related costs and meeting the requirements of the case. This requires decision-making on the following topics:

- Flow-path layout design
- Vehicle scheduling
- Storage location assignment
- Unit-load selection
- Type of automated transport
- Fleet sizing
- Idle-vehicle positioning
- Battery management

A literature review on similar automated transport and storage systems has identified a research gap: *the need for integrated analysis of flow path layout designs and their impact on material flow effectiveness in automated vehicle systems, considering vehicle scheduling and storage location policies*. Not many studies focus on the conceptual design of integral design alternatives for in-plant transport systems. This research aims to address this gap by examining case-specific requirements and exploring solutions to these challenges.

1.2. Knowledge Gap

The case study highlights a need to explore the feasibility of implementing automated transport systems, focusing on designing solutions that minimize resource-related costs while ensuring the desired level of logistical performance.

Based on the problem statement and case-specific system constraints, a literature study is performed in chapter 3. The literature review identified the following knowledge gap: *the need for integrated analysis of flow path layout designs and their impact on material flow effectiveness in automated vehicle systems, considering vehicle scheduling and storage location policies*. Researching a real-world case of an in-plant transport system in the manufacturing sector contributes valuable insights to the current body of knowledge.

1.3. Research Objective

This research has both practical and scientific objectives. The scientific goal is to provide new insights into the integrated system design process for an in-plant transport system in a manufacturing environment, involving the workflow and decision-making processes. This research aims to contribute to how the various decision-making processes interact and affect the overall system performance. Furthermore, this study aims to augment the existing scientific literature by introducing another case study of an automated in-plant transport system.

The practical aim is to evaluate design alternatives for Tata Steel, quantifying how decision-making in the system design influences performance. This is expected to result in viable system design alternatives, of which the best-performing design is recommended for implementation. The case study addresses the need for an integrated system design incorporating decision-making in flow path layout, vehicle scheduling, and storage location assignment.

1.4. Research Questions

In light of the earlier presented research goal and based on the case presented by Tata Steel, the following research question has been formulated:

What in-plant system design facilitates effective material flow by the implementation of automated transport in a steel coil manufacturing plant?

To answer the main research question, the following sub-questions have been defined:

1. Which theories are applicable for generating new findings on the system design of in-plant transport and storage processes?
2. How is the solution space of the transport and storage system defined, and what challenges in its current operations require innovative changes?
3. What feasible design alternatives for the implementation of automated transport can be developed considering the solution space?
4. How can the system design alternatives that integrate the scheduling of automated vehicles and the assignment of coils to storage locations be modelled?
5. Which system design demonstrates the best results, and what is its impact on the performance metrics?

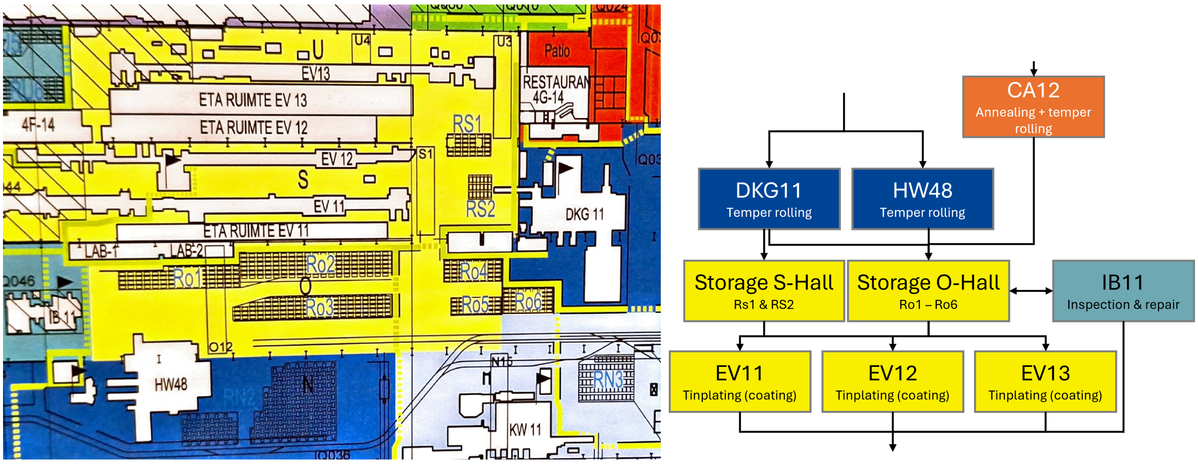
The word effective in the main research question is defined as 'the extent to which inputs do indeed lead to the desired outputs, without too much waste of resources' (Binsbergen, 2022, p. 5)[8]. The first sub-question examines the existing literature on layout design, scheduling, storage location assignment and automated vehicles. Secondly, the current state of the system is analysed. The system analysis defines the solution space, and the boundaries of the system where solutions are to be found, determined by requirements and design environment. The solution space is defined by clients, users, infrastructure and environment. Therefore, this chapter contains an actor analysis, a literature review describing system boundaries of similar systems, and a process analysis by studying quantitative data and interactions between system elements. The analysis identifies relevant criteria for quantifying performance and discusses challenges that require innovative improvement solutions. The third sub-question aims to fill the solution space with innovative design alternatives. These alternatives differ in the level of automation and whether the vehicles are bound to a specific area. This includes considerations on the strategic level, by selecting the most suitable type of AGV for integration.

Constraints imposed by the various alternatives will be used as input to a quantitative model to assess which alternative performs best in terms of the identified criteria. This quantitative model will be developed under the fourth sub-question. The material processing duration for each installation (i.e. inter-arrival time) determines the requirement for transport. The task, consisting of a pick-up and delivery location, will be scheduled among the available automated vehicles under constraints imposed by the model. Verification and validation of the quantitative model will follow after the model has been presented. Finally, the best-performing alternative will be compared to the current situation under the 5th sub-question, after which conclusions will be drawn. A framework for this research is outlined in chapter 2.

1.5. Scope

The scope of this thesis is limited to large manufacturing facilities with cylindrical-shaped goods. The goods may not be stacked on top of each other to avoid potential damage. There are numerous factors involved in the implementation of automated vehicles. This study concentrates on key aspects such as flow-path layout, vehicle dispatching, unit-load selection, idle-vehicle positioning, and battery management. While it also addresses the assignment of coils to storage parks, it does not consider the specific location within those parks. Other common topics, such as routing, deadlock resolution, and failure management, are intentionally excluded from the scope of this study.

The scope of the case presented by Tata Steel is limited to automating the transport of coils supplied to the Electrolytic Tinplating (ET, Dutch: EV) production lines. Within Packaging, there are four tinplating lines, of which 3 are in this project's scope: EV11, EV12 and EV13. These three tinplating lines are part of work area 4. Nearly all coils are supplied from the temper rolling production lines located in work areas 2 and 3: Hardening Roller 48 (HW48), Double Cold Rolled 11 (DKG11), and Continuous Annealing 12 (CA12). While CA12 anneals the steel, it also includes its own temper rolling line, similar to DKG11. Additionally, if a coil is damaged during the process, the defective section can be cut out at Inspection Track 11 (IB11). Therefore, the scope of this case is the material flow from HW48, DKG11, CA12 and IB11 towards EV11, EV12 and EV13. Between these installations, the coils are stored in the O-hall (Ro2-Ro6) storage parks and the S-hall (RS1 & RS2) storage parks. The facility layout of the scope is presented in Figure 1.1a. Furthermore, the mixed traffic scenario will be analyzed, with recommendations based on how different modes of transportation affect each other.



(a) Facility layout

(b) Material flow scope

Figure 1.1: Factory layout and scope

1.6. Structure

This report is structured as follows. The methodology will be outlined in chapter 2. Secondly, chapter 3 analyses the current body of literature on the flow path layout, scheduling of automated transport and assigning storage locations to non-stackable goods in deep-lane storage systems. To answer the second sub-question, a system analysis will be performed in chapter 4. Chapter 5 will answer the third sub-question by generating several design alternatives. In chapter 6, a quantitative model will be developed to evaluate the performance of the system design alternatives. The experiments and evaluation of design alternatives will be presented in chapter 7. Finally, the conclusion, discussion and recommendations are provided in chapter 8.

2 Methodology

This chapter discusses the methods used to address the main and sub-research questions. For each sub-research question, the relevant methods are presented in Table 2.1. The sub-sections go into more detail about the proposed methods. Figure 2.1 presents the thesis process.

What in-plant system design facilitates effective material flow by the implementation of automated transport in a steel coil manufacturing plant?

Sub-question	**Methods**
SQ1. Which theories are applicable for generating new findings on the system design of in-plant transport and storage processes?	Literature review
SQ2. How is the solution space of the transport and storage system defined, and what challenges in its current operations require innovative changes?	Secondary data analysis, interviews, literature review
SQ3. What feasible design alternatives for the implementation of automated transport can be developed considering the solution space?	Expert opinion, functional analysis
SQ4. How can the system design alternatives that integrate the scheduling of automated vehicles and the assignment of coils to storage locations be modelled?	Discrete-Event Simulation
SQ5. Which system design demonstrates the best results, and what is its impact on the performance metrics?	Experiments, quantitative analysis

Table 2.1: Sub-questions and related methods

2.1. Literature Review

The project definition in chapter 1, addressed the focus of this research. This thesis starts with a literature review on the topics relevant to the case in chapter 3. The literature review examines prior research to identify applicable theories for the system design of a manufacturing facility. Based on relevant literature and theories, a research gap is identified which aims to contribute to the existing literature by presenting an integrated system design process.

Furthermore, in chapter 4, similar forklift AGV studies conducted for Tata Steel are discussed. These studies provide insights into cost calculations, identify challenges for implementing automated transport, and offer an overview of the process steps followed in those projects.

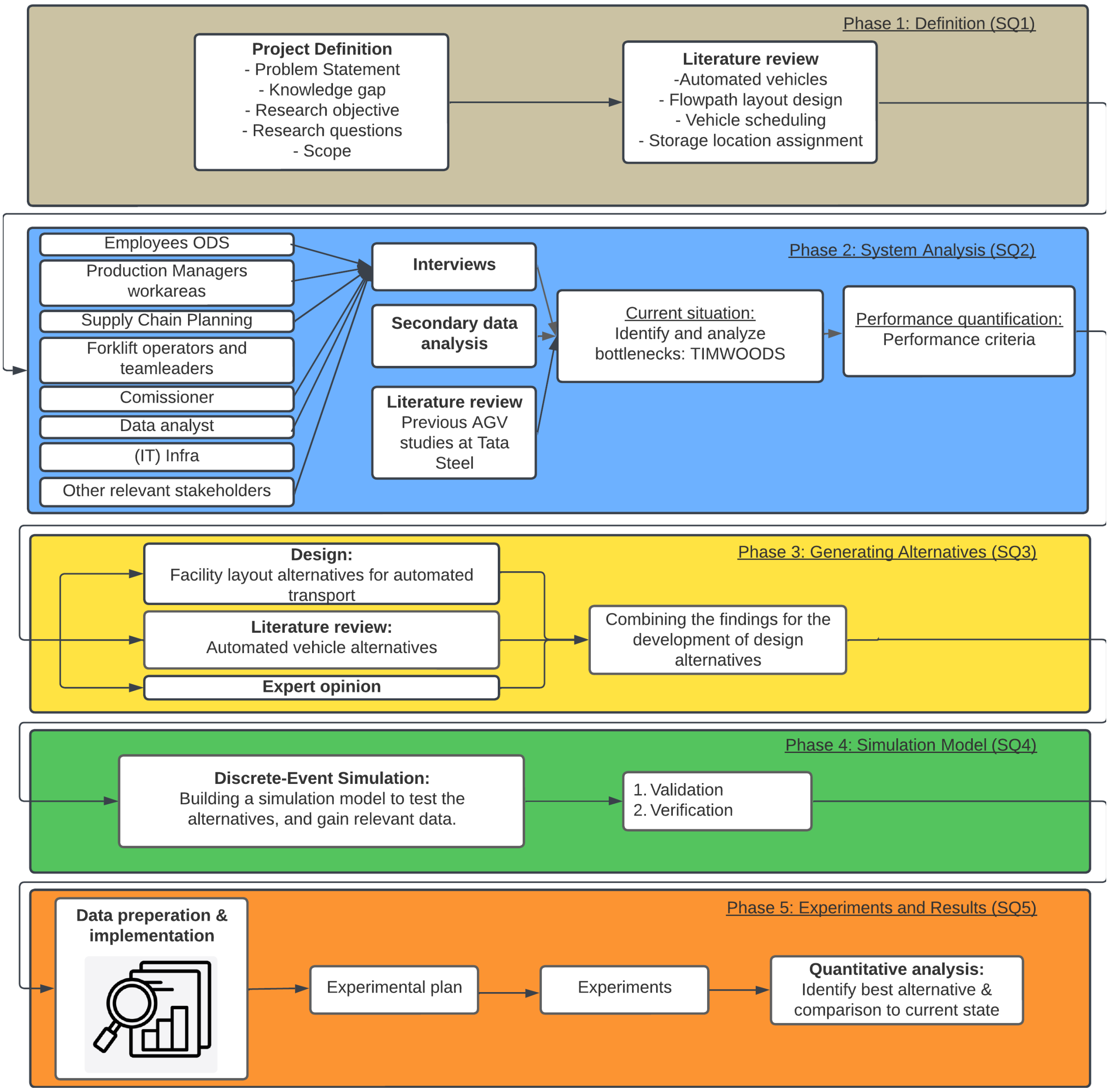


Figure 2.1: Graphical representation of the methodology

2.2. Interviews

As presented in Figure 2.1 interviews are the first step of the system analysis. For these interviews some questions will be drawn in advance, however, it will be an open conversation. Many employees can give information on the current operations, bottlenecks and their ideas on implementing automated vehicles. Initially, conversations were scheduled with the employees of ODS (Operational Development and Support), the production managers of the involved work areas, logistic coordinators and actors with knowledge of the data systems. Further stakeholders became apparent as the thesis matured.

2.3. Secondary Data Analysis

Secondary data analysis involves utilizing existing data collected by others for purposes other than the research question at hand. This analysis will provide insights into current operations and can be used as input data for the quantitative model.

2.4. Discrete-Event Simulation

A discrete-event simulation model will examine different alternatives, which will be compared to the baseline (current operations). Simulation has been selected as the quantitative method over linear programming because of its capability to incorporate stochastic influences. This decision was made after the literature study and current state analysis were performed. Stochastic elements are inherent to the problem, suggesting that a simulation model is the most appropriate choice. Discrete-event simulation allows the study of complex systems with discrete changes (e.g. transportation, manufacturing), changing the state of the system.

Simulation entails creating a model of the system under analysis and conducting experiments on the model to observe how the system responds to different conditions [61]. Simulation predicts the behavior and increases the understanding of the system but does not provide an optimal solution. It allows for testing the feasibility of the proposed design, being able to predict the impact of change in the physical system, and the ability to analyze the system state beyond a level of detail that an optimization model can describe.

3
Literature Study

The purpose of this literature study is to analyse what theories apply to the development of a system design for different industries where automated transport is implemented. The system design mainly focuses on transport by studying automated vehicle systems, the flow path layout design and vehicle scheduling. Moreover, the literature study focuses on how goods are assigned to storage locations under different warehouse layouts of similar industries and their relation to the implementation of automated vehicles. This study addresses what still has to be researched in the existing body of literature and provides theories to solve the case of Tata Steel. The primary focus of the scope lies within manufacturing environments, some articles of other industries have been added. Within scheduling, the focus is on dispatching policies and not on routing. A literature study on state-of-the-art automated vehicles has been performed to a lesser extent. The case does not require a large fleet size and there are not many different paths that can be taken, therefore decisions related to routing and fleet sizing are not the focus of this literature study. This chapter aims to address the following sub-question:

Which theories are applicable for generating new findings on the system design of in-plant transport and storage processes?

The studied theory has a specific focus on problems faced in the case of Tata Steel. The characteristics of the case led to a study on the flow path layout, scheduling problems, and (deep-lane) storage location assignment with a focus on manufacturing facilities. Besides, the capabilities and characteristics of automated vehicles are important to consider. There are several other issues theories on in-plant transport systems design covers, such as routing, conflict avoidance & deadlock resolution, failure management and battery management. These are not covered in the literature study since it is not the main focus of this case. Furthermore, the distinction between call systems and milk runs is often covered in the design of in-plant transport systems. Call systems deliver transport on demand, while milk runs are often single-loop unidirectional flow paths constrained to a fixed time schedule. Since forklift AGVs carrying steel coils have a capacity of 1 coil, and the demand for transport has high variability, milk runs do not make a lot of sense, therefore only call systems are considered.

3.1. Methodology

The search strategy for scientific papers in Scopus is described in Table 3.1. The Delft University of Technology repository and Scopus have been used to find relevant literature. Filters were applied to search for literature from 2010 onwards. Keywords under transport were included to reach literature on automated transport. Warehouse management keywords were included to gain more information on the optimal storage of goods. The keywords listed under operations specify the type of industry and the associated operations. Furthermore, flow path layout design keywords were added.

Concept groups	Transport, Warehouse Management, Operations, Flowpath Layout	
Keywords	Transport:	AGV, AMR, Automated, Intelligent, Autonomous, Robot, Forklift
	Warehouse Management:	Inventory, Storage, Layout, Warehouse, Parkmodel, Deep-Lane, Blocking
	Operations:	Packaging, Order*, Steel, Coils, Industry, Supply Chain, Intra-facility, FMS, Block Stacking, Scheduling, Dispatching
	Flowpath Layout:	Configuration, Flowpath, Layout, Design, Transfer, Zoning
Truncation	(Transport) AND (Warehouse Management) OR (Transport) AND (Operations) OR (Transport) AND (Flowpath Layout) OR (Transport) AND (Warehouse Management) AND (Operations)	

Table 3.1: Conceptual and methodological framework for literature review

The abstract, introduction, conclusion, and suggestions for future research have been read for each relevant paper. The papers related to scheduling that have been reviewed are presented in Table 3.3; they all use quantitative methods. Furthermore, the system aspects, the number of vehicles, the modelling approach and the solving method are noted. Most articles were found by applying the snowballing method to articles that presented an overview of the literature.

The approach for finding relevant articles and information on scheduling and the storage location assignment consists of 2 steps. First literature reviews have been examined, indicating what the body of literature currently exists of and how the problems are categorized. Based on this understanding, articles identified through snowballing and Scopus search results present various approaches to solving similar problems. For all papers in Table 3.3 and Table 3.4, the modelling approach and solving method are indicated. The two primary modelling approaches are (Mixed) Integer Linear Programming (ILP) and (Discrete-Event) Simulation. The selected modelling approach for this study has been discussed in section 2.1 and is based on the literature study.

The literature study starts with an overview of automated vehicles. Followed by the findings from literature reviews on the flow path layout. Then, a study on scheduling vehicles to tasks in a manufacturing environment is presented. Next, there is a review on assigning storage locations to goods. Finally, the conclusion and discussion will state what knowledge gap has been identified and how this study will fill this gap.

3.2. Automated Vehicles

Automated guided vehicles (AGV) and Autonomous mobile robots (AMR) are both used in a wide range of intra-logistical operations, including manufacturing operations. AGVs need infrastructure to localize and guide the vehicle, while AMRs use vision-based guidance systems such as LiDAR to operate autonomously (see Figure 3.1). The characteristics of both systems are described in Table 3.2.

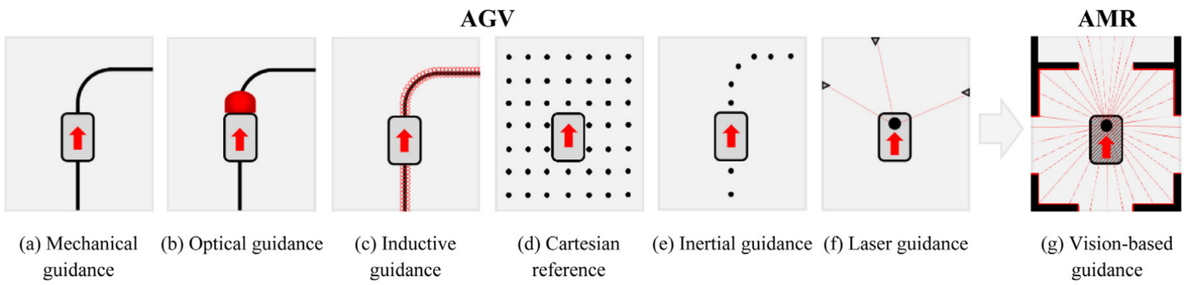


Figure 3.1: Top view of guiding systems for AGVs and AMRs [23]

Aspect	AGV	AMR
Navigation	Guided navigation, pre-established path	Autonomous, artificial intelligence, Simultaneous Localization and Mapping
Safety	Stops for obstacles	Navigates around obstacles
Installation	Requires construction	Fast & easy, during operation
Flexibility	Low	High, intelligent, easy to scale
Reliability	Very reliable, robust	Difficult to predict
Scope of application	Large and heavy payloads, fixed layout	Dynamic environments, order picking, replenishment, transporting boxes
Investment	Low acquisition costs, additional construction costs	High maintenance & acquisition costs, expensive software and hardware, no construction

Table 3.2: AGV vs AMR [16][23]

The control software and hardware of AMRs allow for autonomous operations in dynamic environments. Powerful onboard computers, artificial intelligence and ubiquitous sensors allow it to understand its operating environment and make routing choices. For many industries, this enables them to enhance operational flexibility and improve performance in terms of quality and cost-efficiency (in some cases) [23]. The automated vehicles for a steel coil manufacturing plant also need to be equipped with a mast and coil boom allowing to load coils on the vehicle. Because of the heavy loads, most suppliers of automated forklifts only supply AGVs. Therefore, in chapter 5, the decision has been made to only consider AGVs.

3.3. Flowpath Layout

The efficient design of flow paths has a direct impact on the performance of a manufacturing system. The flow path layout connects machines with other load-handling stations. The flow path affects travel time, operating expenses, the complexity of the control software, degree of congestion, and the number of vehicles [57][67]. A set of nodes and arcs creates a fully connected network. Travel along these arcs can occur in either a single direction (*unidirectional*) or both directions (*bidirectional*). The layout of the case study does not facilitate unidirectional flow paths, vehicles should be able to drive in both directions. Therefore this review only considers bidirectional flows. On most arcs, vehicles can pass each other, making the arc a multiple-lane guide path.

Besides the most conventional system being a fully connected bidirectional flow path, where each vehicle can traverse all arcs in any direction, there are other developments. Zoning compromises dividing the operating area into one or multiple zones. This requires decision-making on the design of zones and the transfer points [67]. The transfer station in between the zones can serve vehicles from both sides. This allows the transport of loads over the shortest path. Furthermore, congestion and deadlocks can't occur if the zone is operated by one vehicle. The area of the zones may not be changed with fixed transfer points, often resulting in a bottleneck zone which can't be relieved by the resources of other zones. A dynamic zone strategy adapting the zones in real-time would allow to overcome this problem.

Dividing the service areas into multiple zones can enhance cost efficiency and productivity. It may improve the system's responsiveness since vehicles drive shorter trips and are available more quickly due to the lower throughput time [23]. Zoning compromises several activities:

1. Analyzing the service area.
2. Determining fixed and/or dynamic transfer points.
3. Configuring zones.
4. Determining the number of vehicles per zone.

According to Fragapane et al. (2021): 'The main objectives when designing zones and service points are to minimize travel distance, traffic, and throughput time while distributing the workload throughout the system, to increase and – ideally - maximize system throughput and resource utilization' (p. 413) [23]. Fragapane et al. [23] also notes that new methods are needed to design work zones and determine the handover locations. Furthermore, the use cases found for manufacturing facilities did not include an in-process inventory, which can provide additional complexity due to the large number of nodes and arcs.

3.4. Scheduling

To support the decision-making process of scheduling machines and transport options simultaneously in a manufacturing environment a wide range of literature is available. Most models apply mixed integer (linear) programming models with heuristic algorithms. Simulation has also been applied and often results in more accurate results. Furthermore, stochastic methods such as queuing models have been applied. This section presents an overview of several papers which use mathematical modelling or simulation as a method in a manufacturing environment for the scheduling of tasks. Simulation is used to model the dynamic behaviour of a system over time. It provides a detailed understanding of how the system operates under different conditions. It allows to capture complexities and uncertainties inherent in the system. Simulation can be complex and time-consuming, and it does not focus on finding the optimal solution. Optimization, on the other hand, aims to find the best solution to a problem. It is suitable for finding the best allocations of resources, such as scheduling tasks and can handle complex problems. Challenges are the precise formulation, it may be computationally intensive and may not capture all complexities and uncertainties of the real-world system. In Table 3.3, the findings are presented.

The articles focus on different industries, such as Manufacturing Systems (MS), Flexible Manufacturing Systems (FMS), container terminals and warehousing. Some articles within warehousing have a specific focus on Very Narrow Aisles (VNA). A different range of vehicles, jobs, stations, and additional vehicles, such as Quay Cranes (QC) and yard cranes, are listed. The acronyms for the modelling approaches are Constraint Programming (CP), Linear Programming (LP), Integer Linear Programming (ILP), Mixed Integer (Linear) Programming (MI(L)P) and Discrete Event Simulation (DES). The following abbreviations present the type of optimization algorithms: Heuristics/Meta-Heuristics (H/MH), Genetic Algorithms (GA), Auction Theory (AT), Memetic Algorithm (ME) and Exact Optimization (Ex). These algorithms are used since these problems are often NP-hard, and can therefore not be solved by an exact algorithm in polynomial time.

The modelling approach of most papers related to the scheduling of automated vehicles is mathematical modelling. However, some articles focus on (discrete event) simulation studies as well. These studies use scheduling and dispatching rules to define the simulation model. Some studies use the simulation model to measure the performance of the mathematical model [62]. One article presents a similar case, where there are multiple shops where goods exit (end-of-line area), one storage area, and multiple shops where goods are delivered to (loading area) [24]. It presents a wide range of scheduling rules and performance criteria.

Table 3.3: Overview of analysed papers related to scheduling

Ref	Objective	Industry/ Configuration	Type and number of vehicles	Modelling Approach	Solving Method	Future research
[15] (Corréa, Langevin, and Rousseau, 2007)	Scheduling & conflict-free routing of the vehicles by decomposition method.	FMS with one central warehouse.	1-6 AGVs	Scheduling: CP; Conflict-free routing: MIP	H/MH	Longer horizon, more tasks or more AGVs.
[47] (Polten and Emde, 2021)	Scheduling the storage and retrieval of unit loads for VNA using AGVs.	Warehousing, VNA	5-30 AGVs	Access policies; MIP	H/MH	Different layouts, additional cross aisles, integrating positive safety distances, and integration of storage assignment
[69] (Yang et al., 2018)	Simultaneous scheduling and routing of quay cranes, AGVs and yard cranes in automated container terminals. Goal: minimizing the makespan.	Automated container terminals. Simultaneous loading/unloading operations.	16 AGVs, 8 QCs, yard cranes, 4 - 400 containers	Bi-level programming model (MIP)	GA	More accurate heuristic algorithms
[14] (Chen et al., 2019)	Optimize the coordination between AGVs and automated cranes in container terminals through a multi-commodity network flow model and ADMM.	Container terminals	20-60 AGVs & 2-4 automated yard crane.	Alternating Direction Method of Multipliers (ADMM)	GA	More handling agents, incorporating additional practical factors, employing more effective mechanisms like the cutting plane method.
[39] (Nishi, Hiranaka, and Grossmann, 2011)	Simultaneous scheduling and conflict-free routing problems for AGVs.	FMS, container terminals, warehousing systems, and service industries	2-4 AGVs, up to 100 jobs, 2 layouts	Bi-level decomposition algorithm	H/HM	Cases with significant processing to transport time ratios and developing an algorithm to tackle a wider range of problems.
[30] (Lacomme, Larabi, and Tchernev, 2013)	Simultaneous scheduling of machines and AGVs. Job-shop model. Minimizing the makespan.	FMS	2 AGVs, 6 machines, 6 jobs	Disjunctive graph	MA	Address stochastic transportation time.
[71] (Zeng, Tang, and Fan, 2019)	Minimize the makespan in cell-part scheduling, optimizing the cooperation between machines and AGVs.	Highly customized and complex products.	2 AGVs	Integer nonlinear programming (INLP)	AT	Not addressed
[21] (Fazlollahtabar, Saidi-Mehrabad, and Balakrishnan, 2015)	Scheduling multiple AGVs in a MS. Model that minimizes earliness and tardiness.	Container terminals, heavy industry, and FMS	12 AGVs, 17 shops, 45 jobs	MILP	H/HM	Not addressed

Table 3.3: Overview of analysed papers related to scheduling

Ref	Objective	Industry/ Configuration	Type and number of vehicles	Modelling Approach	Solving Method	Future research
[19] (Fazlollahtabar, 2016)	A parallel automated assembly line system to produce multiple products in a semicontinuous system.	Assembly line	Max of 9 AGVs	LP (Minimum cost flow)	H/HM	Application in real-world scenarios, implementing AI for a better dispatching rule.
[20] (Fazlollahtabar and Hassanli, 2018)	Simultaneous scheduling and routing for AGVs, optimizing paths, minimize collisions and waiting time.	MS	3 AGVs, 8 shops	ILP	Ex	Deadlock resolution factor should be considered.
[72] (Zheng, Xiao, and Seo, 2014)	MILP model for the simultaneous scheduling of machines and AGVs.	FMS	Up to 4 AGVs and up to 9 machines	MILP	H/MH	Enhancing the efficiency and scalability of the MH algorithm, exploring additional cases and the applicability in a dynamic scheduling environment.
[6] (Bakshi et al., 2019)	Efficient scheduling of AMRs to complete prioritized tasks in MSs under task space constraints.	MS	3 AMRs, 700 tasks	Recurrent Neural Networks (RNNs) with Long Short-Term Memory (LSTM)	H/MH	Extending to an algorithm that handles multiple AMRs simultaneously. Scalability and robustness of the algorithm.
[33] (Lei et al., 2020)	Minimize makespan in the flexible flow-shop scheduling problem with dynamic transport waiting times.	Smart MS	2 AGVs	MILP	MA	More complex scheduling problems should be explored.
[28] (Kaoud et al., 2020)	Simultaneous scheduling problem of AGVs and machines in FMSs, aiming to minimize makespan.	FMS	2 AGVs, 4 machines, 10 job sets	DES	-	Integration with heuristic approaches and with real-time manufacturing data (IoT)
[62] (Um, Cheon, and Lee, 2009)	Minimizing vehicle congestion, vehicle utilization and maximizing throughput for AGVs in a FMS.	FMS	9-13 AGVs, 6 machining centers.	Simulation and multi-objective nonlinear programming (MONLP)	Evolution strategy (ES)	Incorporation of other factors as machine breakdown, vehicle charging, traffic problems, transportation cost, space utilization etc.
[66] (Viharos and Németh, 2018)	Scheduling of AGVs and assembly operations on workstations to minimize the overall manufacturing time.	MS	2 AGV pools, 5 Robots, 6 workstations	DES	H/MH	Combine the module with external schedulers for better scheduling results
[24] (Gebennini et al., 2008)	To develop a simulation-based approach for supporting AGV systems design in end-of-line logistics.	Logistics, food- and beverage packing	10-12 AGVs, manual forklifts	DES	-	The effect of truck loading time on the occupation of storage area.

3.5. Storage Location Assignment

The case of Tata Steel indicates the necessity for assigning steel coils to a storage location in a way that minimizes the transport time for automated vehicles, minimizes the number of relocations, and maximizes the use of space. Reyes, Solano-Charris, and Montoya-Torres [48] present an overview of articles which tackle the Storage Location Assignment Problem (SLAP). This review identifies which articles relate to a certain topic or methodology. A second review document has been used to find relevant articles between 2019 and 2024 [36]. Additionally, Scopus has been used to find relevant literature.

SLAP tries to optimize the storage of goods which is a crucial role for a warehouse management system. The allocation of storage spaces and optimization of logistical resources to maintain efficient operational flow requires complex decision-making. These issues can be addressed using exact methods, heuristics, meta-heuristics, simulations, policies and rules, information technology tools, and multi-criteria approaches [48]. These methods can identify the performance based on several performance measures such as space & distance, time, operational efficiency, handling costs, infrastructure and human factors [48]. The largest part of the papers focuses on minimizing the travel distance and using exact methods to handle the problem.

To integrate the storage location assignment problem with the scheduling of automated vehicles, it would be convenient if the modelling approach matches. Therefore, the choice has been made to focus on simulation and optimization models. An overview of the studied articles has been presented in 3.4. One of the studies that stood out minimized the number of replacements or sorting operations [10]. Besides, the term 'Autonomous Block Stacking Warehouse Problem' (ABSWP) comes close to the case presented by Tata Steel. Even though coils are not stacked, these problems present deep-lane storage configurations, where relocations would be needed to obtain an item which has other items in front of it in the same lane. This problem consists of solving a series of several interdependent problems [43] [44]:

1. The layout problem: Before operations can start, the layout must be set.
2. The vehicle dispatching problem: When an item arrives at a source location, a vehicle needs to be dispatched to pick it up.
3. The storage location assignment problem: where the item needs to be placed.
4. The unit-load selection problem: when a sink demands an item, the correct one needs to be selected.
5. The unit-load relocation problem: Dispatching a vehicle to move the item & relocating items when no orders are present to reduce blockages and improve service times.

The second, third and fourth items are modelled by Pfrommer and Meyer [43], of which an open-source code is available. A gap that needs to be filled within this research is incorporating the layout problem. Furthermore, a manufacturing facility would provide an interesting new use case.

Lanza, Passacantando, and Scutellà [32] present an extensive literature review, discussing the several types of SLAP, such as stacking, multi-level and deep-lane storage assignment. Regarding the logistics of steel coils, mainly the scheduling of cranes in combination with storage locations and the arrival time of trucks has been researched [35][58][59][68]. Other similar studies focus on the triangular stacking of coils and their location assignment [38][59].

Warehousing in the food industry approaches the case of Tata Steel better. Due to the high cooling costs, the space should be as small as possible. However, blocking higher-priority items in a deep-lane storage system must be avoided to reduce the loading time of trucks. Zaerpour, Yu, and De Koster [70] consider one-sided access of lanes while reducing the retrieval time for every storage location. While Boysen, Boywitz, and Weidinger [11] focuses on minimizing the number of lanes used and compares one-sided access to two-sided access. This study shows that two-sided systems generally perform better, particularly when the pick-up time is hard to anticipate. No studies were found that focus on the efficient storage and retrieval of steel coils in a deep-lane storage configuration.

Table 3.4: Overview of analysed papers related to the storage location assignment problem

Ref	Objective	Industry/ Configuration	Keywords	Modelling Approach	Solving Method	Future research
[1] (Accorsi, Baruffaldi, and Manzini, 2017)	Design a model that assigns goods to the optimal *lane depth, storage mode* and *storage zone* by minimizing costs from time and space inefficiencies.	End-of-line warehouses, food and beverage industry, deep-lane & block stacking.	Block storage; Unit-load; Deep lanes; Optimisation; Layout	ILP	Exact	Deep-lane storage systems from *brown field*, where physical constraints need to be involved.
[10] (Bodnar and Lysgaard, 2014)	Allocation and aisle positioning problem (SAAPP) with gravity flow racks, minimizing the number of replenishments.	Material handling, FIFO	SLAP; product allocation; warehousing; dynamic programming	Graph-representation, dynamic programming	Exact	Not adressed.
[44] (Pfrommer et al., 2022)	Demonstrate the feasibility of a vehicle control system dealing with complex decision-making problems related to Block Stacking Warehouses (BSW).	Warehousing	Autonomous BSW; Benchmark dataset; DES; SLAP, SLAP-stack	DES	-	Extension to more use cases and embed the missing layout problem and the unit-load relocation problem.
[32] (Lanza, Passacantando, and Scutellà, 2022)	Simultaneous decision-making on SLAP and sequencing decisions for each product type. Optimizing the storage capacity while adhering to the FIFO policy	Tissue logistics	-	MILP	H/HM	Extending to put away and pick up operations, routing of vehicles and the assignment & sequencing of storage locations.
[70] (Zaerpour, Yu, and De Koster, 2015)	A model for a shared storage policy which allows for different products to share the same lane, minimizing the total retrieval time	Warehousing, cross-docking	Warehousing; Cross-docking, Compact storage system; Shared storage	ILP	H/HM	Further development of compact storage configurations and policies for overlapping storage and retrieval processes.
[38] (Nadali, Iranpoor, and Malekian, 2024)	Improving the performance of a crane-operated warehouse in a triangle stacking style.	Steel coil manufacturing	Coil selection; Multi-crane scheduling; GRASP algorithm	MILP	H/M & Ant Colony	Investigating where trucks carry multiple coils, SLAP for stacking of 3-4 layers.
[42] (Öztürkoğlu, 2020)	A multi-objective product allocation problem minimizing the average storage usage and total travel distance.	Pallet block stacking warehouse	Warehousing; storage utilization; unit load; bi-objective	MILP	H/MH	Exploring alternatives to efficiently generate Pareto fronts.
[11] (Boysen, Boywitz, and Weidinger, 2018)	Minimize blockings in deep-lane storage systems to optimize retrieval efficiency. Comparing one-lane vs two-lane access.	Fresh produce distribution centers	Facility logistics; Warehousing; Deep-lane storage; Storage assignment	MILP	H/HM	Solving larger problem instances. Alternative problem setting to avoid blockings

3.6. Conclusion and Discussion

This chapter addresses the first sub-question: *Which theories are applicable for generating new findings on the system design of in-plant transport and storage processes?*

As stated in the introduction, the theory of this literature study focuses on the capabilities and differences between AGVs & AMRs, the flow path layout, scheduling methods for automated transport and the assignment of storage location with a focus on deep-lane storage configurations. Theory on battery & failure management, idle-vehicle positioning, routing, conflict avoidance and deadlock resolution are not the main focus of this study.

Literature related to the flow path layout presented several strategies. Besides conventional bidirectional flow, the zone-based flow approach can be deployed. This approach prevents deadlocks from occurring and influences the cost- and productivity performance of the transport system. New methods are needed to design the zones and handover locations. Manufacturing systems with in-process inventory complicating the design of zones are interesting to consider.

The theory indicated several decision-making policies related to scheduling methods for (flexible) manufacturing systems to facilitate effective material flow between the workstations and/or storage areas. Chapter 5 states vehicle dispatching policies relevant to the case, based on Le-Anh [2] and Azimi [4]. Linear Programming (LP) methods were deployed often focusing on minimizing the makespan as the main objective. The objectives in LP studies often minimize the time needed for all operations or the total vehicle capacity needed. Based on these models scheduling decisions are made. However, proper performance estimations consider more detailed aspects of the system in which the AGV operates. The stochastic features inherent to a manufacturing facility, the dynamic behaviour, real-time decision-making and the influence of dispatching and allocation rules were better captured in DES studies. Container terminals were found to capture similar problems due to the low capacity of the container handling equipment. Scheduling rules in DES studies were found often to be based on operational criteria such as the shop floor status, production requirements, and system priorities. A similar approach will be used in this research. The difference is that this study focuses on the entire systems design while other studies focus on a more detailed scope.

Regarding the assignment of storage locations, there was not much literature available on manufacturing facilities. In the allocation of large items (often blocks such as pallets) and deep-lane storage systems, most studies were performed for warehousing operations. The most used policies are class-based (CB) and random-based (RB). The storage policies are highly dependent on the available information, such as the duration of stay, whether the sink location is known so the storage can be assigned based on the shortest distance etc. The closest-open-pure lane is a policy applied in deep-lane storage systems having to do with items that can be grouped based on type or order for example. This policy is well applicable to the case of Tata Steel as it aims to minimize the relocation of items due to blockings. Notably, the SLAP in steel coil manufacturing has only been studied for crane handling operations and stackable coils, not for AGV operations and deep-lane coil storage.

In conclusion, the main theories and modelling approaches identified are listed below:

- Flowpath layout design: conventional & zone-based flow approach, under bi- or unidirectional flowpath constraints.
- Scheduling: Linear Programming (LP) and Discrete-Event Simulation (DES) studies under a wide variety of vehicle dispatching policies (see chapter 5 for the chosen policies).
- Storage location assignment (deep-lane storage): LP and DES studies under class-based, random-based, closest-open-pure-location, demand forecasting or other storage policies.

By synthesizing the challenges presented by the case and insights from the literature review, the following knowledge gap has been identified: *the need for integrated analysis of flow path layout designs and their impact on material flow effectiveness in automated vehicle systems, considering vehicle scheduling and storage location policies*. Furthermore, the case of Tata Steel is a brownfield project where storage facilities and physical constraints need to be involved. The literature emphasizes the need for more case studies in brownfield projects. By studying the system design of a steel coil manufacturing industry and applying relevant theories, this thesis aims to generate new findings on the design process and decisions related to implementing automated transport.

4 System Analysis

This chapter first defines the solution space by describing the current information- and process flow for the transport operations and storage process. The goal of this chapter is to describe the use case and to answer the following research question:

SQ2: *How is the solution space of the transport and storage system defined, and what challenges in its current operations require innovative changes?*

A design process aims to develop an artefact that can function within the system constraints and with a specific desired performance [9]. Since the case presents a complex problem this chapter aims to present a systematic current state analysis and determine its solution space. The solution space is 'the multi-dimensional space limited by boundaries within which the solutions are to be found, determined by requirements and design environment' (Binsbergen, 2022, p. 42)[9]. The solution space is shaped by the infrastructure, control mechanisms, users, environment, and interactions. The sections below aim to give a systematic overview of the solution space and what 'variables' in the design can be varied.

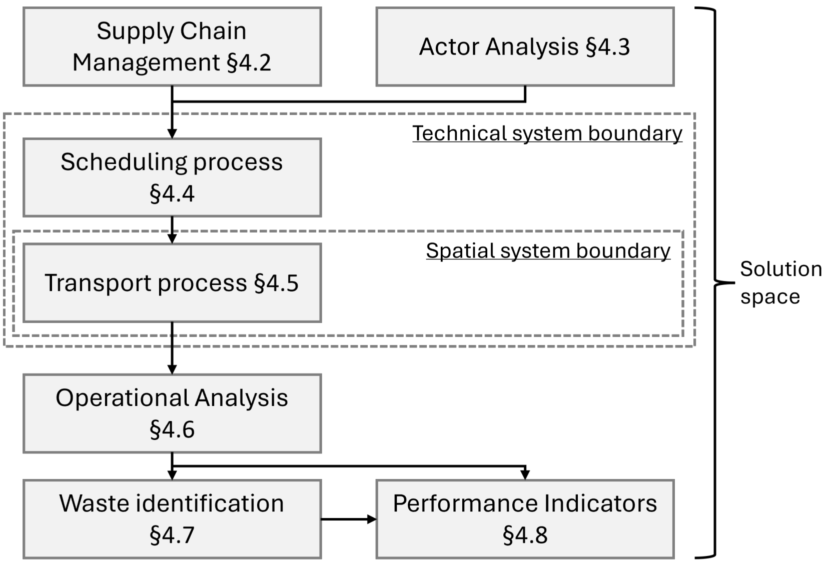


Figure 4.1: Framework system analysis

This chapter starts with a general description of the system under study in section 4.1. In section 4.2, the Supply Chain Management (SCM) system controlling the material flows is described. Following this, stakeholders, consultants, and users of the system are interviewed to provide insights on the interactions within the system and their perspectives on automated transport (section 4.3). The actor and SCM analyses serve as inputs to the black box model for scheduling transport tasks, which is discussed in section 4.4. After defining the scheduling process, a black box model in section 4.5 represents the physical transport process. The two black-box models define the technical system boundary. Subsequently, historical and observational data are analyzed to identify the current system performance in section 4.6. The challenges and inefficiencies in the system are explored in section 4.7. These challenges define the 'variables' within the system that require innovation or more effective approaches. Collectively, these sections establish the criteria that determine the system's performance (section 4.8). Finally, section 4.9 addresses the sub-research question and offers concluding remarks.

4.1. General description

Tata Steel IJmuiden is one of the largest steel producers in Europe, and its packaging factory spans over 1 kilometre. The flow of work-in-process materials requires many intra-logistical transport operations. The transport operations and layout considered in this thesis are visualised in Figure 4.2, which is only a part of the factory. The scope considers all coil handling operations between the temper rolling installations and the electroplating installations of the small route, which refers to the narrower coil width. As visualised, the scope considers four sources/inputs and four sinks/outputs. The coils are stored in a work-in-process inventory between the installations in the indicated storage parks, which currently have a combined capacity of 408 coils. The operations are currently performed with manual forklifts. This thesis investigates how these operations can be automated effectively.

The material flows represented in the case study define the physical system's boundaries. However, at the level of IT infrastructure and planning processes, a broader understanding of larger-scale systems is necessary. Therefore, the section on Supply Chain Management provides an overview of the systems implemented across the factory.

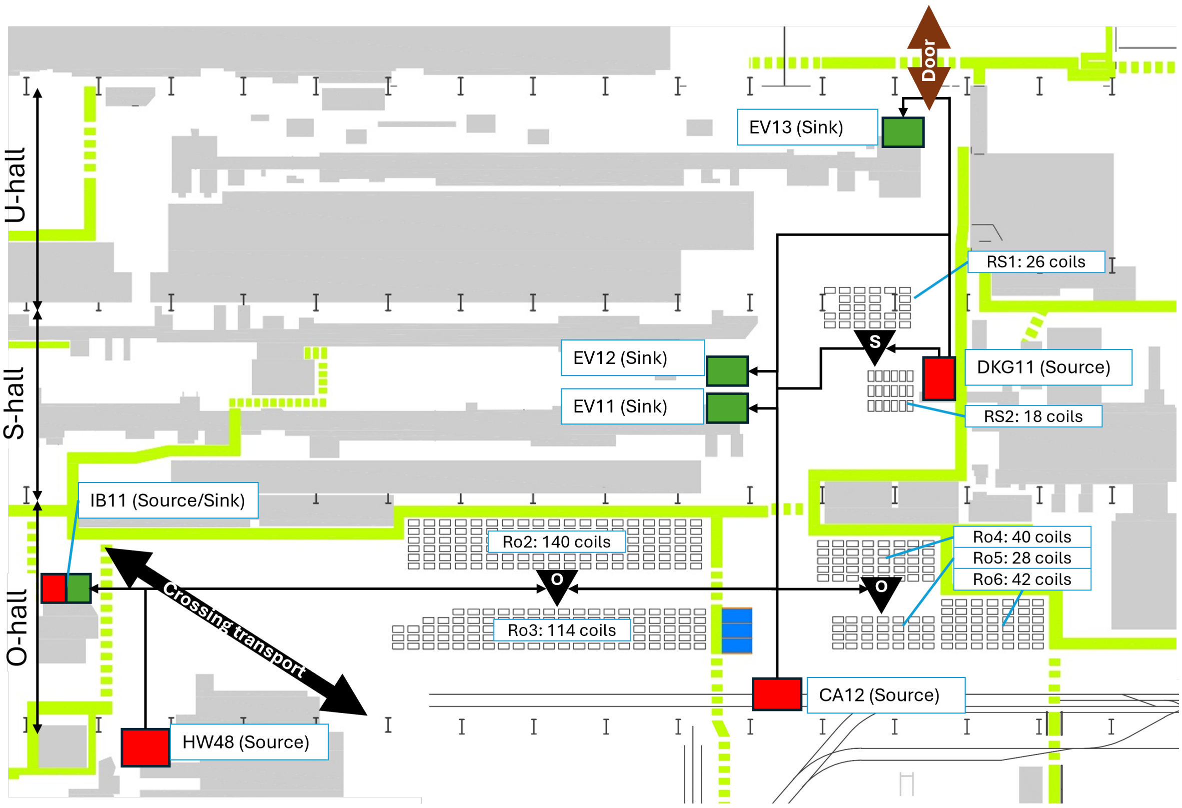


Figure 4.2: Current State Layout

4.2. Supply Chain Management

The Supply Chain Management (**SCM**) System describes the information flow from incoming orders to the physical transport of coils in the factory. This flow is visualised in Figure 4.3. This section presents which systems are in place to plan the orders. This influences the transport tasks that must be executed and constrains the solution space.

The general material flow is determined by the sales department (Customer Relationship Management (**CRM**)) and planned by the Supply Chain Management department. SCM uses Enterprise Resource Planning (**ERP**), which contains information on all business processes, to plan the tasks with Run Sequence Planning (**RSP**). In RSP, 'electronic work issues' (E-Wug) are made to schedule the tasks on the installations. By storing the data in BLITS+, each installation knows which task to perform.

BLITS (dutch abbreviation for Can Information and Tracking System) and **MOMS** (Manufacturing Operations Management System) are different data systems. BLITS is still operational to obtain data on the history of the coil and is used by forklifts and other vehicles. **BLITS+** is the newer version to which the work issues are currently being sent. A machine operator can change the order in which the coils go through the installation (in BLITS+) in case of deviations. Besides, the location of a coil is saved in BLITS+ if the coil has a new location. In conclusion, BLITS(+) is used for administration purposes.

MOMS, on the other hand, is used to convert observations into actions. MOMS contains data on the coil's location and properties and which processes the coil has undergone and is still awaiting. MOMS is used at the installations, while the vehicle operators use BLITS. Furthermore, if the coil contains one or more flaws, it can be put on ARF in MOMS. The coils are then patched up by cutting out deviating parts of the coil. Forklift operators receive their tasks through BLITS (which is linked with MOMS) and decide which task has priority to handle.

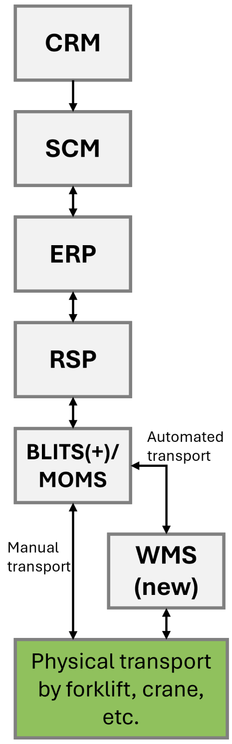


Figure 4.3: Supply Chain Management

In the future, the Warehouse Management System (**WMS**) will ensure the optimal control of automated vehicles, cranes and other automated modes of transport. With the implementation of the WMS, deadheading can be reduced (empty return trips). Besides, small orders can receive priority, which leads to an increase in the total flow [17]. A WMS is in place for new overhead cranes, which can be modified to control automated vehicles.

4.3. Actor Analysis

The actor analysis has two goals. First, it aims to define the system constraints by interviewing actors on the current operations. Second, it seeks to identify challenges and collaborate with stakeholders to develop potential solutions for these challenges. An organogram of the organization with relevant actors in the grey boxes has been visualised in Figure 4.4. The data gathered from the actors are described in Appendix B.

This section is not intended to discuss the results of the actor analysis, but rather to explain the role of the actors. The data collected from actors has been incorporated throughout the report. The system constraints are outlined in section 4.4 and section 4.5. The identified challenges and proposed solutions for implementing automated transport were utilized to develop the design alternatives in chapter 5. An overview of the actors is given below.

- **Operational Development and Support (ODS):** ODS is a group of consultants working on continuous improvement projects for the factory. They were able to help retrieve previous studies and analyze the system.
- **Supply Chain Management:** SCM plans the orders, consisting of a set of coils, on the installations. This department tries to keep coils of the same order together. After a production line has processed a coil, forklift operators are informed through MOMS and transport the coils to their destination.

- **Infra:** The infrastructure department manages all physical infrastructure within the factory. This has led to insights regarding which infrastructure may be adapted and which constraints must be considered.
- **Production Managers:** The production managers are the supervisors of one of the work areas within Packaging. The managers of the work areas temper rolling, tinning and transport & packing were interviewed.
- **Team Leaders:** For work area 6, several team leaders were interviewed. The team leaders could provide more detailed information on the transport operations and storage facilities within the scope of the case study. One finding was that the forklift operators determine the storage location based on the available spaces and the need for grouping coils of one order. The storage position is not assigned by a system in the current operation. After the coil has been placed in a storage area, the QR code is scanned whereafter the location (park, lane, position within lane) is registered. Defining the storage location is also an action of the forklift operator.

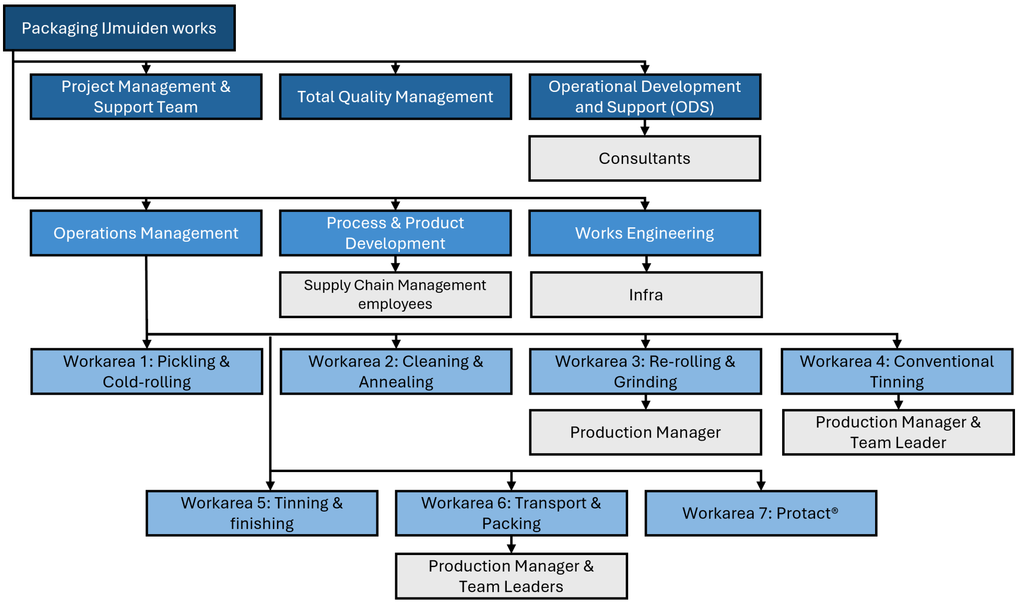


Figure 4.4: Actors

4.4. Black Box Model of the Scheduling Process

A black box model is used to gain insight into the process on the most abstract level. A black box model is a process which converts inputs to outputs and is increasingly used to drive decision-making in several markets. The model emphasizes the lack of visibility into the internal workings of the system. The purpose of this model is to show the inputs, influencing factors and output of the scheduling process in place at Tata Steel. Both the lecture slides and a similar study were used as references [27][55].

The inputs to the black box model can vary over time, such as which tasks need to be fulfilled. The requirements, however, are predetermined and fixed over time. The black box model is visualized in Figure 4.5. The green block represents the input to the scheduling process. Transport tasks are the coils needing to be transported. The requirements and constraints are visualized in orange. Constraints encompass factors like safety constraints, vehicle capacities, and vehicle availability. Parameters influencing the scheduling process, such as transport duration, speed, and pick-up/drop-off locations, are depicted in grey. The disturbances are shown in yellow and represent delays or unavailable resources due to transport damages or charging, for instance. The performance resulting from scheduling the transport is indicated in light blue. The scheduling process should, in the future, be performed by a Warehouse Management System (WMS), which decides the storage locations of the coils and dispatches the vehicles. This model defines this process in its current state. The elements of the black box model are discussed below the figure.

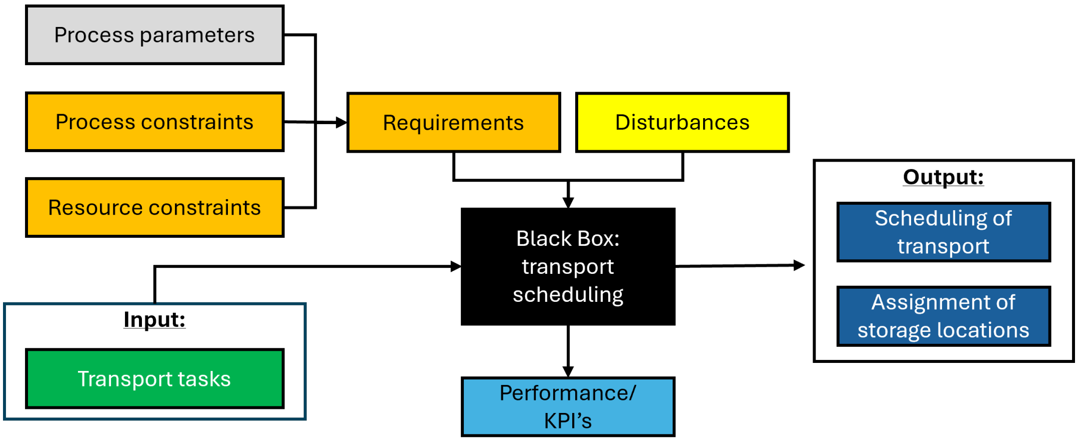


Figure 4.5: Black box model of the scheduling process

4.4.1. Input

The transport tasks serve as the input for the black box model and include the tasks requiring scheduling.

Transport tasks:
- From source (HW48, DKG11, IB11 and CA12) to the storage parks
- From storage parks to the sink installation (EV11, EV12, EV13 & IB11)
- Repositioning of coils

Forklifts are the resources used to transport the coils. Manual forklifts will be replaced by forklift AGVs in future processes. An overhead crane in the N-hall is used to transport coils from the exit of the HW48 towards a location where a forklift can pick them up. The crane is not in the scope of being automated. Other overhead cranes are not included as possible future modes of transport due to capacity limitations. The transport tasks include the main transport tasks as well as sorting operations.

Installations and Throughput Specifications

The transport tasks that need scheduling is linked to the coils' arrival rate at installations. This section discusses the function and relevant specifications of the installations within scope. The DKG11 and HW48 are temper-rolling installations. The EV lines coat the product to protect it against corrosion. The steel coils can be coated with either tin or chrome on various coating lines.

Temper rolling enhances the strength of the steel while providing the necessary surface quality and flatness. After annealing, the material does not possess sufficient strength, which is why this temper rolling is essential. Standard material is produced using single reduction (SR), while higher-strength steel is achieved through temper rolling with a double reduction (DR) mill. HW48 is a single reduction mill, whereas DKG11 is a double reduction mill, though it can also operate as a single reduction mill [12].

Electrolytic Tinplate (ET) is a low-carbon steel coated with tin on both sides through an electrodeposition process. Tinplate is widely used for various packaging materials, including Drawn and Wall Ironed (DWI) steel, the industry standard for beverage cans [12]. Both EV12 and EV13 are ET coating installations.

Electrolytic Chromed (EC) steel is tin-free steel coated with chromium. This material is used in the production of two-piece cans, seamed cans, and various non-welded components, such as ends, lids, crown corks, twist-off caps, and aerosol tops and bottoms [12]. EV11 is an EC installation. EV11 is currently being renovated, therefore the data in Table 4.1 is provided for the future situation and the situation before it was renovated.

The specifications of the installations are stated in Table 4.1[1]. The processing time per coil can vary

[1]The analysis does not include IB11 and CA12 as they were not a part of the initial scope. Only Table 4.5 indicates the share of all installations.

a lot since it depends on the length of the coil. The average processing time is based on data from the year 2021. The data only accounted for shifts where 4 coils or more were processed, since it may happen that a previous watch produces some coils in the successive watch. A day is divided into 3 shifts, the morning (6:00 - 14:00), afternoon (14:00 - 22:00) and night (22:00 - 6:00) shift. Data about the future situation of EV11 is described in Appendix G.

	HW48	**DKG11**	**EV11**	**EV11 (Future)**	**EV12**	**EV13**
Speed (m/min)	1200	1200	390	400	420	540
Capacity/year (kton)	285	185	150	266	160	275
Avg. coils/shift	16.1	12.0	9.3	10.9	11.1	15.9
5% - 95% coils/shift	6-28	5-21	5-14	-	5-17	7-24
Max. coils/shift	56	30	18	19.7	21	33
Estimated length to storage park in O-hall (m)	85	20 (to S-hall)	65	65	70	140

Table 4.1: Throughput Specifications [29] [31] [63]

4.4.2. Requirements

Constraints define the aspects the system must comply with. These can be divided into functional and non-functional requirements. Functional requirements are things the system has to do (activity or process). Non-functional requirements are attributes or characteristics the system must have [8]. These requirements apply to current operations and should be incorporated in the quantitative model of chapter 6.

Functional constraints:

FC1. The system must comply with the constraints as defined in process parameters and process- & resource constraints.
FC2. The system must specify which resource (e.g. forklift) is allocated to each task.
FC3. The new coil position must be saved for every transport operation (park, lane, position within lane or in- or outfeed of an installation).
FC4. The system must indicate the pick-up and delivery location for each task.
FC5. The system must be able to operate in a highly mixed environment. Logistics areas are shared with pedestrians and other modes of transport.

Non-functional constraints:

NFC1. The coils must be placed in a designated location.
NFC2. The system must be able to schedule the transport, ensuring that installations do not have to stop their operations due to full buffer spaces or the absence of coils at the infeed.
NFC3. The system must define the storage location of each coil based on its attributes.
NFC4. The transport operations must at least be able to cope with the demand based on historical data.

In addition to the functional and non-functional requirements, the system is defined by the process parameters, process constraints, and resource constraints, which are discussed below.

Process parameters:

The process parameters have been categorized into three categories: the time it takes to perform a transport task, the prioritization of tasks and the locations where the coils need to be retrieved or transported to. Each storage location can have a different configuration and capacity. The current configuration is visualized in Figure 4.2.

- Time based: empty trip time, loading and unloading, travel time
- Prioritization of tasks
- Locations of installations (with varying numbers of buffer storage positions)
  - Source HW48
  - Source DKG11
  - Source IB11

  - Source CA12
  - Sink EV11
  - Sink EV12
  - Sink EV13
  - Sink IB11
- Locations of storage facilities (with varying number of lanes and until 7 coils deep):
  - Ro2
  - Ro3
  - Ro4
  - Ro5
  - Ro6
  - RS1
  - RS2

Process constraints:
Process constraints refer to the procedural aspects and sequence of activities, timing, and flow within the scheduling process. As listed below, several categories constrain the process. Physical constraints demarcate the area in which transport can take place. Resource constraints limit the number of available vehicles, for example. Resource capacity constraints limit, for instance, the number of coils and payload a forklift can handle. The time constraints ensure that coils won't corrode between processes or that the installation queue reaches overcapacity. Furthermore, there are safety constraints and constraints related to the operating speed.

- Physical constraints of the factory
  - Location of walls and aisles
  - Roof height
  - Width of narrowest passage
  - Location of cellars and underground cables
- Resource availability
  - (Automated) forklift availability
  - Availability of storage places at installations
  - Available places in storage parks
- Resource Capacity
  - (Automated) forklift capacity
  - Storage capacity
  - Capacity for transport operations (congestion)
  - Buffer storage capacity (Table 4.2)
- Time constraints
  - If the thickness is reduced to less than 7% by the DKG11, it needs to be processed within 48 hours by one of the EV lines.
  - Other coils from the DKG11 need to be processed within 72 hours by one of the EV lines.
  - Earliest and latest pick-up time. If the latest pick-up time is exceeded at the exit of a machine, the buffer may be full and the machine has to stop its processes.
- HSE (health, safety and environment) & HARA (food safety) constraints
- Tata Steel policies and standards
- NEN (dutch norms) and EN (European Norm) regulations
- Safety constraints
- Operating speed of forklifts and crane

Resource constraints:
Resource constraints refer to limitations or restrictions on the availability of essential resources. Forklifts and overhead cranes are constrained in several aspects. Furthermore, the steel coils can be positioned vertically and horizontally, and their diameter imposes constraints on the handling sequence.

- Forklifts
  - Payload capacity
  - Volume capacity
  - Dimensions
  - Type of handling
  - Travel distance on one charge or tank
  - Charging time
  - Lifting height

- Steel coils
  - Horizontal orientation
  - Handle coils with the dimensions and specifications as stated in Table 4.3.

4.4.3. Disturbances

Disturbances hinder transport operations. Transport flows that are not within the scope of automation hinder the flow of the to-be-implemented automated vehicles. These can be for maintenance, crossing traffic, and material supply, for instance. Besides, malfunctioning equipment, disturbances in production, and damage to coils are examples of hindering transport operations.

- Crossing traffic
  - Golf carts
  - Buiscar (U-hall (EV1234) to W/T-hall and CA12 to EV123)
  - Forklifts
    - Flow from CA12, DKG11 and HW48 towards the IB11
    - Flow from IB11 to the storage parks (coils EV11, EV12 or EV13 as destination)
    - Unloading wagon in the O-hall to the storage park coming from CA12
    - Flow from PKB/PIL 11 to flat buiscar.
  - Material supply (tin bars, degreasing agent, sulfuric acid etc.)
  - Disposal of scrap
    - Residual coil scrap (Forklift)
    - Edge scrap (Truck)
    - Steel plate material scrap (Truck)
  - Emergency services (fire brigade, ambulance)
  - Personnel and equipment for maintenance & overhaul
  - Pedestrians
- Planned disturbance: Maintenance
- Damaged coils; loading and unloading faults
- Equipment malfunction
- Production disturbances
- Sales disturbances
- No forklift operators available

4.4.4. Performance Indicators

The performance indicators are influenced by both the scheduling and physical systems and are discussed in section 4.8.

4.4.5. Output

The black box model's output provides statistics on the selected criteria. The scheduling of transport operations and assignment of storage locations are also outputs of the black box model and influence the criteria. Currently, the tasks are assigned by the supply chain management department. The assignment of storage locations and transport scheduling is entirely in the hands of the forklift operators. All installations work FIFO (First-In-First-Out), and forklift operators try to group coils from the same order.

The output consists of the following elements:

Scheduling of transport:
- Pick-up and delivery time
- Allocation and operations of forklifts

Assignment of storage locations:
- Storage park
- Lane
- Position within lane

4.5. Physical System Analysis

The physical system analysis describes the system analysed from the flow component perspective, the steel coils. In subsection 4.5.1, a black box representation of the physical system is visualised. This is followed by a more detailed description of the system's characteristics in subsection 4.5.2.

4.5.1. Black Box Model of the Physical System

A black box model is used to represent the system on the most abstract level and used to drive decision-making processes [55]. This section describes the black box model of the physical system. The input and output of the physical system are steel coils, the object that flows through the system. Component classes are the installations, forklifts and storage parks. Additional constraints are the facility layout and how coils are planned on the installations by supply chain management. The performance can be quantified through many criteria. Some of the most relevant criteria in the physical process include the throughput, cycle time and resource utilization of the forklifts.

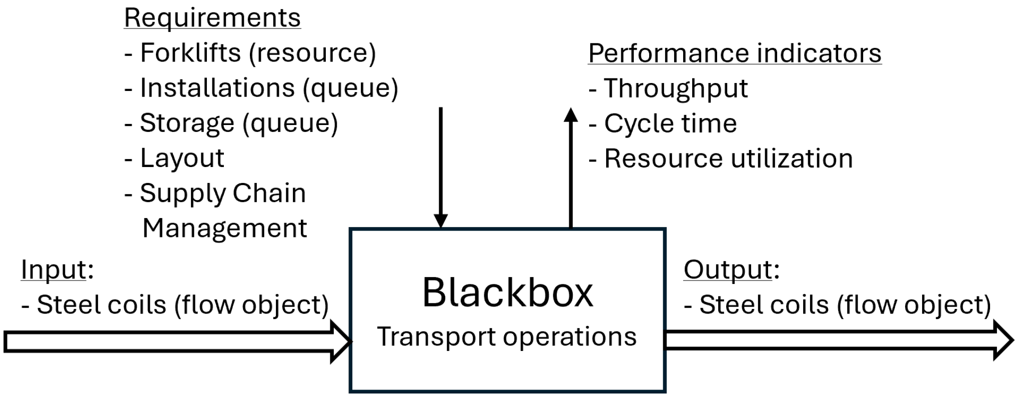


Figure 4.6: Black box model of the physical system

Each component class can be described by its attributes and processes. Component classes interact with each other. The events in the physical system are the transport of a coil from source to storage and from storage to sink. The component classes have the following attributes and processes:

Installations

- Attributes are the number of buffer storage positions and the location of the installation.
- Installations interact with forklifts by addressing the need to transport a coil from a source or to a sink component.
- The components are divided into the source (supplying installations) and sink (requesting installations) components. Source components are the DKG11, HW48, IB11, CA12. Sink components are EV11, EV12, EV13 and IB11.
- The processes of a source component can be defined as:
  - Start: create a coil
  - Enter: put a coil in queue
  - Reactivate: request transport for the coil
  - Hold: hold the coil in queue until transport arrives
  - Leave: remove a component from the queue
- A sink component follows the following structure:
  - Reactivate: a coil is requested to the installation
  - Enter: put a coil in queue
  - Hold: hold the coil in queue until the installation has a position available
  - Leave: remove a component from the queue

Forklifts

- Attributes of the forklift are its size, capacity, speed, turning radius, costs etc. The component class 'Forklifts' is the fleet of forklifts (the individual components).

- Forklifts are resources transporting steel coils and interact with both the installations and the storage parks.
- The process can be defined as:
  - Passivate: wait until transport is requested
  - Hold: resource state is busy, drive to request
  - Hold: resource state is busy, pick-up coil
  - Hold: resource state is busy, transport to destination
  - Hold: resource state is busy, drop-off coil
  - If: if a request is waiting, start the loop again
  - Else: drive to idle-vehicle position and start the loop again

Storage

- Attributes are the number of storage positions, the number of lanes and their depths and the dimensions for the patching around the coils.
- Storage parks are queues and interact with forklifts. The process can be defined as:
  - Enter: put a coil in queue
  - Hold: hold the coil in queue until taken out by a forklift
  - Leave: remove the coil from the queue

4.5.2. Characteristics of the System

This section provides more detailed information on the case. The scope of this project is to (partially) automate the transport between the outfeed of DKG11, HW48 & CA12 towards the infeed of EV11, EV12 & EV13. IB11 has been added to the scope to cover most of the transport operations in this area. IB11 patches up damaged coils, after which the coils proceed their route. The following information corresponds with Figure 4.2:

- The in- and outfeed of installations contain several buffer positions as indicated in Table 4.2. The positions on the rewinder or unwinders are considered part of the installation and are therefore not considered in the quantitative model of chapter 6.

Location	# Positions	Comments
Outfeed DKG11	5	After rewinder 4 positions
Outfeed HW48	3	After rewinder 2 positions
Infeed EV11	4	2 unwinders and 2x1 positions
Infeed EV12	4	2 unwinders and 2x1 positions
Infeed EV13	4	2 unwinders and 2x1 positions

Table 4.2: Buffer storage

- The coils supplied to EV11, EV12 and EV13 originate from HW48, DKG11, CA12 and IB11. IB11 has a small contribution as this installation is used to patch up damaged coils. Coils originating from CA12 are transported on a wagon to the indicated source for CA12. These are often delivered by 6 in one batch (3 per wagon). The coils are unloaded from the wagon and put into storage.
- Storage parks RS1 and RS2, with a combined capacity of 44 coils, are solely used between DKG11 and the EV lines.
- Storage parks Ro2 and Ro3, with a combined capacity of 254 positions, are primarily used as storage between HW48 and the EV lines. Furthermore, CA12, IB11 and some DKG11 coils are also placed here.
- Storage parks Ro4, Ro5, and Ro6 with a combined capacity of 110 coils are due to the renovation of EV11 not being used in the current situation. This area is currently needed for building materials; however, it can be put back into use in the future.
- The crossing in front of IB11/HW48 is 1 of the 2 crossings with the highest number of transport operations in the factory. The modes of transport driving here are golf carts, forklifts for coils, smaller forklifts (for consumables), freight carts, tractors (with or without buiscar), pedestrians,

scrap trucks, cleaning services, contractors (cars and trucks), special transport for installation overhaul, flat carts for steel sheets and more.

- On the top right, a door is indicated; this door does not have to be used for coil transport. However, trucks with scrap material and other modes use this passage. These modes can also take a detour and do not necessarily require the use of this door.
- The green paths are pedestrian paths, and zebra crossings indicate a crossing with other modes. Two pedestrian paths are being crossed that are within the scope of this project.

Data on the transport operations and storage amount kept between the installations is described in section 4.6. From Figure 4.2 the main challenge observed, is the crossing in front of IB11/HW48.

The installations handle coils with specifications as stated in Table 4.3.

Coil Dimensions	Unit	Value
Coil weight min	[ton]	-
Coil weight max	[ton]	25
Coil width min	[mm]	450
Coil width max	[mm]	1300
Coil diameter min	[mm]	450
Coil diameter max	[mm]	2100
Diameter core min	[mm]	410
Diameter core max	[mm]	610
Material thickness min	[mm]	0.13
Material thickness max	[mm]	0.56

Table 4.3: Coil dimensions

4.6. Operational Analysis

The previous sections analyzed the system using a black box model for scheduling and physical processes. This section presents an operational analysis that 'deals with the measurement and evaluation of an actual system in operation' [22]. Specifically, it analyzes and quantifies data related to transport operations (subsection 4.6.1) and inventory levels (subsection 4.6.2). The analysis serves multiple objectives:

1. Quantify the current state for a better understanding of the system.
2. Quantify possible challenges, mainly crossing transport at the intersection.
3. Visualize the variability inherent to the production system.
4. Identify reliable data sources suitable for input into the quantitative model in chapter 6.
5. Serve as comparison for the model developed in chapter 6.

First, reliable and accurate data sources must be identified to perform the analysis. Based on the DMAIC method from 6σ, the measure phase within indicates the 'Measurement System Analysis' (MSA) method. MSA serves as a tool to evaluate the variation inherent in every type of inspection, measurement, and testing equipment. It provides a systematic approach for assessing the accuracy and reliability of the measurement process, thereby gauging the quality of the measurement system. Both precision and accuracy should be adequate.

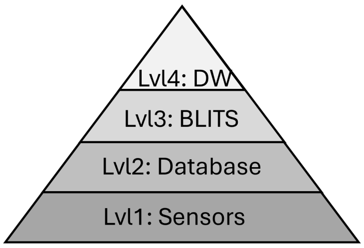


Figure 4.7: Data systems in 4 levels

The data systems of PAC are divided into 4 levels as visualised in Figure 4.7. The first level is the physical sensors, of which the data is saved in the second level, the database. The third level is BLITS, and the fourth is Data Warehouse (DW). In section D.1, the data validity is justified, and the choice to use data from level 2 (database) instead of the data from level 4 (data warehouse) has been motivated. Many disruptions cause the data on the 4th level to be less accurate. In Figure 4.8, an overview of the data collection process has been visualised.

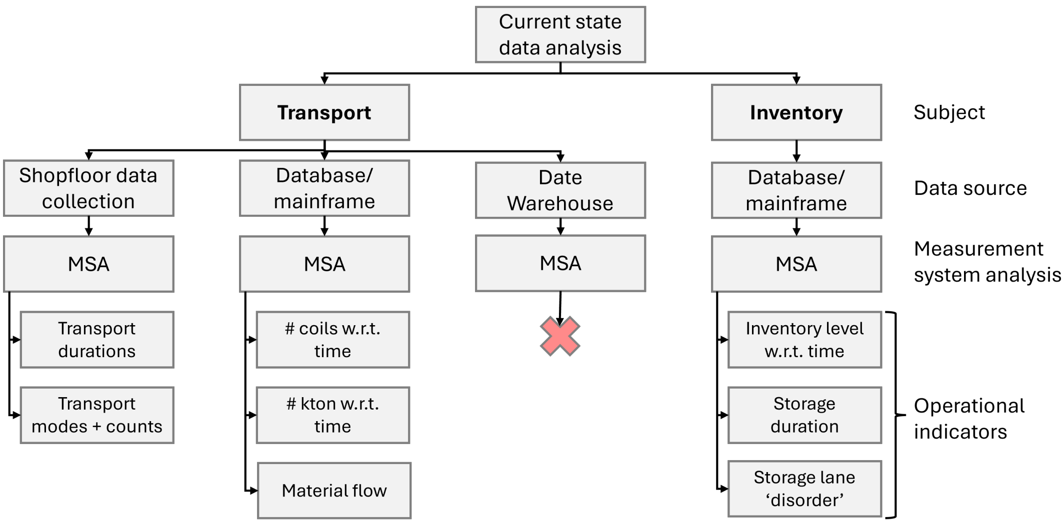


Figure 4.8: Current state data analysis overview

4.6.1. Transport Operations

The data from the database between 01-01-2021 and 31-03-2024 has been used to determine the amount of coils transported between the installations [31]. The data contains the installation of origin 'DKG11' or 'HW48', and by which EV it was processed, 'EV11', 'EV12' or 'EV13'. Furthermore, it contains the ID of the coil, the weight and the time & date an installation handled the coil. This data was filtered as described in section D.1.

The outfeed of coils in kilotons and total amount per month originating from DKG11 and HW48 have been described in Figure 4.9a and Figure 4.9b respectively. Figure 4.9c indicates the amount of coils transported between the installations. Furthermore, Table 4.4 shows the statistics for the number of coils transferred to the EVs.

Installation	Mean, μ	Median	Min	Max	σ	μ + σ	μ + 2σ	μ + 3σ
DKG11	174	187	0	355 (wk50 '22)	83	256	339	421
HW48	206	211	0	410 (wk24 '22)	91	297	388	479
HW48 + DKG11	379	417	0	671 (wk7 '22)	155	534	688	843

Table 4.4: Statistics for the number of coils transferred from DKG11 & HW48 to EVs per week

Table 4.5 shows the proportion of coils transported along specific routes relative to the entire scope of the analysis. This table indicates that DKG11 coils are mainly processed by EV12. HW48 has the largest share in coils processed by EV11 and EV13.

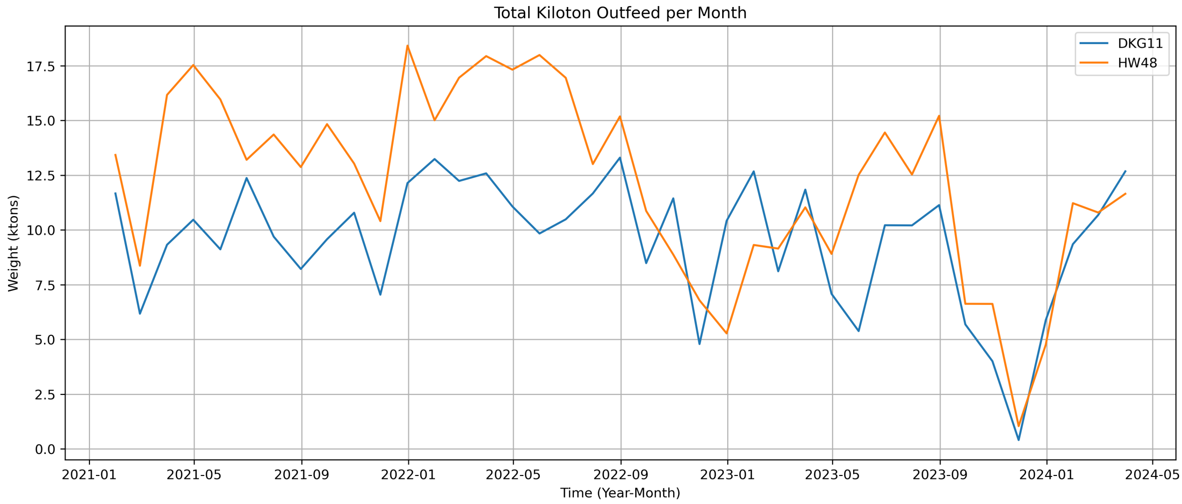
Destination → Origin ↓	EV11	EV12	EV13	IB11	% of total
DKG11	5,3%	19,4%	7,2%	0,3%	32,2%
HW48	8,9%	7,1%	23,5%	6,2%	45,7%
CA12	3,8%	4,0%	13,6%	-	21,3%
IB11	0,1%	0,3%	0,3%	-	0,7%
% of total	18,2%	30,7%	44,6%	6,5%	100,0%

Table 4.5: Material flow percentage per route

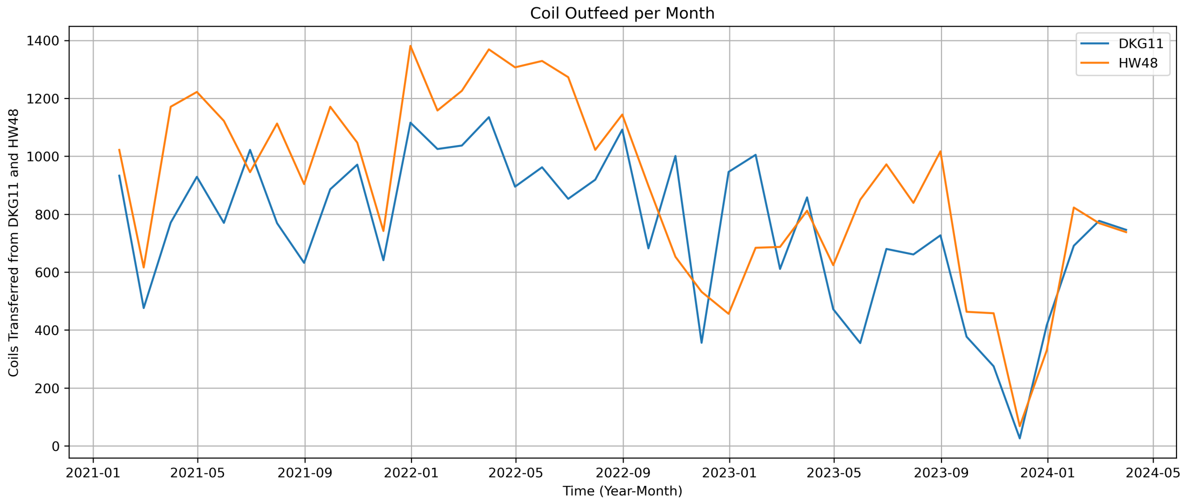
The EV lines produce scrap material which needs to be transported elsewhere. Table 4.6 presents the statistics of the number of times scrap was picked in the area of the EVs based on 4-2023 till 3-2024.

	Number of counts	Average/shift
EV11 & EV12 (Entrance U-hall)	661	0.61
EV13 (Entrance S-Hall)	985	0.91
Combined	1646	1.52

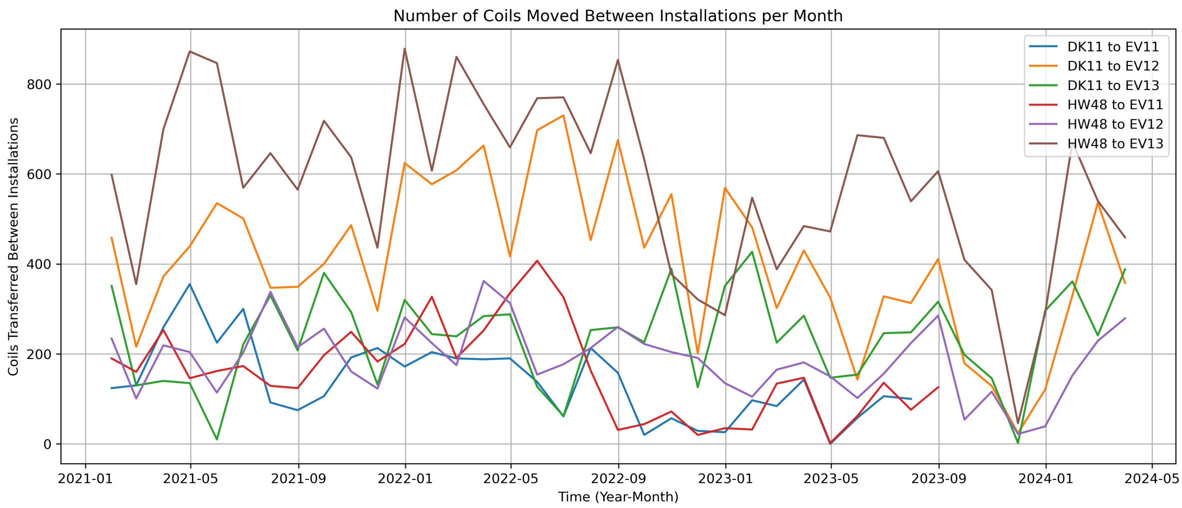
Table 4.6: Transport operations for scrap material [46]



(a) Outfeed per month (kton)



(b) Outfeed per month (number of coils)



(c) Number of coils transferred between installations per month

Figure 4.9: Monthly Outfeed and Coil Transfer

Shop Floor Data Collection
Observations are done in the factory to measure the number of transport movements on the crossing in front of the outfeed of HW48/ next to IB11, as visualised in Figure 4.2. The statistics for the amount of transport movements are indicated in Table 4.7. The duration for specific activities a forklift performs is stated in Table 4.8. The counts are based on three observations, 11-4-2024 9:33-10:35, 16-4-2024 8:30-9:31 and 5-5-2024 14:36-15:24. According to the team leader of the transport department (work area 6), there is not one specific peak moment, the busiest period is Monday till Friday between 7:00 and 16:00. Therefore the observations are done at different moments. The statistics on the transport counts indicate the vehicle category 'other'. These can be cleaning services, cranes for the overhaul of installations, contractors, trucks (e.g. garbage or scrap material) and more.

Mode of transport	Average Frequency #/hour	Peak period; max #/10 minutes	% in direction of W/T-hall	% in direction of U-hall	Total Count
All Combined	38.8	13	58.3%	41.2%	108
Forklifts for coils	19.4	12	52%	48%	54
Forklifts for auxiliary goods	5.0	4	71%	29%	14
Golf carts	7.6	6	57%	43%	21
Tractor (Buiscar)	2.2	2	50%	50%	6
Other	4.7	4	69%	31%	13

Table 4.7: Counted transport movements per vehicle category based on 2 hours and 47 minutes

The meanings of the tasks in Table 4.8 are defined as:

- **Pick-up:** The pick-up time starts as soon as the forklift operator decelerates or makes a clear turn towards the coil. The time ends when the vehicle changes from driving backwards to driving forwards.
- **Drop-off:** The drop-off time starts as soon as the forklift operator accelerates or decelerates or makes a clear turn to the drop-off location. The time ends when the vehicle changes from driving backwards to driving forwards.
- **Sorting:** A sorting operation refers to the process of retrieving a coil from its original storage lane and relocating it to another lane. This procedure, commonly known as "digging out," involves picking up the coil and placing it in its new position. This allows to keep the lane pure based on the order number and reduce the overall cycle time for transport requests.
- **Rotating coil:** Coils sometimes need to be rotated 180 degrees, so it can be processed by an installation.

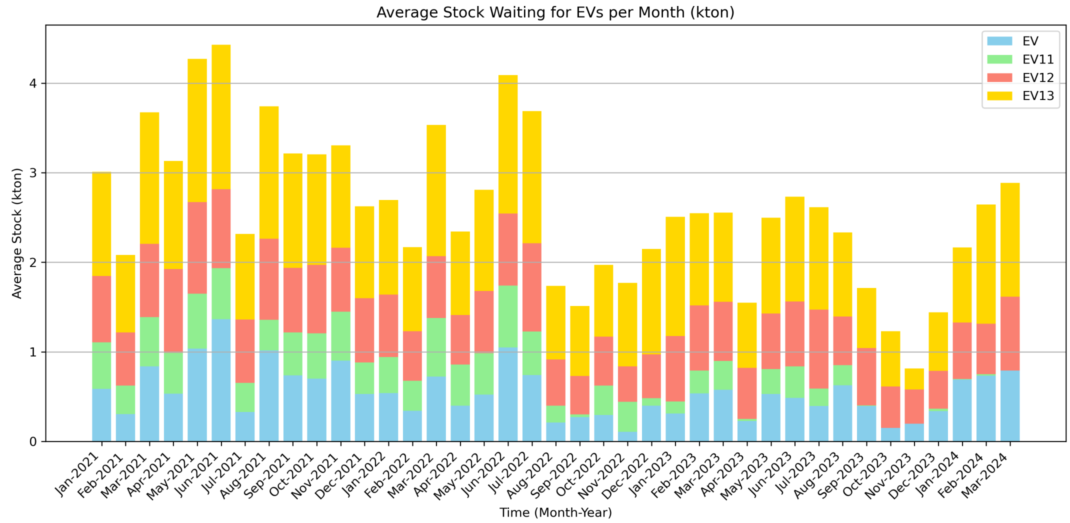
Task	Number of observations	Average duration (s) (μ)	5% (s) ($\mu - 2\sigma$)	95% (s) ($\mu + 2\sigma$)
Pick-up	24	20.5	9.8	31.2
Drop-off	22	25.3	9.2	41.3
Sorting	2	25.3	-	44.5
Rotating coil	3	40.4	34.1	46.7

Table 4.8: Transport Duration Statistics

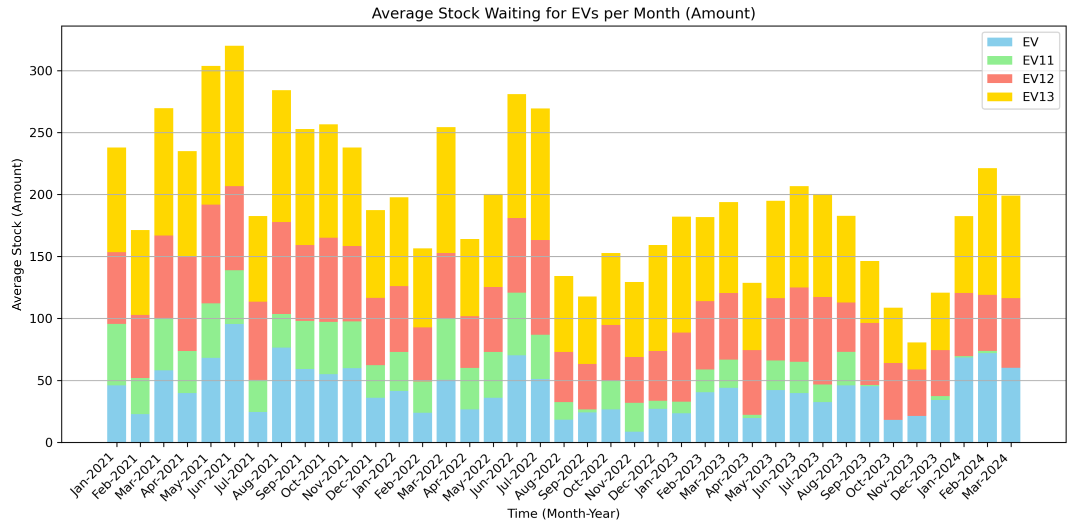
The observations lead to some other findings. The idle-vehicle positioning is often directly next to the storage park. The infeed of coils to the EV lines often happens if both buffer positions are empty, so the operator can deliver two coils right after each other. Lastly, some observations for the task duration were not taken into account because the operator was checking which tasks needed to be performed for quite some time.

4.6.2. Storage

The most reliable data on stock heights are the daily snapshots at 6:00 am [26]. This snapshot contains the information of every coil in the Packaging factory that is in a certain storage park and waiting to be handled by the next installation. Coil-specific information such as the lane in which it is positioned, the hall, the weight, the coil id and the order number are specified. The stock waiting for the EVs is presented in two plots. The first one indicates the average amount and average kton of stock waiting for the EV lines indicated for each month (Figure 4.10). Each bar indicates the average stock in that month which consists of coils waiting for different EV lines. The blue bar 'EV' indicates that the coils have not been assigned to a specific EV installation yet. The second figure indicates a normal distribution of the stock height represented for both the number of coils and the amount of kton, which is based on days (Figure 4.11). The statistics of this figure have been indicated in Table 4.9.



(a) Average stock waiting for EVs represented per Month (kton)

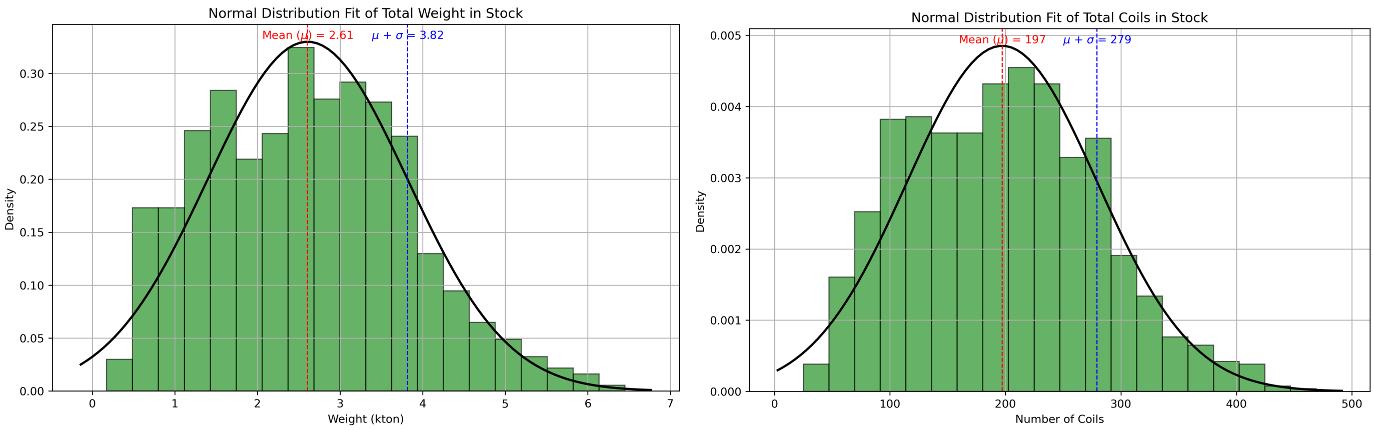


(b) Average stock waiting for EVs represented per Month (Amount)

Figure 4.10: Stock height on average per month

Unit	Mean, μ	Median	Mode	Mode Count	Min	Max	σ	μ + σ	μ + 2σ	μ + 3σ
Number of coils	197.1	195.0	222	11	25	469	82.21	279.31	361.52	443.73
Amount of kton	2.61	2.59	0.52	2	0.17	6.45	1.21	3.82	5.03	6.24

Table 4.9: Statistics for the amount of coils or kton in stock



(a) Normal distribution of weight in stock waiting for EVs

(b) Normal distribution of coils in stock waiting for EVs

Figure 4.11: Normal distributions of stock

The amount of different orders per lane is an interesting statistic as well. Therefore the data was grouped per date, storage park (O-hall or S-hall) and lane. The occurrences of unique order numbers for each lane were calculated of which the results are shown in Table 4.10. There are outliers since some orders have not been assigned to a specific lane. Furthermore, the data is based on how well the forklift operators assign the locations to the coils. The data often shows there is no position within the lane indicated. Besides, it is a common problem that operators do not assign the coils to their locations well. However, the results show that there are a lot of lanes that store multiple orders at once.

Table 4.11 indicates the number of coils in one order (size) present in the storage park, and how often this size appears (frequency). This data underscores the challenge of assigning a lane to a specific order. With many small orders and limited lanes, reserving each lane for one order isn't feasible.

Order Count	Frequency	%
1	71709	44.82
2	38629	24.14
3	22418	14.01
4	12898	8.06
5	6394	4.00
6	3598	2.25
7	1523	0.95
8	800	0.50
9	421	0.26
10+	1598	1.00

Table 4.10: Amount of orders per lane

Size	Frequency	%	Size	Frequency	%
1	87302	41.70	11	1749	0.84
2	37158	17.75	12	1670	0.80
3	22302	10.65	13	1246	0.60
4	15523	7.41	14	1107	0.53
5	9948	4.75	15	957	0.46
6	7263	3.47	16	806	0.38
7	5472	2.61	17	649	0.31
8	3675	1.76	18	594	0.28
9	2861	1.37	19	602	0.29
10	2348	1.12	20+	6148	2.94

Table 4.11: Number of coils per order in stock

Figure 4.12 shows the boxplot of coil storage durations from 01-01-2021 to 31-03-2024 (based on Lagerberg [31]). The statistical summary of storage time is presented in Table 4.12.

Origin	Destination	Mean, μ	Median	Min	Max	Sigma	$\mu + \sigma$	$\mu + 2\sigma$	$\mu + 3\sigma$
DKG11	EV11	35.74	17.85	0.02	1798.41	72.70	108.44	181.14	253.84
DKG11	EV12	34.36	17.30	0.57	3338.71	68.09	102.45	170.54	238.63
DKG11	EV13	36.03	16.22	0.68	2167.36	64.25	100.28	164.53	228.78
HW48	EV11	73.80	41.87	0.57	3877.21	128.55	202.35	330.90	459.45
HW48	EV12	76.63	41.45	0.78	2800.30	118.37	195.00	313.37	431.74
HW48	EV13	70.40	40.33	0.00	3908.74	114.92	185.32	300.24	415.16

Table 4.12: Storage Duration (hours)

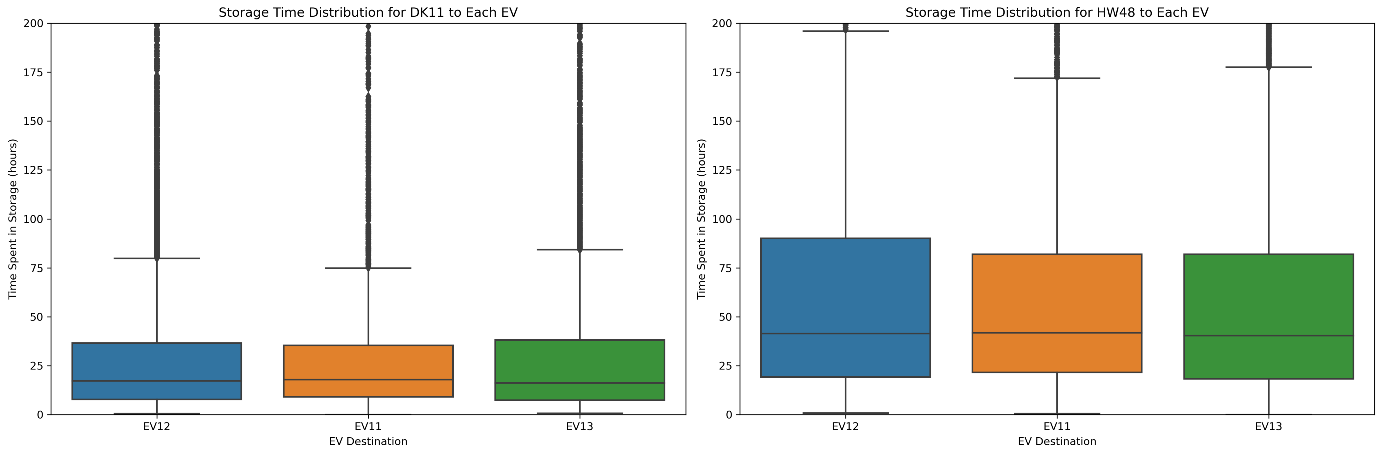


Figure 4.12: Boxplot for the amount of time coils are kept in stock between installations

4.7. Challenges and Waste Identification

For the identification of waste within the current process, TIMWOODS can be applied, a technique used in Lean 6σ methodologies. Each letter in TIMWOODS represents a specific type of waste, Transport, Inventory, Motion, Waiting, Overproduction, Overprocessing, Defects and Skills underutilized. The relevant wastes are described below. Furthermore, safety and employee shortages are discussed as bottlenecks. The wastes are partially identified by investigating previous studies which are discussed in Appendix C.

4.7.1. Employee Shortage

Due to the challenge of finding employees, many vacancies remain open as visualised in Figure 4.13. To remain competitive and guarantee the continuity of production, innovation and automation are necessary. With the film- and laminating installations going into operation and the renovated EV11, the number of coils to transport will increase. Forklift operators are already on a tight schedule. Each manual forklift that is replaced by an automated alternative saves 5FTE because the company works with 5 teams. Besides, there is a relationship between workload and the amount of transport damages. More efficient processes or alternative ways of transport requiring less FTE, and a manageable workload are desirable.

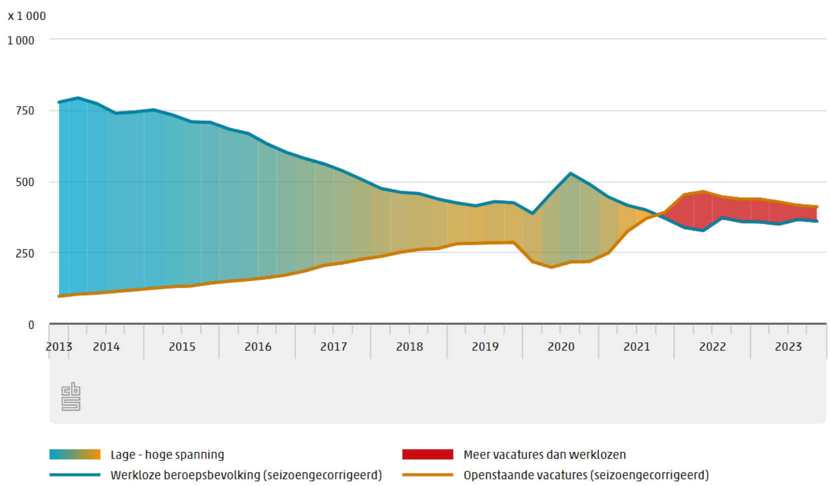


Figure 4.13: The number of open vacancies and unemployment [13]

4.7.2. Safety

In the period between November 2007 and June 2014, 10 safety incidents were reported related to scanning the coils. Forklift operators have to move between razor-sharp coils [18].

4.7.3. Transport, Motion and Defects - Transport Damage

Transport damages are damages to the coils, infrastructure and forklifts arising from transporting the coils. According to an investigation of TSPway, it appeared that in the year 2014, €455,000 of material was lost as a result of transport damage, but this damage occurred almost entirely after temper rolling [45]. Based on another report from 2014, the damages to vehicles result in €265,000 per year and to the infrastructure (fences, roller doors, racks) in €150.000 per year [18]. Lastly, the reparation of handheld scanners results in a cost of €4.000 per year. Handheld scanners are used to scan the coil and define its position in BLITS.

4.7.4. Inventory and Overproduction - Coil Repositioning

Human-operated storage location assignment is 'based on experience and a set of rules' [44]. Due to the lack of information flow, e.g., during shift changes, coils are often assigned inefficiently to their storage locations. AGVs are computer-controlled and do not experience this problem. Digging out coils blocked by coils standing in front of them can take much time. Sorting often occurs when the storage parks are largely filled. Due to the storage layout, several coils may need to be re-positioned before the targeted coil can be retrieved, leading to a waste of time and a higher chance of transport damage. Moreover, this causes lost coils since re-positioned coils are often not returned to their original position and are not assigned to their new locations. There are shifts (8 hours) where 2 hours were spent on repositioning coils, or 25% of the operators' workload [65]. Coils are grouped by order, as shown in Table 4.10. Multiple orders are often present within the same lane, which may lead to the need for repositioning coils. Full inventories are a result of a larger input upstream than output downstream. Installations upstream will stop operating if the storage downstream is full.

4.7.5. Waiting

Operators in manually operated forklifts take brakes, e.g. to lunch or bathroom brakes. This reduces the operational time, an AGV does not experience this. Besides, forklift operators often have to look at their screens with available tasks. Based on observations, this can take up 10-20% of their time.

4.7.6. Overprocessing - Lost Coils

The scanning process of coils is time-intensive for forklift operators. They often avoid it due to their heavy workload. A person is required (about 1FTE) to find lost coils since many are not registered well into the system. Forklift operators sometimes forget to scan the coil and define its new position in the system, then the coil is lost. A cost estimation has been made for this, based on 5.5% search hours concerning operating hours for a forklift operator and €16 per operating hour, the search costs result in €39,000 per year [18].

4.8. Performance Indicators

This section elaborates on the criteria for establishing an effective material flow between the installations. Based on the requirements of both black box models, the operational analysis and waste identification, criteria have been defined that are used to find the most appropriate alternative for the case of Tata Steel. As stated in section 1.4, the goal is to establish effective material flow by choosing a well-performing flow path layout along with other decision-making factors. The general objective of internal logistics in a manufacturing facility 'is to continuously satisfy the needs of the assembly lines in the most efficient manner' (Saez-Mas et al., 2020, p. 2)[52]. This is achieved by finding a balance between the delivery reliability & capability and the lowest possible costs.

The literature reviewed in chapter 3, stated several criteria which are used to identify the performance of the system. Criteria found that are similar to the case of Tata Steel took the average service time, total distance per vehicle, the maximum amount of tasks in the queue (for delivery and retrieval), the average throughput per hour and the average turnover time in days into account [44]. Based on the literature, the requirements, previous studies (Appendix C) and discussion with the company supervisor, criteria were drawn for several categories. The categories and corresponding criteria are indicated in Table 4.13. Following the system analysis and discussion with the project commissioner, costs and logistical performance in terms of on-time performance were found to be the most decisive KPIs. The text below identifies which criteria are selected and omitted.

Selected Criteria

Regarding the lead time criteria, the infeed of the EVs must remain continuously supplied. Both the On-Time Performance (OTP) and service time statistics are analyzed. Both metrics are split up in delivery and retrieval. Delivery is the tasks from the source/input to the storage park and retrieval from the storage park to the sink/output. The OTP target is set at 10 minutes. The target is based on EV13 since it has few buffer positions and processes the most material of the EVs. The fastest 5% that 2 coils are consecutively processed by EV13 is 20 minutes, divided by 2 makes 10 minutes. While specific designs may demonstrate a great OTP (On-Time Performance), it is essential also to analyze the average and maximum service times. This provides a more comprehensive understanding of how a particular design or policy affects overall system performance. OTP alone may not fully capture all influences of a specific design alternative. By examining these metrics, the ability to handle situations where the forklift is under constant demand can be better assessed.

The capacity criteria indicate how intensively the resources are utilized. The utilization rate should be at an acceptable level so that the capacity is not wasted while the stability of the system is guaranteed. A high utilization rate may lead to instability.

Costs are especially important when comparing different system design alternatives. Moreover, this describes the feasibility and magnitude of the business case in comparison to the current operations. This criterion consists of capital expenditures (CAPEX) and operational expenditures (OPEX), associated with an asset over a certain period. The metrics include cost savings from damages, fuel, and employee savings. Based on the CAPEX and OPEX, and cost of capital, the Total Cost of Ownership (TCO) can be determined. This is a way of assessing the long-term value of a purchase.

The selected criteria are all assessed as performance indicators. However, there are two **key** performance indicators which will give a decisive choice on which alternative performs best.

KPI 1 Performance = $\frac{\text{OTP delivery} + 2 * \text{OTP retrieval}}{3}$
KPI 2 Costs = Total Cost of Ownership

The retrieval side is considered more important because the installations on the retrieval side have fewer buffer positions, and the EVs are continuous production lines, which are more inconvenient to stop than the batch production lines on the delivery side. In addition to these two metrics, the Internal Rate of Return (IRR) is calculated to estimate whether the design alternative is profitable.

Omitted Criteria

The omitted capacity criteria are the number of resources required, the number of transport operations performed, and the maximum number of tasks in the queue. The number of vehicles required would overlap with the costs. The other two capacity criteria are not taken into account due to their orthogonality, suggesting that these criteria do not overlap in their meaning or measurement. Furthermore, for the number of tasks queued, it would be hard to indicate a performance increase if only small changes are made to the configuration because of the discrete changes.

The inventory criteria emphasize turnover time and variations in storage height. From a lean perspective, these metrics are important for system design. However, since the model in chapter 6 assumes fixed probability distributions for the yield pattern of the installations, these metrics will remain consistent across different alternatives as long and are therefore not considered in the analysis.

After careful consideration, the category HSE was not accounted for, as these are mainly knock-out criteria. These are criteria for which the score or compliance can be answered with yes or no. All alternatives must comply with the HSE requirements; otherwise, they will not be considered. The implementation risk criterion was omitted because the alternatives in the next chapter do not vary enough in this aspect. Risk can be associated with project delays, implementation failure, the reliability of their cyber-physical systems and higher expected costs.

Analysed?	Criterion	Unit	Explanation
	Lead Time criteria		
x	Average service time (retrieval & delivery)	s	The average service time is measured as the time between the moment a transport request is made and drop-off.
x	On-Time-Performance (OTP) (retrieval & delivery)	%	Percentage of tasks performed (request till drop-off) within a 10-minute timeframe
	Capacity criteria		
	Resources required	#	Number of vehicles required
x	Average utilization rate	%	Resource utilization
	Distance travelled	km	Distance travelled per vehicle
	Number of transport operations	#	Amount of transport operations per vehicle
	Maximum tasks in queue	#	The maximum number of tasks in queue indicates the ability to handle peak loads
	Inventory criteria		
	Average turnover time	s	Average duration a coil is in storage
	Inventory level	σ	Inventory level statistic (mean and standard deviation)
	Max storage height	#	Indicates the maximum amount of coils in storage
	Costs		
x	CAPEX	€	Capital expenditure expressed as Net Present Value (NPV) for the considered time frame
x	OPEX	€	Operational expenditure expressed as NPV for the considered time frame
x	TCO	€	Cost of resources during its entire service life
	Risk criterion		
	Implementation risk	Qualitative	The implementation risk is a qualitative measure indicating the risk associated with implementing a certain scenario.
	HSE		
	Safety	Qualitative	
	Emissions	kgCO_2	
	Noise	dB	
	ARBO	Qualitative	
	Energy consumption	kWh	

Table 4.13: Criteria selection

4.9. Conclusion

This chapter analyses the system in its current state. A black box model for both the scheduling and transport processes is outlined, which together make up the technical system boundary. This describes the process flow, scope of the case study, input-output relations, requirements, and performance indicators. Hereafter, the operational data of the system quantifies the current state of the transport operations and inventory levels. Based on TIMWOODS wastes in the system are identified. Finally, performance criteria are drawn. This chapter aims to answer the following sub-question:

SQ2: *How is the solution space of the transport and storage system defined, and what challenges in its current operations require innovative changes?*

The solution space is 'the multi-dimensional space limited by boundaries within which the solutions are to be found, determined by requirements and design environment' (Binsbergen, 2022, p. 42)[9]. Therefore, this chapter aims to define the design environment and requirements in which solutions are to be found. The system is constrained by maximum queue sizes at the installations and in-process inventory, availability of forklifts, facility layout, and other characteristics defined in this chapter.

Installations have buffer positions (a queue) where coils can be positioned before or after the installation processes them. The inter-arrival time of coils and the buffer size of an installation relates to the maximum service time for transporting a coil. The service time relates to how many resources (vehicles) must be deployed. The current in-process inventory has a capacity of 408 coils. Due to variability in the production system, historical data indicates that capacity can be reached at certain moments. The other extreme is an empty inventory, which occurs as well.

Based on TIMWOODS the wastes in the system are identified. The main waste seemed to be transport damages to the material and resources. Sorting coils in the storage park causes many additional transport operations, leading to a higher chance of transport damages and additional scanning operations. Since the scanning operations are often not performed, the coils get lost. These scanning operations are a safety hazard. The identified bottlenecks and wastes form the basis for investigating the feasibility of automated transport.

Several performance indicators are established. The On-Time Performance metric measures the percentage of coils processed in a 10-minute window for both delivery and retrieval tasks. Transport should not be the bottleneck of the production system, a too-long service time may result in the standstill of a production line. Therefore OTP is the main logistical performance indicator. The average and maximum service times are quantified as well to get a better understanding of how design alternatives influence the system performance, which may not be captured through OTP. The performance indicator average vehicle utilization rate defines how intensive resources are used. Lastly, the Total Cost of Ownership (TCO) define the costs over the service life of an in-plant transport system design. The Key Performance Indicators (KPIs) that provide the basis for selecting the optimal design alternative are:

KPI 1 Performance = $\frac{\text{OTP delivery}+2*\text{OTP retrieval}}{3}$
KPI 2 Costs = Total-Cost of Ownership

Furthermore, the Internal Rate of Return (IRR) must be calculated to estimate whether the design alternative is profitable. The client aims to find the right balance between the delivery reliability & capability and the lowest possible costs.

5
Generating Alternatives

In this chapter, the design alternatives are established. The sub-question being addressed in this chapter is formulated as follows:

What feasible design alternatives for the implementation of automated transport can be developed considering the solution space?

This chapter starts with a set of requirements on automated vehicles, vehicle types and manufacturers which meet the requirements for implementation in section 5.1. The main functions of the system are discussed in section 5.2. The scope (section 5.3) discusses for which functions none or only a single mean is considered. The sub-functions of the system are discussed in section 5.4. The process is represented in an FFBD in section 5.5. The means of the sub-functions and the morphological chart are presented in section 5.6, and the chosen alternatives in section 5.7. Furthermore, the facility design for corresponding to the implementation of forklift AGVs are visualised in section 5.8. Previous automation studies discussed in Appendix C were used as inspiration to assess the feasibility and develop the alternatives.

5.1. Vehicle Requirements

This section defines a list of requirements established for the implementation of automated vehicles. General requirements of the system and operations were defined in section 4.4. Requirements consist of constraints and objectives. Constraints define the aspects the system or design must comply with, while the objectives are preferences for which the design tries to comply as much as possible. These can be divided into functional and non-functional requirements. Functional requirements are things the system has to do (activity or process). Non-functional requirements are attributes or characteristics the system must have. Interviews, abstraction of the process, and investigating previous studies have been performed as elicitation techniques to come up with requirements [8].

Functional constraints:

FC1. The automated vehicle must be able to load and unload coils at all installations.
FC2. The system must monitor the activities of the automated vehicles (e.g. location) during operation.
FC3. The automated vehicle must detect other vehicles and avoid collision.

Non-functional constraints:

NFC1. The automated vehicle must be fully automatic.
NFC2. The automated vehicles must be able to change and/or charge their batteries automatically.
NFC3. The automated vehicle must be able to be controlled manually in case of an emergency.
NFC4. The automated vehicle and facility design must comply with NEN-EN-ISO 3691-4 (2023) (Motorised vehicles - Safety requirements and verification - Part 4: Driverless industrial trucks and their systems). The norm requires clearances around units as visualized in Figure 5.1.

NFC5. The dimensions of the automated vehicle should adhere to the following constraints:

Constraint	Unit	Value
Minimum lifting height	[m]	1.0
Maximum height of vehicle	[m]	3.9
Maximum turning radius of vehicle	[m]	4.2
Maximum wheel pressure of vehicle	[ton]	20.0

Table 5.1: AGV dimensions

Figure 5.1: Dimensions of clearance around storage units

Functional objectives:

FO1. The automated vehicles should minimize hindrance to other modes of transport as much as possible.
FO2. The automated vehicle should not damage the coils.

Non-functional objectives:

NFO1. The length and width of the automated vehicle preferably do not exceed 6 x 2.1 [m] (including carrier shaft).
NFO2. The automated vehicles should integrate with the warehouse management system (WMS).
NFO3. The automated vehicles should be operational for 98% of the time, excluding disturbances from the environment.
NFO4. The automated transport system should be available 99.8% of the time.
NFO5. The automated vehicle should be capable of operating over floor unevenness of up to 2mm.
NFO6. The automated vehicle preferably integrates with the entire factory for interchangeability.
NFO7. Implementing automated vehicles should keep the maintenance and purchase costs to a minimum.
NFO8. The turning circle of the automated vehicle should be maximized to 4.2m. This is the turning circle of the existing PAUS forklift truck. Hence, the AGVs can drive the same routes as the current forklift trucks.
NFO9. The performance of the AGV for loading, travelling, and unloading should meet at least half the performance of the existing 25T forklift trucks, resulting in specific speed performances.

5.1.1. Types of Automated Vehicles

Figure 5.2 visualises the types of coil-handling vehicles. The design of the load handling stations should be adapted if portal-trucks or spoon-trucks were to be implemented. Therefore only the counterbalance forklift and reach-truck are viable alternatives. Previous studies indicated the preference for counterbalance forklifts [41] [45] [64].

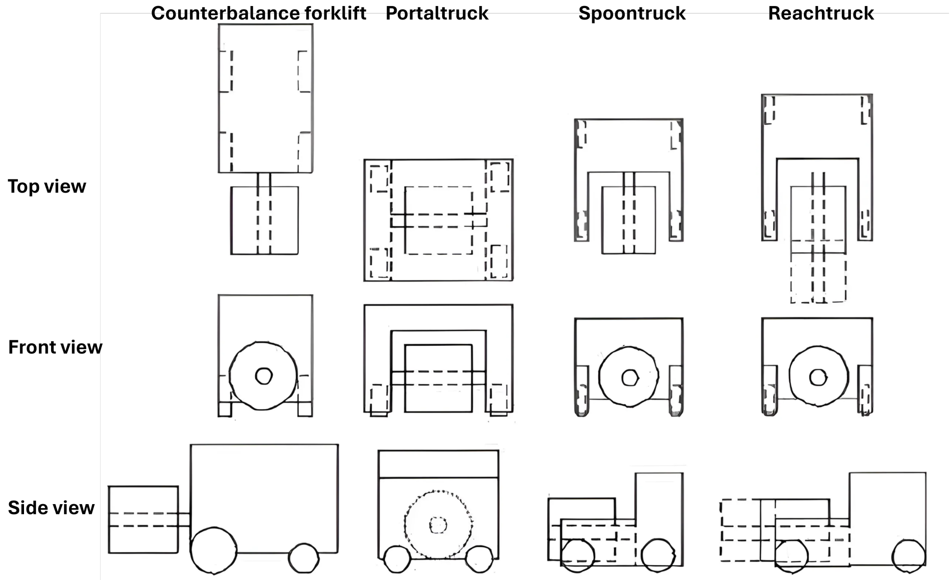


Figure 5.2: Vehicle Types

Table 5.2 states the specifications of trucks that are currently in operation (Paus & MKF), and automated coil handling trucks (Bertolloti, Solving & Rocla). Information on empty cells could not be retrieved. Appendix E shows the design of these trucks and additional specifications. In the facility design, the dimensions of the Solving AGV were taken into account. The length of the Bertolloti AGV may have a hard time reaching all installations and, therefore, does not satisfy FC 1.

	Paus	**MKF**	**Bertolloti**	**Solving**	**Rocla**
Type	Counter-balance	Counter-balance	Counter-balance	Counter-balance	Reach-truck
Automated	No	No	Yes	Yes	Yes
Length excl.pole (mm)	4437	4150	5067	4575	
Width (mm)	2090	1900	2430	2350	
Height (mm)	3150	3000	4278	3880	
Turning radius (mm)	4200	3680	Approx. 5000	4156	
Capacity (kg)	26500	26500	30000	25000	
Weight (kg)	34000	29800	34000		
Speed loaded (m/s)	2.2	2.2	0.8		
Speed unloaded (m/s)	2.6	2.6	1		
Propulsion	Diesel	Electric	Electric	Electric	Electric
Costs AGV			395.000	510.050	

Table 5.2: Specifications of current and automated coil handling trucks

5.2. Main Functions

The main functions of the system are the transport of steel coils and the scheduling process. The main functions interact with each other, if transport is requested, the scheduling process determines which vehicle will be allocated to it, and defines its origin and destination. Thereafter, the physical transport carries out the operations.

Transport of coils

Manual forklifts perform current transport operations. Both electric and diesel forklifts are in operation of MKF and Paus, respectively. The transport operations can be divided into two transport legs. The first one is from the source to a dedicated storage location. The second one is from the storage location to a sink installation. Each transport task consists of driving to the concerned installation, requesting the transport, pick-up, transport to destination, and drop-off. After the task is performed the vehicle can be allocated to the next task, otherwise, it may go to an idle-vehicle position or stay at its current location. Forklifts may only perform one task at a time due to their capacity.

Scheduling process
The function scheduling process covers the entire process of what task should be performed by which vehicle. This consists of a pick-up location, drop-off location, and priority. The scheduling process requires multiple decisions to be made. As discussed in chapter 3, decisions must be made regarding vehicle dispatching, the storage location assignment and the unit load selection. Furthermore, decisions on battery management and idle-vehicle positioning need to be made. A predetermined shortest path is considered for routing, so no decisions have to be made on that level. However, decisions regarding the flow path layout are essential to consider.

5.3. Scope

Several sub-functions of the system have been identified based on the functional, technical, and spatial decomposition. However, not all design aspects of the system are within the scope of this study. This section clarifies which system design functions are omitted from the morphological chart. The following list specifies the design issues not represented in the model.

- Deadlock resolution: deadlocks occur when two or more robots obstruct each other's movements, preventing them from reaching their destinations. This typically happens in narrow passageways where the robots cannot pass by each other [21]. By modelling deadlocks, the model better represents congestion, blockings, and collisions. Since this is not the focus of this research it was left out of the scope.
- Failure management: failure management is not considered.
- Safety management: Although forklift AGVs may operate in the same area as other transport modes, it is recommended to separate the flows to avoid potential confusion and high variability in travel times. Drawing from a similar case, the use of barriers appears to be the most feasible solution. However, safety management at the intersection separating AGVs from other modes is not included in the quantitative model, nor in the criteria.

Furthermore, several sub-functions must be considered to represent the real-world scenario accurately. Because the case specifies the design requirements for these sub-functions, they are not included in the morphological chart. These functions each have a single means of implementation, as all alternatives are modelled the same for these sub-functions. The goal is not to optimize system effectiveness through these functions but to meet specific requirements that dictate their behaviour. Below is a list of these functions and their representation in the simulation model.

- Pick-up and delivery point optimization: Studies on automated vehicles often consider the pick-up and delivery point in their alternatives. This case's source and sink locations are fixed since it is a brownfield project. The locations are visualised in Figure 5.10.
- Routing: routing involves determining the shortest path for material flow. However, due to the limited scope of this project, multiple routing options are not considered. Including routing is not expected to enhance material flow effectiveness significantly. Therefore, the distances and routes between the stations are fixed.
- **(1) Unit load selection**: The unit-load selection sub-function concerns which load should be picked up from the queue. Coils that have been in storage for over 48 hours and originate from DKG11 have the highest priority. Additionally, supply chain planning tries to plan coils from the same order consecutively on an installation. If a coil in the storage park has the same order number as the one that was processed last on the installation, that coil should be selected. Otherwise, it is based on the fill percentage of the storage park. Since a high fill rate is related to a higher chance of coil sorting operations. If it comes to selecting a park with the highest fill rate, the coil within the park is prioritized on a First-In-First-Out (FIFO) basis

5.4. Sub-Functions

Based on the main functions and the functional, technical, and spatial design domains, the next step is to describe the relevant sub-functions. The following sub-functions are defined: in-plant transportation, flow path design, idle-vehicle positioning, battery management, vehicle dispatching, and storage location assignment. The means for the functions are identified by an analysis of the current system, a literature review, and a stakeholder analysis, all of which have different perspectives on the system.

(2) In-plant transport

This sub-function is concerned with the physical transportation of the steel coils. The function does not involve fleet sizing, for each alternative, the fleet size is one of the considered variables.

(3) Flow path design

The flow path design involves the pathways the vehicles will follow within the facility. The objective is to create an efficient flow of material ensuring smooth operations.

(4) Idle-vehicle positioning

The idle vehicle position involves determining the optimal locations for the vehicles to wait when they are not actively engaged in tasks. This is crucial for maintaining operational efficiency, ensuring quick response times for new tasks, and avoiding congestion in high-traffic areas.

(5) Battery management

This sub-function involves managing the power needs of the vehicles by ensuring they are adequately charged to maintain continuous operation. This includes monitoring battery levels, scheduling charging sessions, and optimizing the location and usage of charging stations within the facility.

(6) Vehicle dispatching

The vehicle dispatching sub-function is concerned with the decision-making process of assigning vehicles to specific tasks based on various factors such as task priority, vehicle availability, and current location. Dispatching policies can be workstation or vehicle-initiated. Workstation-initiated policies require the workstations to pick an idle vehicle. A policy is considered vehicle-initiated if a vehicle selects a coil among some of the coils that need transport. Effective dispatching is crucial for maintaining an efficient workflow within the facility.

(7) Storage location assignment

The sub-function storage location assignment involves determining the optimal storage location for each incoming coil. This process ensures efficient use of storage space, easy retrieval, and smooth workflow operations. Key considerations include the order number of the coil, avoiding blockings, storage duration and the proximity to other stations. This sub-function aims to minimize the time it takes for a transport task to be performed by strategically assigning storage locations. As mentioned in chapter 4, one of the wastes is over-processing due to retrieving blocked coils.

5.5. Functional Diagram

This section represents the process and defines how the sub-functions are related to the process. Furthermore, it illustrates how the physical flow and control or decision-making flow interact. A Functional Flow Block Diagram (FFBD) is visualized in Figure 5.3.

The blocks within the diagram and the colours represent the following:

- Grey block: grey blocks represent the processes and flow of the coils.
- Yellow block: the yellow blocks represent the processes and flow of the vehicle.
- Grey and yellow block: the blocks that contain both colours indicate that the vehicle is moving the coil.
- Control or physical: in the bottom left of each block is indicated whether it concerns a physical or decision-making process (control).
- Sub-function: the number on the bottom right is linked to the sub-functions as defined in section 5.4.

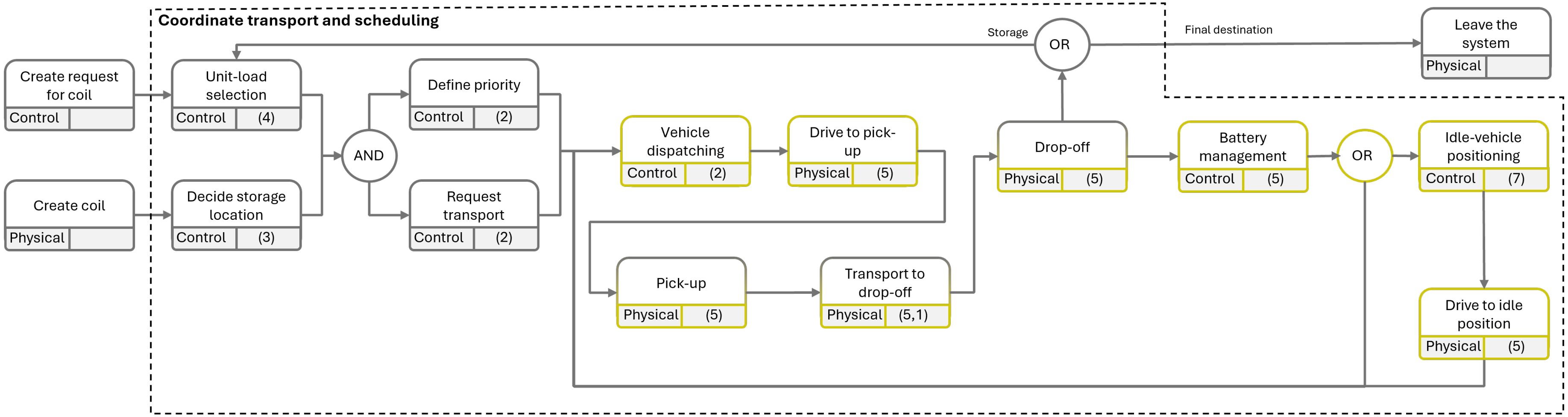


Figure 5.3: FFBD

5.6. Means

This section identifies possible solutions to perform the identified functions. This eventually should lead to an effective and efficient system [9]. A morphological chart of the sub-functions and related means is visualized in Figure 5.5. The meanings of the solutions are discussed in the text below.

In-plant transport

The current means of transportation are manual forklifts. Almost only electric forklifts are used, however, diesel-powered forklifts are also still in operation. As discussed in section 5.1, counterbalance and reach truck AGVs are the only viable automated vehicle types. Since Rocla no longer supplies reach truck AGVs, and no other suppliers were found, counterbalance AGVs are the only considered means of automated transport.

In an earlier design stage Autonomous Mobile Robots (AMRs), overhead cranes, walking beams and conveyors were considered as well (see Figure 5.4). However, these means are not considered in the morphological chart since they would not result in viable design alternatives. The literature study stated that AMRs are less often used for heavy loads. Moreover, no suppliers were found to deliver AMR forklifts which handle loads this heavy. The overhead crane was omitted from the transport means since the crane in the O-hall does not have the capacity to transport all coils. Besides, it can only pick-up and drop-off coils in the same production hall, and not transport them across multiple halls. A walking beam is used at the outfeed of some production lines, however, it has a low capacity and is unsuitable for long-distance transport. Conveyors can be seen in other factories as well, however, this is mainly implemented when the number of coils flowing through the system is very high and they all originate from the same location.

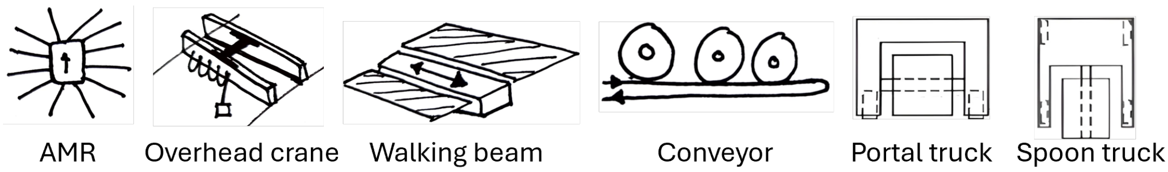


Figure 5.4: Omitted means of transport in earlier stages of design

Flow path design

The flow path layout is crucial in realizing an efficient system. The means of transport may be allocated to a specific zone or use a conventional design, where they may operate within the entire system. When the zone-based flow layout is chosen, the material will be transferred at a location where both zones intersect. As discussed in chapter 3, the zone-based flow layout might increase the performance. It reduces the travel distance and prevents deadlocks from occurring. Nevertheless, it increases the number of trips and restricts vehicles to one zone, reducing the system's flexibility. Furthermore, the choice between a uni-directional or bi-directional flow path can be made. This study only considers bi-directional flow paths.

Idle-vehicle positioning

The idle vehicle position defines where the transport will be located if there are no tasks to perform. The objective is to locate the means of transport as close to the next task as possible, without being an obstacle. The vehicle can stay at the station where it dropped off the last coil (last station). Zone-based positioning indicates that each means of transportation in the fleet has its own fixed idle position in different zones of the system. The position can be based on demand forecasting as well, then the vehicle will be located as close as possible to the station that is expected to request transport most soon. A fixed parking spot is a fixed location for all means of transportation. Lastly, a schedule ensures that all areas are covered periodically and prevents long idle times in one spot.

Battery management

Battery management is a common topic considered in increasing the performance of an automated transport system. Electrical-powered transport modes which are not connected to the grid (AMR, AGV, manual forklift) need to charge their batteries. A battery swapping station offers a higher availability than conventional charging methods, as it allows for quick battery replacement. Inductive charging, applied at idle vehicle positions, enables wireless charging without the need for physical contact, making it a convenient option. The concept of an electric net, inspired by bumper cars, provides continuous power through an overhead electric grid, ensuring that vehicles remain charged while in operation.

Vehicle dispatching
A wide variety of dispatching rules can be used according to the literature [4][2]. Some of these rules are discussed as possible means for this case. Current operations use a combination of multiple dispatching rules. The list below indicates the options considered. Thereafter the combination of current operations is discussed.

- *First-Come-First-Served (FCFS)*
  Tasks are assigned to vehicles based on their arrival time.
- *Random Workstation (RW)*
  The tasks are chosen at random out of the list of available requests.
- *Least Utilized Vehicle (LUV)*
  Another workstation-initiated dispatching policy is choosing the vehicle which is utilized the least.
- *Minimum Work-in-Queue (MWQ)*
  Tasks of load handling stations with the smallest buffer are prioritized.
- *Minimum Available Storage Positions (MASP)*
  Tasks of load handling stations with the least available buffer positions are dealt with first.
- *Smallest Distance (SD)*
  Tasks with the shortest travel distance to an available AGV are prioritized.

The current rules at Tata Steel utilize a combination of multiple dispatching rules. The priority list is defined below.

1. Tinning lines (EV11, EV12 & EV13) and IB11 with the least amount of supply (MWQ).
2. Temper rolling installations (DKG11 and HW48) and IB11 outfeed with the least amount of available buffer positions (MASP).
3. The CA12 wagon is assigned the lowest priority.
4. If there are still competing tasks, the SD rule is put into practice.

Storage location assignment
There are many policies available for the storage location assignment [48], of which some are discussed. Random-based storage indicates that the storage location is assigned at random. The class-based storage policy organizes products into categories and allocates them to designated locations based on specific classification criteria [48]. The Closest Open Pure Lane (COPL) policy assigns coils to the closest storage location which contains coils of the same order and otherwise empty lanes.

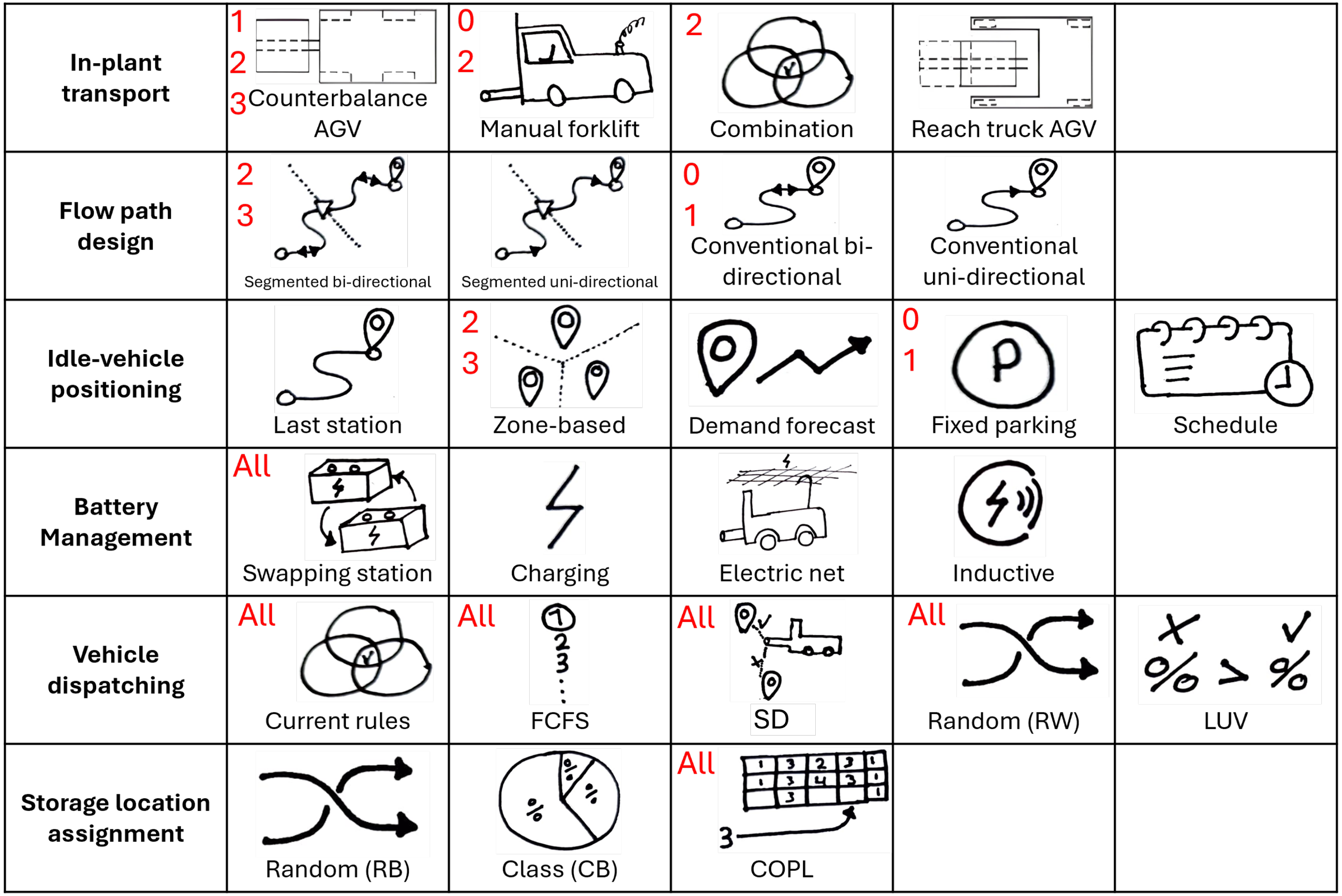


Figure 5.5: Morphological chart

5.7. Design Alternatives

Based on the morphological chart in Figure 5.5, design alternatives were drawn. The alternatives are generated by testing the objectives and the constraints. This resulted in several infeasible means of transport and some means of battery management that were not preferred. The influence of fleet sizing and several vehicle dispatching policies on performance is tested in the experiments in chapter 7. Furthermore, the storage location assignment is consistent among the system design alternatives.

5.7.1. Base Case: Manual Forklifts, Conventional Flow

The base case (i.e. current state) will be modelled first. The layout for this case is presented in Figure 4.2, and the source and sink locations match with the locations as presented for the design alternatives (Figure 5.10). The simulation model will be validated and verified with the data obtained in chapter 4 before the design alternatives are modelled. The design alternatives use the simulation model framework of the base case. In this situation, one manual forklift operates in the entire scope.

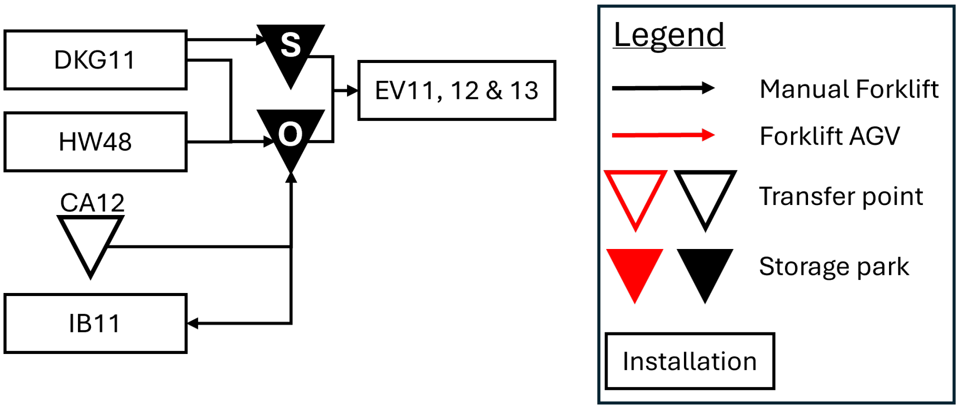


Figure 5.6: Conceptual Model of the Base Case

5.7.2. Alternative 1: Fully Automated Conventional Flow

The first alternative is quite similar to the base case, however, with forklift AGVs implemented instead of manual forklifts. The forklift AGVs may operate in the entire area. It uses a conventional bi-directional flow path structure. When the forklift AGVs are idle, they will move to a parking.

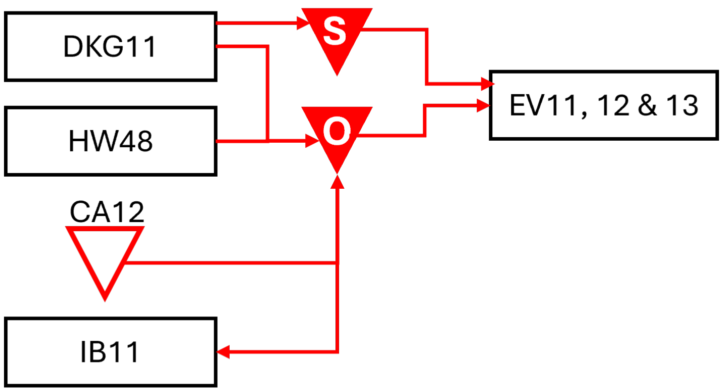


Figure 5.7: Simulation Alternative 1

5.7.3. Alternative 2: Partially Automated Zone-Based Flow

The second alternative presents a partially automated design. The coil handling operations in the S- and U-hall are automated in this case and the operations in the O-hall are performed by a manual forklift. In between the O- and S-hall, a load transfer area is made, and the forklift AGV will take over. This alternative will be simulated with one forklift AGV and one manual forklift. It uses a bi-directional zone-based path structure because of the load transfer station in the middle. An expert opinion influenced the decision to study a partially automated design. The client expressed interest in exploring this option because it represents a more gradual transition towards full automation of the scope. Additionally, this approach allows the storage parks in the O-hall to maintain their original capacity while minimizing disruptions to crossing traffic. The idle-vehicle positions will be in the zone the vehicle operates.

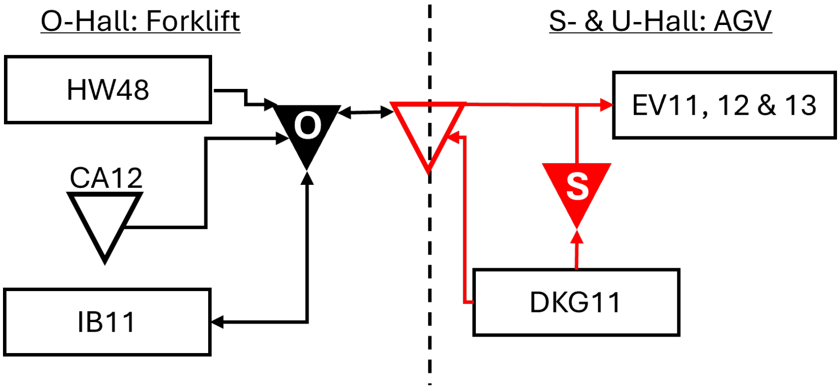


Figure 5.8: Simulation Alternative 2

5.7.4. Alternative 3: Fully Automated Zone-Based Flow

The third alternative is a combination of the first and second alternative. The scope is performed with forklift AGVs only. A load transfer station is placed in between the O-hall and S-hall. This design has a zone-based bi-directional flow path layout. The placement of the load transfer station was recommended based on expert advice, as this passage is the only location where the zones can effectively be separated. This strategic positioning is crucial for preventing deadlocks. Two sets of AGVs will perform all the tasks, one set for the O-hall and one for the S- and U-hall.

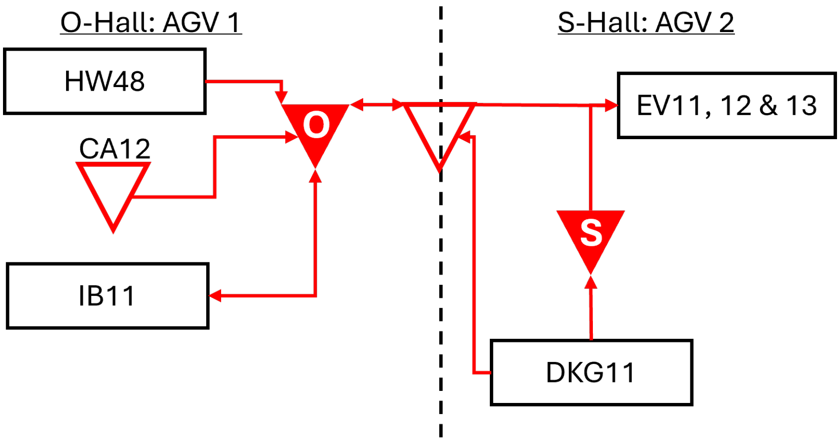


Figure 5.9: Simulation Alternative 3

5.7.5. Future situation

As discussed in chapter 4, EV11 will have a higher throughput in the future. Moreover, EV11 will only be supplied by CA12. The client is mainly interested in how the AGVs will perform in this case. Therefore, the alternatives will be evaluated based on historical data and the future situation.

5.8. Facility Design

The current facility design has an in-process inventory capacity of 408 coils waiting for the EV installations. In the future scenario, considering the implementation of the forklift AGVs, the necessity for forklift AGVs to minimize interaction with other traffic and compliance with minimum clearances in the storage area results in a reduced capacity of 349 positions. The layout of the current facility design is visualised in Figure 4.2. The facility layout with automated forklifts implemented is shown below (Figure 5.10). The red area is the operating area defined as the 'O-hall', and the green area is defined as the 'S/U-hall'.

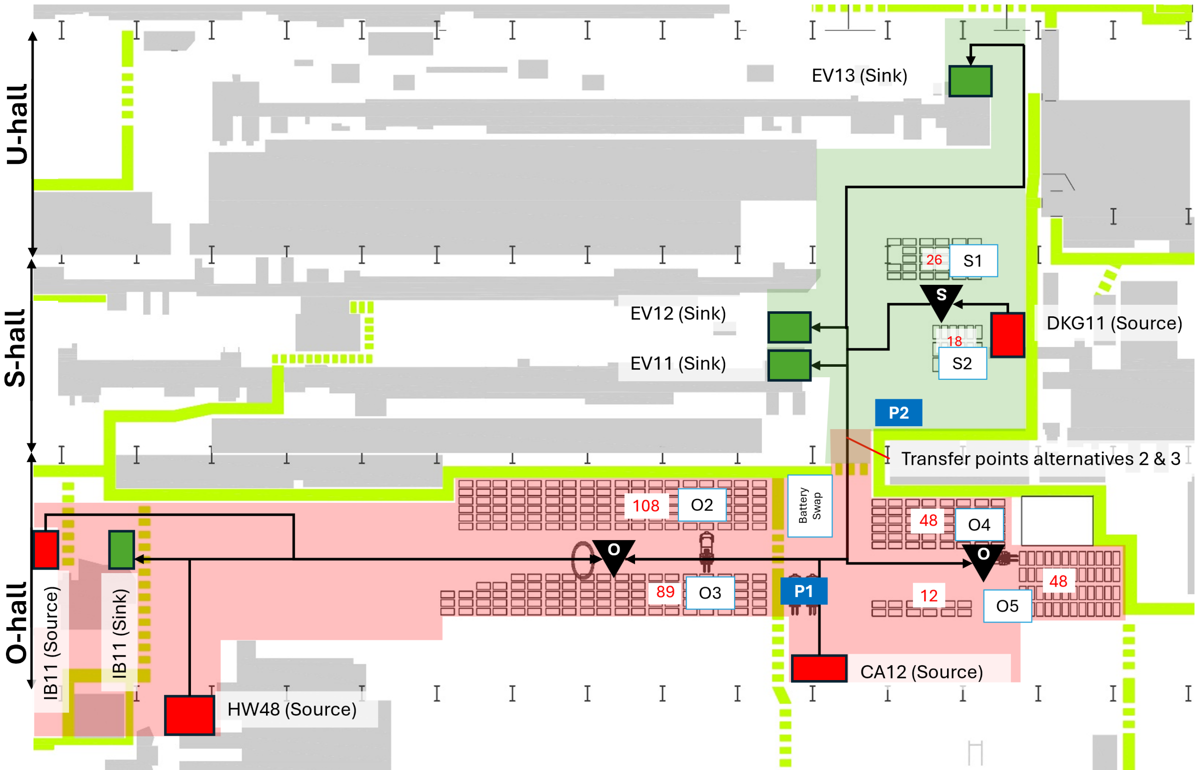


Figure 5.10: Layout with forklift AGVs implemented

5.9. Conclusion

Through the synthesis of an expert opinion, previous automation studies and process analyses, the main functions, sub-functions and means were identified. Based on these means, several alternatives and experiments were generated to answer the following sub-question:

What feasible design alternatives for the implementation of automated transport can be developed considering the solution space?

The selection of the automated vehicle type was the first step in the analysis. After evaluating several suppliers, a counterbalance forklift AGV was chosen as the best fit. The supplier is stated in section F.3. Following this, the main and sub-functions of the system were identified. The main functions are the transport of material and the scheduling process. The scope clarified which sub-functions were excluded and established that the storage location assignment, unit-load selection and battery management would remain consistent across all alternatives. The design alternatives and experiments will test different means for the sub-functions of in-plant transport (which considers the material handling device), the flow path design, idle-vehicle positioning, and vehicle dispatching. A FFBD defines how the sub-functions relate to the process.

For each of the sub-functions, several means were identified. Three alternatives were generated by testing whether the combination of means is within the solution space.

Alternative 1 considers a conventional bi-directional flow path layout design, with a fleet of automated forklifts. The fleet of forklift AGVs uses the same parking if they are idle (P1).

Alternative 2 considers a zone-based approach as a flow path layout. A transfer station between the O- and S-hall is used to transfer the material between the zones. A manual forklift serves the zone in the O-hall, while one or more forklift AGVs serve the other zone. Both zones have their own idle-vehicle parking spot (P1 and P2).

Alternative 3 is similar to alternative 2. The only difference is the use of one or more forklift AGVs in the O-hall instead of a manual forklift.

The battery management and storage location assignment sub-functions were kept consistent across all alternatives. AGV batteries are swapped when empty, while manual forklift batteries, which only need to be changed once per shift, were not considered. The storage location assignment policy COPL could unfortunately not be modelled into detail. The storage location is assigned based on the order identification number and, otherwise, on the fill percentage of a storage park. The vehicle dispatching methods, including First-Come-First-Served (FCFS), Shortest Distance (SD), random assignment, and a combination of the existing rules, were tested across all alternatives in the experiments. Implementing the automated system in the O-hall reduced 59 storage positions due to the clearance required around the coils.

6 Model Development

This chapter describes the process of setting up a discrete event simulation model to evaluate the design alternatives. It addresses the following question:

How can the system design alternatives that integrate the scheduling of automated vehicles and the assignment of coils to storage locations be modelled?

Firstly, the requirements for the simulation model are discussed in section 6.1. Secondly, the conceptual model is presented indicating the level of abstraction in section 6.2. Thirdly, the software selection is covered in section 6.3. In section 6.4, the model is implemented, and the input is discussed in detail. The experimental setup and verification & validation of the model are then discussed in section 6.5 and section 6.6, respectively. Concluding remarks are made in section 6.7.

6.1. Simulation Model Requirements

Requirements for the system design were defined in subsection 4.4.2. Chapter 5 defined additional requirements for the vehicle specifications, and this section will define additional requirements for developing the simulation model.

Functional constraints:

FC1. The model must account for pick-up, drop-off, rotation, loaded transport and unloaded transport in the time delays.
FC2. The simulation model must use probability distributions based on real-world data for easy scaling when higher turnovers are expected (i.e. not directly implementing historical data).
FC3. The simulation model must prioritize coils originating from DKG11 when they are over 48 hours in the model.

Non-functional constraints:

NFC1. The simulation model must be able to retrieve results on quantitative performance indicators.
NFC2. The model must be able to incorporate vehicle dispatching rules and storage policies.
NFC3. The simulation must be able to run for a year to visualize the storage variation well.
NFC4. Solving the simulation model must be finished within a reasonable time (0-1 hours).
NFC5. The simulation model should visualise an animation for better validation.

6.1.1. Assumptions

The simulation model is based on the following assumptions.

- A homogeneous fleet of manual forklifts and a homogeneous fleet of forklift AGVs.
- All processes for each job are known.
- One vehicle can transport only one job.
- The job can't be removed from the vehicle until the assigned storage place or machine is available.
- The routing of each job type is available before making scheduling decisions.

- Arriving items may be sent to any storage park, and EVs may request coils from any storage for the historical case.
- CA12 will supply the additional future demand for EV11.
- Retrieval tasks prioritize DKG coils over 48 hours in the system. After that, coils with the same order number as handled previously by the installation and, finally, storage parks with the highest fill percentage.
- Urgent orders are not taken into account.
- Coils of the same order number arriving consecutive after one another are sent to the same storage facility.
- Coils that don't have a predecessor of the same order number are sent to the storage facility with the lowest fill rate.
- Vehicles drive at a constant speed. Acceleration and deceleration are represented in the pick-up and drop-off.
- Delays for manual forklifts caused by eating, toileting, getting out of the vehicle (for scanning the coil or other operations) and checking/picking their tasks are not included in the model.
- Deadlock resolution and failure management are not considered.
- Battery swapping is only considered for forklift AGVs and not for manual forklifts, as this only happens once per shift (8 hours).

6.2. Conceptual Model

The conceptual model captures the aspects and behaviours of the system. Determining the level of abstraction compared to the real world is a crucial part of the model development. The complexity of the model should align with the quality of the available data [51]. Furthermore, the level of abstraction depends on the research aim, available resources, and time constraints. The system characteristics that have been incorporated are discussed in chapter 5. The model's objective is to acquire quantitative KPIs to compare and evaluate various design alternatives. The primary objectives include the on-time performance and the number of forklift AGVs needed.

The conceptual model is represented in Figure 6.1, it is a swimlane flow chart. A swimlane diagram is a chart that displays a series of processes connected by arrows to indicate their order, using 'swimlanes' to assign each process step to a specific category. It is often used to depict complex business or transport processes that require multiple attributes [5]. The process within each lane is represented by black arrows and the information flow between the lanes by grey arrows. The material flow is driven by the arrival of coils at the source and the demand for coils at the sink. Consequently, the inventory level in the Work-In-Process (WIP) inventory is determined by this dynamic.

The quantitative KPIs have been illustrated in the figure as well. The service time and on-time performance are based on the time between the transport request of a coil and when it is dropped off at its destination. The utilization rate of the vehicle is measured as well. The average turnover time, inventory levels, distance, queue sizes, number of transport operations, and waiting tasks are also recorded for validation purposes. These are not represented in the swim lane diagram because they are not part of the performance criteria.

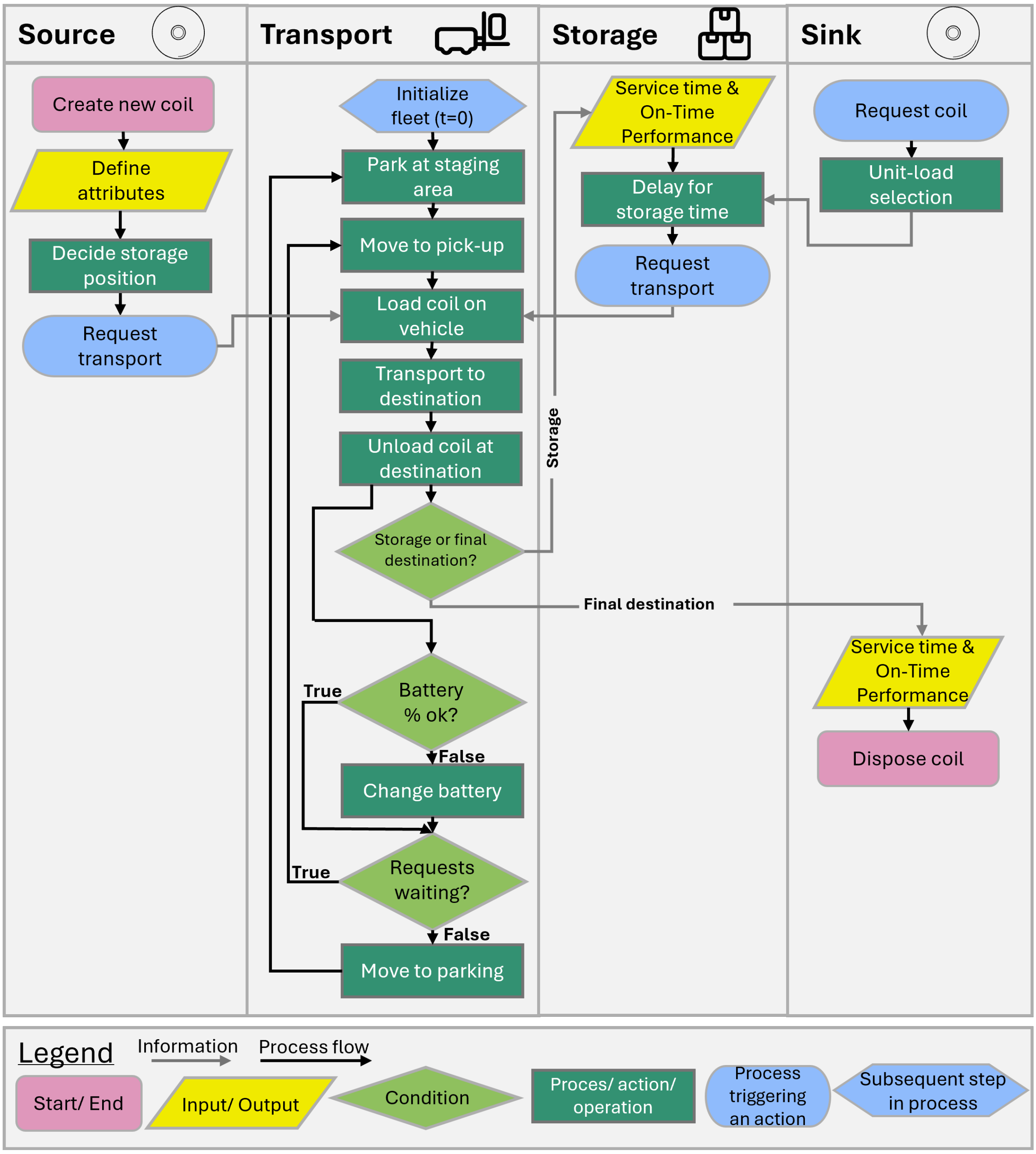


Figure 6.1: Conceptual Model: Swimlane Diagram [37]

6.3. Software Selection

The requirements to decide on which Discrete-Event Simulation software to use are presented in Table 6.1. Based on a Pugh chart of a similar simulation study of AGVs in a manufacturing environment, a part of the scores were obtained [34]. Simio and Arena showed the highest scores. Since the company had a strong preference for Arena, the choice was made to use the Arena software from Rockwell Automation.

Software Requirements	**Anylogic**	**Arena**	**Simio**	**FlexSim**	**Plant Simulation**	**Python**
Easy to use (user-friendly)	4	4	4	5	4	2
Online support	5	4	4	5	4	1
Support from experts within the company	1	5	3	0	0	3
Tutorials to learn about the software	4	3	4	5	3	3
Animation possibilities	5	4	5	5	5	3
AGV number calculation	4	4	4	4	4	4
Detailed output data, charts and graphics	5	5	5	4	4	5
Free version	3	5	5	5	4	5
Ability for the company to develop it further	2	5	5	2	1	3
Total	33	**39**	**39**	35	29	29

Table 6.1: Pugh chart for software selection [34]

In addition to the simulation model created with Arena software, another model is developed by the software developer of SLAPstack. SLAPstack is a block-stacking warehouse simulation designed for the Autonomous Block Stacking Warehouse Problem (ABSWP) and can be used to test the Storage Location Assignment Problem (SLAP) [44]. The simulation tool's functionality was expanded to incorporate SLAP specifically for the manufacturing industry. This expansion was tailored for this case by the developer of the simulation model. The developer of the software had limited time, leading to a delay in obtaining the results. Consequently, the results from SLAPstack were **not** analyzed during the thesis process. More information on this simulation model is discussed in Appendix H.

The SLAP is challenging to implement in Arena simulation software due to the large number of nodes and arcs involved. As a result, the Arena model is limited to considering individual storage parks without accounting for specific positions within the parks. The interaction between the two models was designed such that SLAPstack would provide data on sorting operations, which could then be integrated into the Arena simulation model resulting in additional vehicle utilization. However, since the results from SLAPstack have not yet been analyzed, sorting operations are excluded from the scope of the Arena simulation model. Consequently, the COPL policy is simplified to assigning coils to storage parks based solely on their order number. The requirement NFC 2 could only be met to a certain extent.

6.4. Model Implementation

This section discusses the general inputs of the model. It does not focus on the alternative-specific details. First, an overview of the inputs and outputs from the simulation model is given. Hereafter data on the inter-arrival time, downtime, material handing operations, size of an order, coil weights, AGV range and transport distances are discussed.

6.4.1. In- and Outputs of Simulation Model Implemented in Arena

The simulation model replicates the original system, incorporating innovations in process times, control logic, resources, and modified processes and interactions within the configurations. The input below indicates which aspects are configuration-specific and which are universal across all configurations. The inter-arrival time and downtime of installations are configuration-specific since both the current state, as well as the future state are modelled.

Input	**Scope**	**Reference**
Flow path layout	Configuration-specific	Section 5.7
Idle-vehicle position	Configuration-specific	Figure 5.10
Vehicle dispatching policy	Configuration-specific	Subsection 7.1.1
Fleet size	Configuration-specific	Subsection 7.1.2
Storage capacities	Configuration-specific	Figure 1.1a & Figure 5.10
Inter-arrival time	Configuration-specific	Subsection 6.4.2
Downtime of installations	Configuration-specific	Subsection 6.4.3
Unit-load selection	Universal	Section 5.3
Storage location assignment policy	Universal	Section 6.3
Number of buffer positions	Universal	Table 4.2
Material handling delays	Universal	Subsection 6.4.4
Size of an order	Universal	Subsection 6.4.5
Coil weight	Universal	Subsection 6.4.5
Battery management	Universal	Subsection 6.4.6

The outputs used to evaluate performance are the service time, on-time performance, and utilization rate. Additionally, the model generates many other outputs that were analyzed to validate its behaviour.

6.4.2. Inter-Arrival Time

In section 4.6, historical data was analyzed. Based on this data, the period of 1-2-2022 up to 31-7-2022 has been used to acquire probability distributions for the inter-arrival time. This data showed a relatively high turnover and was not heavily influenced by downtime due to breakdowns or corona. The data has been grouped by installation and categorized based on whether it involves deliveries to or retrievals from the storage park. Details on how the data was collected and processed are provided in Appendix I.

Hereafter the data has been fitted onto a triangular, uniform, normal and lognormal distribution (see section I.1 for the code). Hillier and Lieberman [25] has been used as a reference for fitting the distributions. A lognormal distribution indicated the best fit for most stations, based on a low Kolmogorov-Smirnov (KS) statistic. A lognormal distribution is frequently used to represent task times that have a distribution skewed to the right [3]. All KS statistics are below 0.1, which is generally considered a good fit. Since coils are unable to be processed within a short time-frame a minimum of the shortest processing time for that installation was used, making the distribution truncated. The distributions are indicated in Table 6.2 below.

Where LogMean= μ_l and LogStd= σ_l

$$\mu_l = e^{\mu+\sigma^2/2} \tag{6.1}$$

$$\sigma_l^2 = e^{2\mu+\sigma^2}\left(e^{\sigma^2}-1\right) \tag{6.2}$$

Station	**Distribution type**	**Value (hours per unit)**	**KS-statistic**
HW48 delivery	Lognormal(μ_l, σ_l)	$\mu = 0.587$, $\sigma = 1.781$	0.07292
DKG11 delivery	Lognormal(μ_l, σ_l)	$\mu = 0.38202$, $\sigma = 0.12770$	0.09274
CA12 delivery	Lognormal(μ_l, σ_l)	$\mu = 0.32364$, $\sigma = 0.09236$	0.06792
IB11 delivery (destination: EVs)	Normal(μ, σ)	$\mu = 32.893$, $\sigma = 59.084$	-
EV11 retrieval	Lognormal(μ_l, σ_l)	$\mu = 0.68945$, $\sigma = 0.28943$	0.04906
EV11 future situation	Confidential, see **??**		
EV12 retrieval	Lognormal(μ_l, σ_l)	$\mu = 0.50951$, $\sigma = 0.18488$	0.03478
EV13 retrieval	Lognormal(μ_l, σ_l)	$\mu = 0.39704$, $\sigma = 0.14505$	0.06192
IB11 retrieval (origin: DKG11)	Normal(μ, σ)	$\mu = 79.807$, $\sigma = 116.25$	-

Table 6.2: Throughput simulation model input data

6.4.3. Downtime

To account for the downtime of the installations, the simulation model stops the operation of the installations according to a certain interval. The downtime is implemented in 2 categories, short and long downtimes. The data was gathered by adding all unplanned-, planned- and logistic losses (excluding external stagnation) into one list for each installation. Coils that were produced by the considered installations for other material flows are not within the scope. This occurred several times and was also accounted for as downtime. The data was then split into short and long durations. The sum of all short downtimes is the same as the sum of all long downtimes. Hereafter the average duration and inter-arrival time were determined. Appendix I indicates how this data was retrieved. Since these are all constant values, the model stays relatively stable. This approach has been applied since the use of probability distributions or other methods was not reliable enough.

In the future case scenario, CA12 experiences less downtime. The downtime labelled 'CA12 (future state A)' represents the historical downtimes of CA12, excluding material flows that were left out of scope. Since the material will still be transferred from CA12 to EV14 in the future scenario, 'CA12 (future state B)' accounts for these out-of-scope material flows. This additional production helps balance the increased throughput of EV11 in the future state.

Installation	Mean Duration Short (h)	Mean Duration Long (h)	Mean Interarrival Short (h)	Mean Interarrival Long (h)
CA12	4.14	50.35	12.46	145.44
DKG11	0.23	15.18	1.32	84.95
EV11	1.22	37.06	5.80	176.57
EV12	0.89	23.32	5.70	147.88
EV13	0.53	6.97	4.84	64.08
HW48	0.15	7.84	0.77	40.16
CA12 (future state A)	2.06	21.20	51.23	456.03
CA12 (future state B)	-	15	-	168

Table 6.3: Downtime data

6.4.4. Material Handling Delays

Regarding the material handling delays for the manual forklifts, the observations from Table 4.8 have been used. For the forklift AGVs, it is based on the estimations performed for the KB2 project (Appendix C). This includes acceleration, deceleration, searching for the hole in the coil and driving in an operational hazard zone (in a storage park). Since the depth in a storage park and the operational hazard length may vary, the pick-up and drop-off time at storage parks are represented as a normal distribution. The pick-up and drop-off time at installations are represented as a constant value.

Coils from CA12 must be rotated 180 degrees before entering tinning lines EV11 and EV13. Similarly, coils from DKG11 or HW48 must be rotated 180 degrees before entering the tinning line EV12.

Operation	Distribution type	Value (s)
Forklift pick-up	Max(Normal(μ, σ), a)	$\mu = 20.5, \sigma = 5.3$, $a = 14.2$
Forklift drop-off	Max(Normal(μ, σ), a)	$\mu = 25.3, \sigma = 8.0$, $a = 15.1$
Forklift pick-up wagon	Max(Normal(μ, σ), a)	$\mu = 37.0, \sigma = 12.2$, $a = 24.9$
Forklift $180°$ coil rotation	Normal(μ, σ)	$\mu = 40.4$, $\sigma = 3.15$
AGV pick-up at installation	Constant	64.8
AGV drop-off at installation	Constant	56.8
AGV pick-up at storage	Uniform(min, max)	$min = 64.8, max = 104.8$
AGV drop-off at storage	Uniform(min, max)	$min = 56, max = 96.8$
AGV battery exchange	Constant	554.9
AGV $180°$ coil rotation	Constant	121.6

Table 6.4: Material handling delays (section D.3)

The speeds defined for manual forklifts and forklift AGVs are indicated in Table 6.5.

Vehicle	Loaded/unloaded	Nominal speed (m/min)
Forklift	Loaded	120
Forklift	Unloaded	120
AGV	Loaded	50
AGV	Unloaded	60

Table 6.5: Nominal speed vehicles

6.4.5. Order Number and Coil Weight

Each coil is assigned an order number and a weight when created in the simulation model. Section D.2 shows a difference between the number of coils of one order number coming through an installation consecutively and the order size. The order size was used as an indicator since this is also what Supply Chain Planning plans on. The size of an order is based on Table D.4, and is implemented in the model as stated in Table 6.6. The order number influences the storage location assignment and unit-load selection. The weight of each coil is assigned based on historical data as well.

Attribute	Distribution type	Parameters
Number of coils in the same order number (#)	Min(Max(Integer(Lognormal(μ, σ)), a), b)	$\mu_l = 7.80$ $\sigma_l = 19.19$, $a = 1$, $b = 491$
Weight DKG11 (ton)	Min(Max(Normal(μ, σ), a), b)	$\mu = 14.34$ $\sigma = 4.27$, $a = 3.01$, $b = 22.8$
Weight HW48 (ton)	Min(Max(Normal(μ, σ), a), b)	$\mu = 13.62$ $\sigma = 4.72$, $a = 3.02$, $b = 23.10$
Weight CA12 (ton)	Min(Max(Normal(μ, σ), a), b)	$\mu = 15.57$ $\sigma = 4.99$, $a = 3.02$, $b = 23.67$

Table 6.6: Parameters of assigned attributes

6.4.6. Battery Management

The AGV changes its battery after driving 3000 m [56]. The location of the battery swapping station is indicated in Figure 5.10. The forklifts change their battery once every shift (8 hours), this has not been implemented in the simulation model.

6.4.7. Transport Network

The distances are calculated based on Manhattan distances. The dimensions are measured in an AutoCAD file with the actual dimensions of the factory. The distances are indicated in appendix D.4.

6.5. Experimental Setup

This section addresses the experimental setup. Increasing the number of replications makes the model estimates more statistically reliable. A *replication* is 'the generation of one sample path which represents the evolution of the system from its initial conditions to its ending conditions' (Rosetti, 2021, §3.2)[51]. Each replication represents a different sample path and utilizes another stream of pseudo-random numbers, resulting in different outputs. All replications start from the same input parameter settings. Arena automatically uses the same pseudo-random numbers for each replication number, so comparing the results with different parameter settings does not depend on the randomness of the input variables. Arena automatically changes the random seed per replication when multiple replications are performed.

A critical decision for the experiments is determining the sample size or number of replications. Confidence intervals may form the basis for decision-making. The appropriate sample size can be obtained through the confidence interval half-width [51]. Since the distribution for the arrival rate of entities (steel coils) is directly influenced by the randomness of the individual replications, the sample size will be determined based on the number of coils arriving. The duration of the run is set to a year, 24 (hours) times 365 (days). Figure 4.9 indicates high variability in the number of transport operations that need to be performed throughout the year. Therefore, the decision was made to run the model for a year.

An initial pilot sample size of $n_0 = 3$, results in an average of output $\mu = 37799$ coils and a half width of 220. The half-width is half of the 95% percentile confidence interval for the metric. The standard deviation can be calculated as follows:

$$\sigma = \frac{\text{Half width} \cdot \sqrt{n_0}}{z_{\alpha/2}} = \frac{220 \cdot \sqrt{3}}{1.96} = 194.41 \tag{6.3}$$

With a desired margin of error corresponding to 0.5% to the mean number of entities, $\epsilon = 0.005 \cdot 37799 = 189.00$. The number of replications can be calculated as follows [51]:

$$n \geq (\frac{z_{\alpha/2} \cdot \sigma}{\epsilon})^2 = (\frac{1.96 \cdot 194.41}{189.00})^2 = 4.065 \tag{6.4}$$

Therefore, the number of replications should be at least $n = 5$ to achieve a 95% confidence interval with a margin of error of 0.5% of the mean number of entities. The simulation model does not include a warm-up period because the storage parks start with an initial storage level.

6.6. Verification and Validation

Verification and validation (V&V) are significant elements of any simulation study. Through V&V, confidence in the simulation model is obtained so that the results can be used in decision-making. Verification ensures that the computer implementation of the model operates as intended, confirming that the model is built correctly. According to Sargent (2010), validation is defined as 'substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model' (p. 183)[53], i.e. building the right model [49].

The verification and validation follow the structure proposed by Robinson [49] and Sargent [53]. First, the verification and white-box validation are discussed in subsection 6.6.1. This is followed by the validation in subsection 6.6.2, which discusses the conceptual model validity, black-box operational validity and data validity.

6.6.1. Verification and White-Box Validation

According to Robinson (1997), verification of the simulation model is 'the process of ensuring that the model design (conceptual model) has been transformed into a computer model with sufficient accuracy' (p. 53) [49]. In other words, building the model right. Robinson [49] treats verification and white-box validation together since they are performed continuously throughout the model coding. While verification ensures that the model represents the conceptual model, white-box validation ensures that the content of the model represents the real world.

The conceptual model is implemented in the Arena simulation software under the supervision of an expert in this field, whose job is simulation modelling for Tata Steel. Discussions on the implementation and progress updates were held during the simulation phase. The model is implemented stepwise. By gradually increasing the complexity and running the model between the steps, errors could be traced and resolved easily.

An *animation* is made which visualizes the stock levels of all individual storage parks, the number of available positions on the outfeed and infeed of all installations and all operations of the forklift. A dashboard is added indicating the number of busy vehicles, the number and distance of loaded, empty and total trips per vehicle and the utilization rate per vehicle. Furthermore, the number of tasks waiting and the total number of coils in storage are indicated. Figure 6.2 shows what the animation looks like without the dashboard, the colour bars indicate the number of occupied buffer positions at the installations, and the number in the storage parks indicates the stock level. The animated model shows a behaviour as expected. This verifies the control of flows, cycle times, travel times and the control logic (vehicle dispatching), which are all part of the verification procedure according to Robinson [49].

Figure 6.2: Animation

In combination with animation, several checks were performed to verify the model logic and behaviour. Many conditions were tested to verify the model, such as changing the capacity of storage facilities, setting a production line to zero or extremely high throughput, and other tests which verified the model logic and behaviour. Besides, Arena allows to trace the entity through the simulation model, which helps to verify the model. By stepwise increasing the complexity and running the model again whenever changes were made, the visual checks and output reports verified the expected behaviour. Therefore, the model is verified and well represents the conceptual model as visualised in Figure 6.1. The comparison of the simulation model with real-world data is not reported for all iterations, however by doing this continuously, the model is white-box validated. The final comparison of the model with real-world data is discussed in the black-box operational validation.

6.6.2. Validation

According to Robinson 1997, validation is 'the process of ensuring that the model is sufficiently accurate for the purpose at hand' (p. 53) [49] , in other words, building the right model. Based on the theories of Robinson [49] and Sargent [53], the validation is divided into conceptual model validity, black-box operational validity, white-box operational validity and data validity. The white-box operational validity has already been discussed in the previous section.

Conceptual model validation

Conceptual model validation is defined as 'determining that the theories and assumptions underlying the conceptual model are correct and that the model representation of the problem entity is "reasonable" for the intended purpose of the model' (Sargent, 2010, p. 185) [53]). The conceptual model is represented in section 6.2. The representation of the problem entity is validated by the material flows as represented in RM reports[1] and the expert opinion of the internship supervisor and production manager of the transport department. The modelling assumptions are challenged and discussed with the internship supervisor.

Black-Box Operational Validation

Operational validity is defined as 'determining that the model's output behaviour has sufficient accuracy for the model's intended purpose over the domain of the model's intended applicability' (Sargent, 2010, p. 186)[53]. Validation testing and evaluation are a part of operational validity. Black-Box Validation determines that 'the overall model represents the real world with sufficient accuracy' (Robinson, 1997, p. 54) [49]. The sub-parts of the model are validated in subsection 6.6.1. Whether the problem entity or system is observable i.e. there is historical (real-world) data available on the operational behavior

[1] RM Reports is a logistical tool of Tata Steel, indicating the material flow between installations

is an important attribute in operational validity. Therefore operational validity can be distinguished into two types of validation: 'comparison' and 'explore model behaviour'. Comparisons involve assessing how the simulation model's output behaviour aligns with the output behaviour of the real-world system. Exploring the model behaviour means 'to examine the output behaviour of the simulation model using appropriate validation techniques, including parameter variability-sensitivity analysis' (Sargent, 2010, p. 189) [53]. The downside of operational validity where the system is not observable (explore model behaviour), is that it is not possible to obtain the same degree of confidence in the model as comparison validity methods.

Several validation techniques are employed. The first technique considered is *event validity* or calibration. This method evaluates how closely the simulation model results align with the real-world system by comparing their occurrences. The simulation model is compared to data from which the probability distributions were derived. This data has been converted to represent a year. The first results were not satisfactory enough. Some probability distributions were multiplied with a factor for fine-tuning. The results of this calibrated model are indicated in Table 6.7.

	Current situation		**Future situation**	
	#	**kton IN**	**#**	**kton IN**
Expected result	37494	512.7	49200	680.9
Simulated result	37342	512.3	49659	694.5
Deviation	-0.4%	-0.08%	0.9%	2.0%

Table 6.7: Event validity based on yearly ouput

Two other validation techniques are employed comparing the model's behavior with real-world data. The first one is an analytical calculation of the utilization rate. The same parameters were used, section D.5 indicates the calculation. The model indicated a utilization rate of 37.8% compared to the analytical calculation of 36.9%. The difference can be explained by the fact that the analytical calculation assumes that all coils from the DKG11 pass through the storage facility in the S hall, whereas this does not always occur in the model. Additionally, in the model, the pick-up and drop-off times are incorporated as a normal distribution, with a minimum but no maximum. These differences result in a slightly unequal utilization rate.

Secondly, the turnover time for coils originating from DKG11 and HW48 to the EVs are compared in Table 6.8. Figure 4.12 showed a boxplot of the historical data. Although there is a significant difference, the test validates that the model does prioritize DKG11 coils over HW48 coils in a similar way.

Percentiles	**25%**	**50%**	**75%**
DKG11 historical data (h)	$0<t<8$	$8<t<17.3$	$17.3<t<35$
DKG11 simulation within bounds historical data	36.3%	27.1%	21.5%
HW48 historical data (h)	$0<t<19$	$19<t<40.5$	$40.5<t<83$
HW48 simulation within bounds historical data	32.6%	22.3%	25.2%

Table 6.8: Comparison of the turnover time percentiles

All other validation techniques are of the type 'explore model behaviour'. An *animation* is made which visualizes the stock levels of all individual storage parks, the number of available positions on the outfeed and infeed of all installations and all operations of the forklift. The animation has been discussed in subsection 6.6.1.

Degenerate tests determine the degeneracy of the model's behaviour by selecting values of the input and internal parameters. *Extreme conditions tests*, tests whether the outputs of the system are plausible for any extreme and rare combination of simulation model inputs. Furthermore, in *parameters variability - sensitivity tests*, the input and internal parameters are changed, determining the effect upon the model's output. Since these three validation techniques are closely related, Table 6.9 states the tests performed. For each test, a hypothesis is stated before the test is carried out, and the observations are substantiated by quantitative results. The results indicate that the model performs as expected.

Test nr	Test description	Hypothesis	Hypothesis correct?	Test results
1	Installations don't experience downtime. The real production time = clock time, no sale/logistics-, planned- or unplanned losses for every installation. Test performed with an unlimited storage capacity.	The utilization rate of the vehicle will increase significantly.	Yes	Utilization rate forklift from 37.8% to 55.0%. The input increased by 51.4% and the output by 41.2%.
2	Input and output 5x as high, i.e. interarrival time divided by five for every installation. Test performed with an unlimited storage capacity.	Utilization rate reaches its max., the average number of tasks in queue increases, service time gets worse.	Yes	Utilization rate to 100% . Installations are often not able to operate due to full outfeeds or empty infeeds.
3	No fixed parking, parking is the last visited location.	Total distance driven will be shorter and the average service time will increase.	Yes	The average service time increases by 8.6% for delivery and 8.1% for retrieval. The distance decreases by 14.5%.
4	Vehicle speed set to 3km/h.	Utilization rate will increase.	Yes	Utilization rate from 37.8% to 68.9%.
5	Vehicle dispatching random based.	Service time delivery will improve, and retrieval will worsen.	Yes	The average service time decreases by 5.4% for delivery and increases by 2.5% for retrieval.
6	Storage capacity is 50% of the initial capacity.	Less coils will run through the system due to limited storage.	Yes	Decrease of 0.5%.
7	Vehicle is unavailable for 30 minutes every 2 hours.	The average service time will rise.	Yes	The average service time increases by 177% for delivery and 161% for retrieval.

Table 6.9: Validation tests

Finally, the *internal validity* is tested by performing five replications and determining the stochastic variability in the model. The average number of entities arriving in the system equals 37342, with a half-width of 51.7. The half-width corresponds to the 95% confidence interval. This test succeeded since $51.7 \leq 189.00$, the desired error margin as determined in section 6.5.

Data validation

Data validity is defined as 'ensuring that the data necessary for model building, model evaluation and testing, and conducting the model experiments to solve the problem are adequate and correct' (Sargent, 2010, p. 186)[53]. The data-collecting process and variation inherent to the measurement were studied thoroughly throughout the system analysis. A lot is known about the current state. The data from a relatively undisturbed period has been taken as input to the model. In the section subsection 6.6.2, the event validity indicates the deviation between the real-world and the simulation models.

The implications of installation downtimes were tricky to implement. Sales, logistic, planned and unplanned losses define the real production time. First, these categories or subcategories of these losses were modelled, trying to accurately represent the downtimes. However, due to the lack of data in some categories, this did not yield satisfactory nor valid results. Therefore, all downtimes are represented by short and long durations based on all categories combined. The sum of the short downtimes is the same as the sum of the long downtimes. This improved the model balance a lot (input-output relation).

The normal distribution for the coils' weights is based on the middle 99% of the data, eliminating outliers. The installation yield data has also been cleaned where needed. Furthermore, the data determining the duration of manual forklifts is based on observations. Due to the relatively low number of observations (about 25 per type of operation), the confidence in this data is relatively low.

6.7. Conclusion

This chapter addresses the following research question:

How can the system design alternatives that integrate the scheduling of automated vehicles and the assignment of coils to storage locations be modelled?

The simulation model for the current state (base case) is discussed throughout this chapter. The chapter started with defining the requirements and assumptions of the simulation model. A conceptual model was then developed and presented as a swimlane diagram, illustrating the processes within a lane and the information flow between the lanes. Each lane represents a function or station, clarifying the tasks performed at each station or by each function. This conceptual model was subsequently implemented in Discrete-Event Simulation software.

The model was implemented using Arena DES software, chosen primarily due to the client's preference, as the company already utilizes this software. The implementation clearly defines the system's inputs and outputs. In order to implement the model, the inter-arrival time, downtime, material handling delays, size of an order, coil weight and transport distances are quantified. Lognormal distributions fit the best on the inter-arrival times, these distributions are 'frequently used to represent task times that have a distribution skewed to the right' (Arena, 2004, p. 119)[3]. The three alternatives are adjustments to the current state model. They are not reported in this chapter, however, their model behaviour and logic were validated.

The model was built to simulate one year of operation, with input parameters carefully selected to reflect real-world conditions. By running five replications, the model provides reliable insights. Finally, verification confirmed that the simulation model accurately aligns with the conceptual model, ensuring consistency between the two. The validation process further demonstrated that the model accurately represents the real-world system and its operational processes.

7 Experiments and Results

This chapter discusses the experiments and results obtained from several simulation model runs. This chapter aims to find the best-performing alternative and indicate its viability and performance compared to the current state. The performance is measured in both logistical performance and costs. This chapter addresses the following research question:

SQ5: *Which system design demonstrates the best results, and what is its impact on the performance metrics?*

Section 7.1 states the experimental plan, in section 7.2 the logistical performance of these experiments are discussed. The costs are estimated in section 7.3 for the viable configurations found in the experiments. Based on the fleet sizing experiment and cost estimation, a Pareto front is drawn in section 7.4. Finally, the preferred alternative is discussed in section 7.5.

7.1. Experimental Plan

This section sets up a plan for a set of simulation model runs, to gain insight into the system behaviour [7]. The experimental plan outlines the experiments to be conducted to achieve the research objective; facilitating effective material flow through automation. The Design Of Experiments (DOE) plays a crucial role in understanding the likely performance of the real-world system. The DOE explores different scenarios. An experiment is a combination of a scenario and configuration. Since the simulation model is implemented as non-terminating (the run length must be defined), the configuration is kept the same across all experiments.

The following activities are considered as part of the DOE (Barton, 2013, p. 343)[7]:

1. State a hypothesis to be evaluated.
2. Plan an experiment to test the hypothesis.
3. Conduct the experiment.
4. Analyse the data from the experiment.

The experiments conducted in this research are designed to examine the impact of resources and dispatching policies on service time, utilization rate and costs. The experiments should identify in a quantitative and predictive way how design or policy variables affect system performance (Barton, 2013, p. 344)[7]. The data will be analysed in section 7.2. The two experiments that will be performed are described below.

7.1.1. Experiment 1: Dispatching policy

The first experiment aims to determine the effect of the dispatching policy on the system's performance. The hypothesis is that the chosen policy influences the balance between the performance of delivery tasks and retrieval tasks regarding service time. Furthermore, the utilization rate is expected to change marginally under different policies. The experiments are performed with the minimum viable number of vehicles.

All alternatives will be tested on five dispatching policies, which were identified in section 5.6:

1. *Random Workstation (RW)*: Tasks are chosen at random.
2. *Combination*:
   These rules prioritize retrieval tasks over delivery tasks and take the buffer availability into account as well. The following priorities are assigned to the requests (a low number indicates a higher priority):
   - Tinning lines (EV11, EV12, EV13) and IB11 output: Number of occupied buffer positions.
   - Temper rolling installations (DKG11 & HW48) and IB11 input: 1 + ('buffer capacity' - 'occupied positions').
   - Coils on the wagon arriving from CA12 are assigned the lowest priority.
   - Tasks with the same priority level are prioritized based on the smallest distance to the vehicle.
3. *Shortest Distance (SD)*:
   Tasks with the shortest travel distance to an available vehicle are prioritized.
4. *Minimum Available Storage Positions (MASP)*:
   Tasks of load handling stations with the least available buffer positions are prioritized.
5. *First-Come-First-Served (FCFS)*: Tasks are assigned to vehicles based on their arrival time.

The results of experiment 1 indicate the key logistical performance indicator. Furthermore, it identifies the performance indicators underlying the KPIs, the percentage of retrieval and delivery tasks completed within a 10-minute time frame.

7.1.2. Experiment 2: Number of vehicles

The second experiment determines the effect of the amount of vehicles on the performance of the system. The goal of this experiment is to identify how service levels and the utilization of vehicles are affected by the number of vehicles. The hypothesis is that by increasing the number of vehicles, the service time will decrease and the utilization rate will decrease as well. The question is what the smallest fleet size can be for a certain configuration to still be viable.

For each alternative the configurations as described in Table 7.1 will be simulated. The experiments are performed on both the current material flow and the future material flow.

# Vehicles → Alternative ↓	**1**	**2**	**3**	**4**
Base case	1 Forklift	2 Forklifts	3 Forklifts	4 Forklifts
Alternative 1	1 AGV	2 AGVs	3 AGVs	4 AGVs
Alternative 2	-	1 Forklift O-hall, 1 AGV S/U-hall	1 Forklift O-hall, 2 AGVs S/U-hall	2 Forklifts O-hall, 2 AGVs S/U-hall
Alternative 3	-	1 AGV O-hall, 1 AGV S/U-hall	2 AGVs O-hall, 1 AGV S/U-hall	2 AGVs O-hall, 2 AGVs S/U-hall

Table 7.1: Configurations experiment 2

The results will be visualized in several plots. For retrieval and delivery tasks, the percentage of tasks performed within a 10-minute time frame is examined. Furthermore, the average service time and average utilization rate will be plotted against the number of vehicles.

7.2. Logistical Performance

This section discusses the results of the experiments based on the (key) performance indicators selected in section 4.8. This results in a preferred configuration for each alternative. For both experiments, the results of the future situation will be discussed since these differences are better perceptible. The complete simulation results of the future and current state are displayed in section F.1.

7.2.1. Experiment 1: Dispatching policy

The first experiment evaluates the choice of dispatching policy on the system performance. The results of this experiment are visualized in Figure 7.1, showing both the percentage of tasks performed within 10 minutes and the maximum service time for delivery and retrieval. The utilization rate and average service time were almost the same among the dispatching policies for each alternative and are therefore not visualized. This section discusses what aspects of the dispatching policy have a perceptible influence.

For the percentage of tasks performed within 10 minutes, the policies show that an improvement in retrieval performance relates to a decline in delivery performance. The 'combination' policy shows the best retrieval performance and FCFS on delivery.

The maximum service time indicates how long it can take to process all tasks for a particular vehicle. The delivery operations for the 3th alternative indicate that maximum service time can take up to 12 hours. The AGV in the O-hall indicates a utilization rate of 76.71%. Although it does not affect the production of the installations, the queue sizes at the installations often get close to their capacities. Additional demand could result in an unstable system.

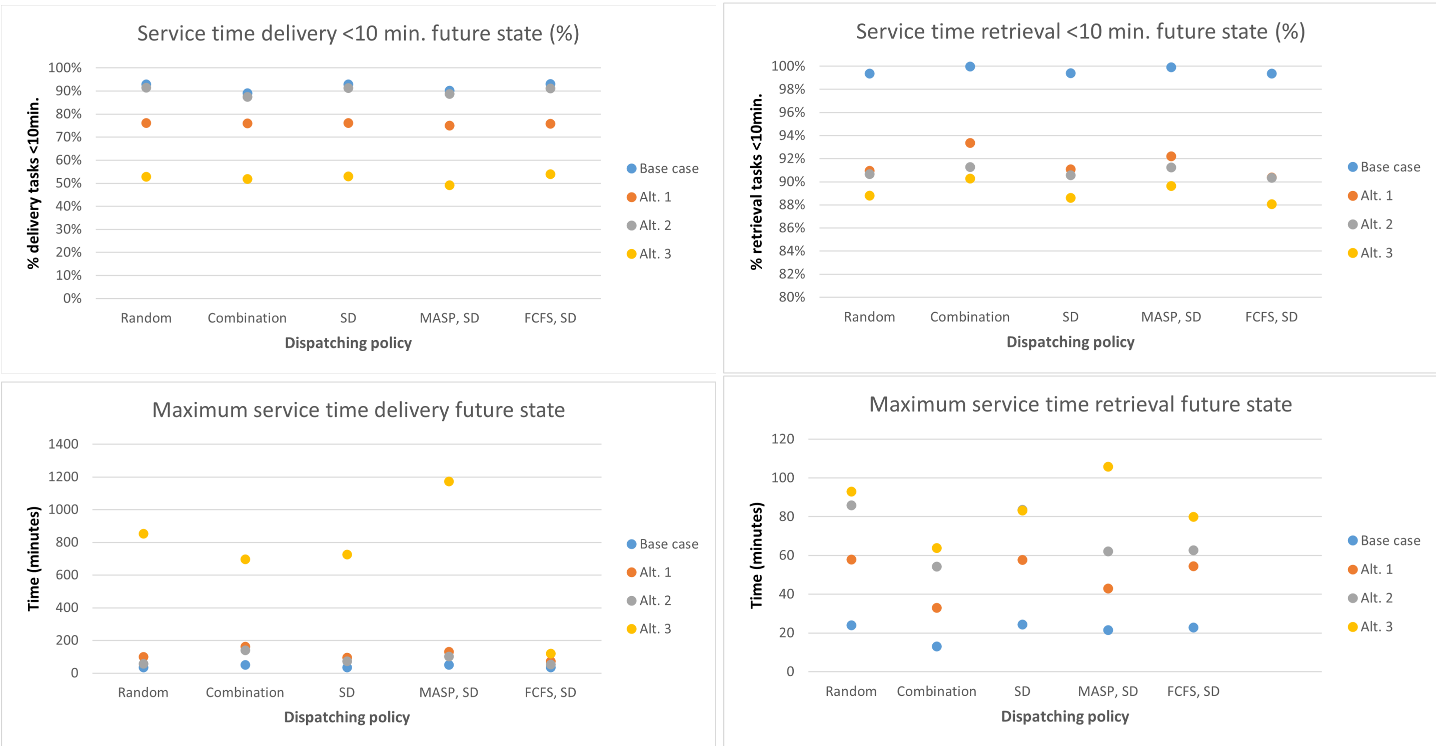


Figure 7.1: Results Experiment 1

This test aimed to determine how the dispatching policy influences the performance. In Table 7.2, the results on the percentage of tasks performed within 10 minutes is indicated for alternative one only[1]. It shows that the 'combination' dispatching policy performs best since retrieval transport operations are prioritized in the performance KPI. This policy will be used in the second experiment.

	Random	Combination	SD	MASP	FCFS
Performance	86.1%	**87.6%**	86.1%	86.5%	85.5%
% service time delivery <10 min.	76.19%	76.00%	76.18%	75.08%	75.84%
% service time retrieval <10 min.	91.00%	93.36%	91.07%	92.21%	90.37%

Table 7.2: Impact of dispatching policies, alternative one future state configuration

[1]The complete results are available in section F.1.

7.2.2. Experiment 2: Number of vehicles

The results of the second experiment are visualised in Figure 7.2. The results show a clear performance drop when forklift AGVs take over the work of manual forklifts. This can be explained by the longer pick-up and drop-off durations, the AGVs' lower speeds, and assumptions made about manual forklifts.

Comparison of the 1st and 3th alternatives

Alternative 1 is feasible from 2 forklift AGVs. For 1 forklift AGV the model indicates that installations often have to be put to a standstill due to the unavailability of buffer positions. This indicates that one forklift AGV for alternative 1 is too low, as it would become the bottleneck of the production system. Alternative 1 outperforms alternative 3 on all aspects except for the average service time for retrieval operations, where the results show almost the same performance. This can be explained by the fact that forklift AGVs may perform any available task in alternative 1. The transport operations in the O-hall are more time-intensive, resulting in a slightly unbalanced workload for alternative 3. The restriction on operating in a specific zone does not allow an idle forklift AGV to perform operations in the other zone. As a result, the 'service time delivery <10 min.' plots, indicate a more effective material flow for alternative 1 compared to alternative 3.

Even though the distance driven per task is smaller for alternative 3, the utilization of the forklift AGVs is still slightly higher compared to alternative 1. The transfer point between the O- and S-hall results in additional transport operations, increasing the utilization of the AGVs.

Comparison of the 1st and 2nd alternatives

The 2nd alternative outperforms alternative 1 regarding performance. The delivery tasks have a lower service time due to the manual forklift operating in the O-hall. However, as the next section will explain, the 2nd alternative is the most expensive.

Conclusion fleet sizing experiment

All plots indicate a performance saturation when increasing the number of vehicles. Enlarging the fleet hardly improves the results. At this level, the performance can only be increased by increasing the speed and reducing the duration for pick-up and drop-off.

The minimum viable fleet size is 1 forklift for the base case, 2 AGVs for alternative 1, 1 forklift and one AGV for alternative 2 and 2 AGVs for alternative 3. For alternative 3, the buffer positions of temper rolling installation HW48 must be increased from two to four to be viable. The key performance indicators for this experiment are presented in Table 7.3. The logistical performance indicators for the minimal fleet size are shown in Table 7.4. Their definition is discussed in section 4.8.

	Base case	**Alternative 1**	**Alternative 2**	**Alternative 3**
Performance 1 vehicle	**96.0%**	29.1%	-	-
Performance 2 vehicles	100%	**87.5%**	**89.9%**	**77.4%**
Performance 3 vehicles	100%	95.9%	97.5%	87.4%
Performance 4 vehicles	100%	98.9%	99.9%	94.9%

Table 7.3: Key Performance Indicator 'Logistical Performance' Experiment 2

	Average utilization rate (%)	**Average service time delivery (min)**	**Average service time retrieval (min)**	**% service time delivery <10 min.**	**% service time retrieval <10 min.**
Base case	47.0%	5.3	2.7	88.1%	100%
Alternative 1	63.8%	11.0	6.8	76.0%	93.2%
Alternative 2	45.0%	5.6	6.5	87.3%	91.2%
Alternative 3	69.0%	23.6	6.7	51.9%	90.2%

Table 7.4: Logistical performance indicators of minimal fleet size, future state

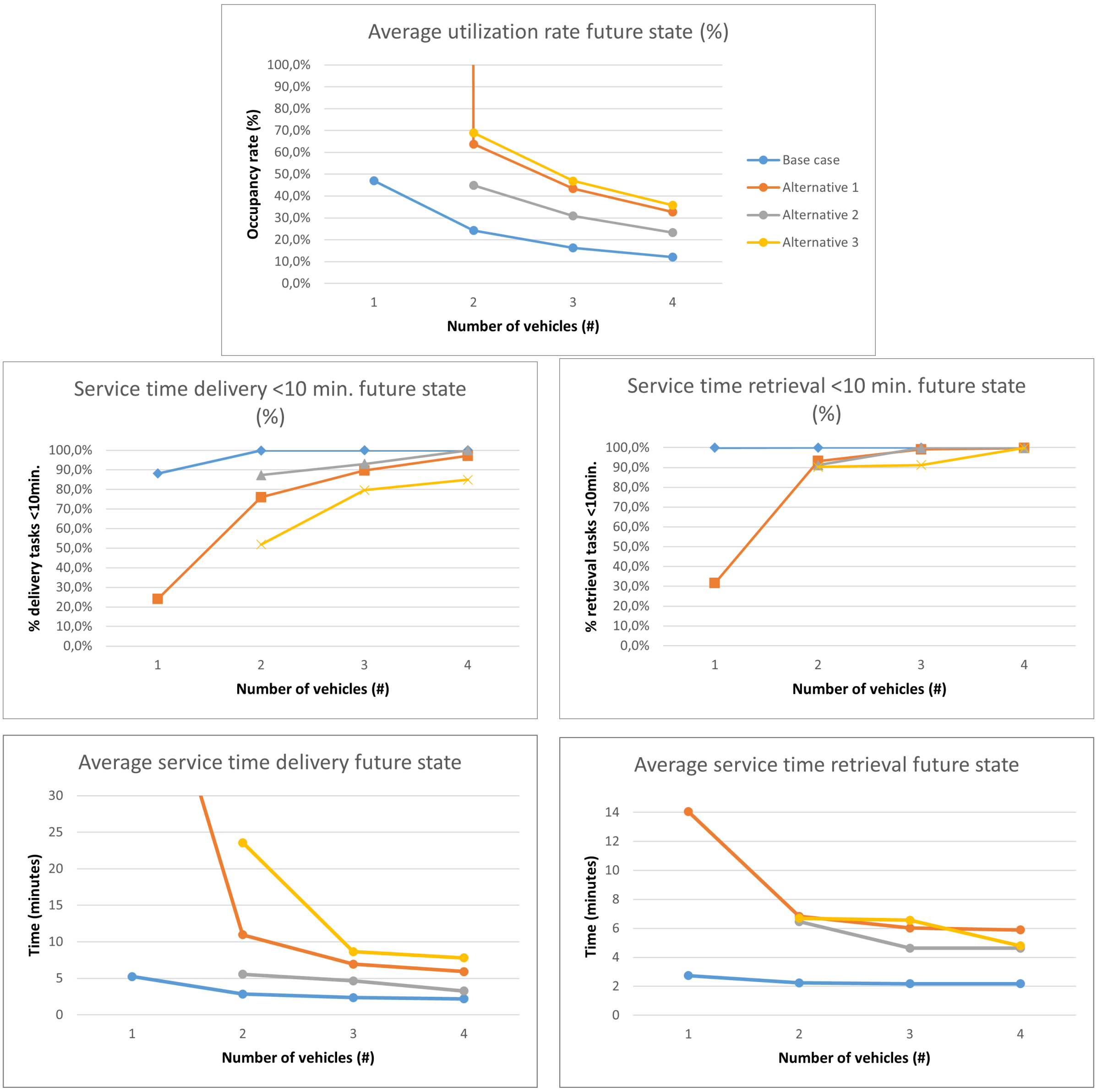


Figure 7.2: Results Experiment 2

7.3. Cost Estimation

In addition to evaluating the system's logistical performance, cost considerations are crucial in selecting the most suitable alternative. This section determines the Total Cost of Ownership (TCO) for each alternative based on two expenditure cash flows: capital expenditures (CAPEX) and operational expenditures (OPEX). The project's cash flow captures both the development and service phases.

The CAPEX estimates are based on previous quotes from KB2 (section C.3). The costs have been estimated for the suppliers Solving, Bertolloti and EK automation. Section F.3 visualizes how the Capital Expenditures for these suppliers are estimated. One supplier was more expensive, while the other two suppliers cost about the same. The supplier that has been chosen is based on the costs and requirements regarding the vehicle length, as discussed in section 5.1. The preferred supplier is indicated in section F.3.

The TCO is estimated considering a twelve-year time frame (2025-2036). This metric accounts only for costs without assigning a monetary value to potential improvements in service time. For the baseline scenario, the TCO includes the estimated manual forklift lease, maintenance expenses, damage repair, and fuel costs. 2024 is considered the base year for discounting future cash flows. The TCO is expressed as Net Present Value (NPV). The NPV recognizes the time value of money principle, 'that a euro today is worth more than a euro tomorrow' (Schraven, 2023, p. 6)[54]. The TCO depends on the forecasted cash flows from the project and the Weighted Average Cost of Capital (WACC). The following assumptions were made while performing the cost estimation:

- The economic life of the project is expected to last at least ten years. The year of commissioning is expected to be 2027. Therefore, the cash flows from 2025 until 2036 are accounted for.
- The WACC applicable to Tata Steel is used to discount future cash flows, with the base year being 2024. This parameter is confidential (see section F.2).
- Wages are increased by 1.5% annually.
- The reduced workload of the forklift driver in the 2nd alternative does not result in less FTE.

The results in Table 7.5 indicate that alternatives 1 and 3 are estimated to be the most affordable options. The calculation of the cost estimation is documented in section F.2. Alternative 2 is by far the most expensive option. In alternative 2, a part of the scope is automated. However, a forklift operator is still needed, making it an expensive option.

Configuration	CAPEX (NPV)	OPEX (NPV)	TCO (NPV)
Base case	-	M€ 4.67	M€ 4.67
Alternative 1&3	M€ 2.26	M€ 1.79	**M€ 4.04**
Alternative 2	M€ 1.72	M€ 4.99	M€ 6.71

Table 7.5: Cost estimation summary

Over the twelve-year time frame, alternatives one and three have a lower TCO than the current situation. This is mainly due to the high cost of wages. By commissioning two forklift AGVs, 5 FTE can be reduced. For alternatives one and three, the Internal Rate of Return (IRR) has been calculated based on the incremental cash flows, subtracting the cash flows of the alternatives from the cash flows of the base case. As indicated in **??**, the IRR is estimated to be 6.4%. Generally, the investment is accepted if the WACC $\leq$ IRR, since WACC $\geq$ 6.4% the investment should not be accepted based on the IRR rule [54]. This would suggest that the return on investment is less than the company's cost of capital, making it financially unattractive because it would not cover the cost of financing.

Given the limited scope of the project, the overhead costs are disproportionately high relative to the price of a single AGV (see **??**). Increasing the scope of the project would relatively reduce the overhead costs, and reduce the amount of FTE's even further. This would lead to a higher IRR, making the investment more financially attractive and potentially justifying acceptance of the project.

7.4. Pareto Front

In a multi-objective optimisation problem, there is a set of solutions that optimize the overall system if no solution dominates all other solutions on both objectives. In the case of Tata Steel, the two objectives are the KPIs, cost and performance. The solutions in this set are called the non-dominated solutions. These solutions define the Pareto-optimal front, or Pareto Front (PF). All other solutions that are not on this front are considered dominated. According to Rondeau (2009), 'solutions are nondominated when improvement in any objective comes only at the expense of at least one other objective' (p. 234)[50].

A Pareto front can be constructed based on the results of experiment 2, which focuses on fleet sizing and based on cost estimations. The cost estimation for other fleet sizes than the minimum viable fleet size is estimated in **??**. This resulted in Figure 7.3. The nondominated solutions on the Pareto-Front are presented in Table 7.6.

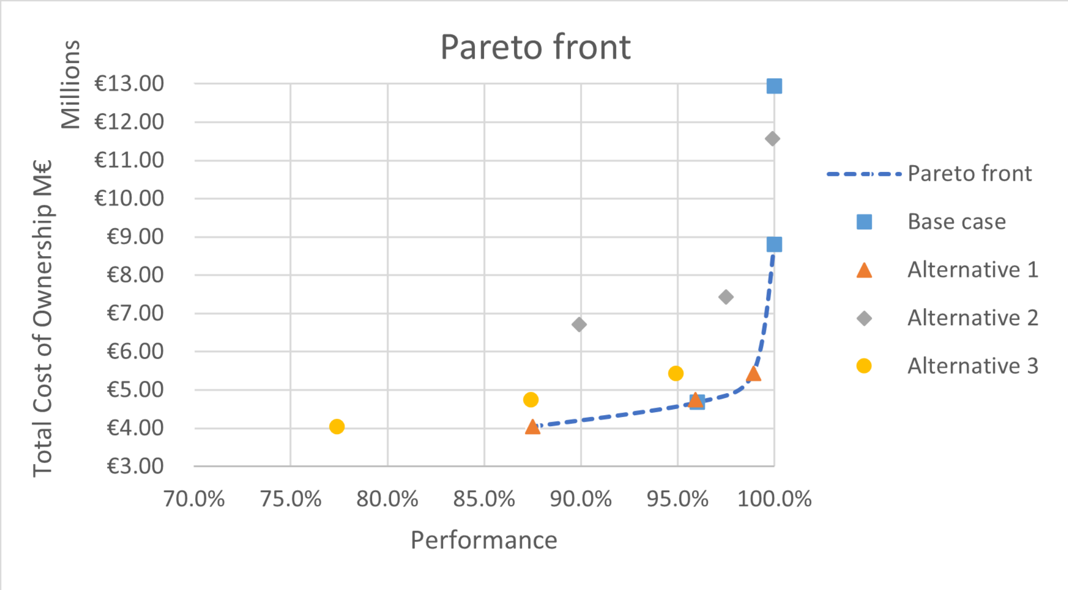


Figure 7.3: Pareto Front

Configuration	# Vehicles	Performance	Costs
Alternative 1	2 AGVs	87.5%	M€ 4.04
Base case	1 Forklift	96.0%	M€ 4.67
Alternative 1	4 AGVs	98.9%	M€ 5.44
Base case	2 Forklifts	100.0%	M€ 8.81

Table 7.6: Nondominated Solutions

The Pareto-Front visualizes that alternatives 2 and 3 are dominated and are not a part of the optimal system design configurations. Section 7.5 discusses the most effective configuration for each alternative based on the Key Performance Indicators (KPIs) and Performance Indicators (PIs). Hereafter, the most effective system design configuration is selected.

7.5. Alternative Selection

Three design alternatives have been derived in chapter 5, which are quantified using a Discrete Event Simulation. The first experiment indicated that the 'combination' dispatching policy, which aligns most closely with current operations, is indeed preferred. The minimum viable number of vehicles for each alternative was confirmed by performing the second experiment.

The results of the Key Performance Indicators (KPIs) are presented in Table 7.7, while the Performance Indicators (PIs) are summarized in Table 7.8. According to the Pareto Front in Figure 7.3, alternatives 2 and 3 are not in the set of non-dominated solutions. Only alternatives one and the current operations (base case) are a part of the optimal system design configuration. First, some notes on the performance of alternatives 2 and 3 will be made. Hereafter, the first alternative and the baseline operations will be compared.

	Base Case	Alternative 1	Alternative 2	Alternative 3
Performance	96.0%	87.5%	89.9%	77.4%
Costs (TCO)	M€ 4.67	M€ 4.04	M€ 6.71	M€ 4.04
Preference Rank	1	2	4	3

Table 7.7: Key Performance Indicators, future state configuration

	Base Case	Alternative 1	Alternative 2	Alternative 3
Average utilization rate (%)	47.0%	63.8%	45.0%	69.0%
Service time delivery <10 min (%)	88.1%	76.0%	87.3%	51.9%
Service time retrieval <10 min (%)	100%	93.2%	91.2%	90.2%
Avg. service time delivery (min)	5.3	11.0	5.6	23.6
Avg. service time retrieval (min)	2.7	6.8	6.5	6.7
CAPEX	-	M€ 2.26	M€ 1.72	M€ 2.26
OPEX	M€ 4.67	M€ 1.79	M€ 4.99	M€ 1.79
Total Cost of Ownership	M€ 4.67	M€ 4.04	M€ 6.71	M€ 4.04
IRR	-	6.4%	No project return	6.4%
Preference Rank	1	2	4	3

Table 7.8: Performance Indicators, future state configuration

Performance Alternatives 2 and 3

Alternatives 2 and 3 are both characterized by its zone-based flow path layout. This flow path design approach is not a good fit with the case presented by Tata Steel. The identified research gap was: *the need for integrated analysis of flow path layout designs and their impact on material flow effectiveness in automated vehicle systems, considering vehicle scheduling and storage location policies*. The effect of the flow path layout on the material flow effectiveness is assessed by applying a zone-based and conventional flow path layout.

The transfer point is situated in between the O- and S-hall. This location is chosen based on the opinion of an expert and because of the constraints of the facility layout. Although the forklifts don't have to drive as much distance as a conventional flow path, the additional pick-up and delivery tasks result in a higher utilization rate. By restricting the forklifts to a zone, the system is less flexible. If a forklift has many tasks requesting transport while the forklift in the other zone has none, the service time deteriorates compared to a conventional approach. The results are highly case-specific. However, it can be generalized that for a manufacturing facility with relatively short distances and high material handling times, a zone-based flow path layout will not outperform a conventional one.

Alternative 2 is omitted due to its costs. The client was interested in the alternative since it would be a smaller step in automation, reducing the risk of failure. However, it would not reduce the number of manual forklift operators. Therefore, it does not result in a project return, making this alternative the least favourable choice.

Alternative 3 is outperformed by alternative 1. Although both options cost the same, as visualized on the Pareto front, alternative 3 is dominated in performance. Additionally, the utilization rate for alternative 3 is higher, which is unfavourable given that both alternatives use the same type and number of forklift AGVs.

Performance Comparison Base Case and Alternative 1

The research question of the thesis is: *What in-plant system design facilitates effective material flow by the implementation of automated transport in a steel coil manufacturing plant?* The reason for the implementation of automated transport was to overcome the identified challenges and wastes, e.g. cost savings from transport damages, employees, over-processing and safety considerations. The current operations have a higher performance. However, alternative one costs less, and the performance is satisfactory (i.e. it will not result in transport being the bottleneck of the production system).

As discussed in section 7.3, the project's Internal Rate of Return (IRR) of design alternative one indicates that it would not cover the cost of financing. If the project scope were to be expanded, the overhead costs could be relatively reduced, potentially making the alternative financially attractive. In conclusion, alternative 1 presents the most effective performance if automated transport were to be implemented. Automation is currently discouraged for this scope as it is not financially justifiable.

8 Conclusion, Discussion and Recommendations

The goal of this thesis is to contribute both practically and scientifically. Practically, the thesis addresses Tata Steel's case study by quantitatively evaluating the performance of various design alternatives. Scientifically, it presents a conceptual process flow for setting up a simulation study addressing integrated decision-making in AGV system designs and performance estimations for a manufacturing facility with in-process inventory. By selecting a set of decision-making aspects in AGV system design, the study investigates the impact of flow path layout design and scheduling policies on system performance in manufacturing environments. The inclusion of storage location assignment further enhances the representation of real-world dynamics.

By analyzing and comparing the performance of different design alternatives for the in-plant transport system of a manufacturing facility, the thesis quantifies the influence of flow path layout design and dispatching policies. Although the storage location assignment is only partially implemented, future research can build on this work, as outlined in Appendix H, where a robust model for further analysis is proposed.

The research process began with a comprehensive review of scientific literature on the design and control of automated in-plant transport systems. This was followed by a detailed analysis of the current system, including a description of the use case and the key performance indicators. Drawing from the literature, expert opinions, and in-depth use case data, three design alternatives were developed and simulated. Each alternative was tested by Discrete-Event Simulation modelling to quantify its performance. One of the three alternatives outperformed the others on the Pareto Front. This process addresses the sub-research questions, which collectively contribute to answering the main research question:

What in-plant transport system design facilitates effective material flow for automated vehicles in a steel coil manufacturing plant?

This chapter covers the conclusion, discussion and recommendations. First, section 8.1 discusses the answers to all sub-research questions. This is followed by answering the main research question. Next, section 8.2 presents a discussion on the thesis. Finally, section 8.3 state recommendations for the commissioner of the thesis and recommendations for further research.

8.1. Conclusion

This section answers the sub- and main research questions.

SQ1: Scientific Literature

A literature study has been performed to gain knowledge on the type of automated vehicles used in steel coil manufacturing facilities, and theories related to the flow path layout, scheduling policies and storage location assignment policies. The literature study provides both a review of the literature as well as an overview. By doing this, both the applicable theories and shortcomings are identified, leading to a research gap. The literature study answers the first sub-question:

Which theories are applicable for generating new findings on the system design of in-plant transport and storage processes?

The main theories and modelling approaches for the reviewed topics are listed below:

- **Automated vehicles:** Automated vehicles can be distinguished into Automated Guided Vehicles (AGVs) and Autonomous Mobile Robots (AMRs). The word guided in AGVs indicates that the vehicles use an external system to localize and guide the AGV. Both systems have their benefits, since most suppliers of automated vehicles don't have robust AMRs in place, the thesis considers AGVs.
- **Flowpath layout:** The flow path layout analysis focused on conventional bi-directional layouts and zoning. Studies have shown that zoning, where AGVs operate within designated zones and transfer materials at transfer stations, can enhance cost efficiency and productivity. Zoning helps prevent congestion and deadlocks.
- **Vehicle scheduling:** The review of scientific papers related to scheduling indicates the wide variety of modelling approaches. Optimization and Discrete-Event Simulation (DES) came forward as the most applied methods. DES studies imitate the operations of a stochastic system that will continue operating indefinitely [25]. The choice was made to perform a DES, because of the stochastic features inherent to a manufacturing facility. Moreover dispatching and allocation rules were better captured in DES studies. There is a wide variety of vehicle dispatching policies which are often based on the objectives and the system under study.
- **Storage location assignment:** Mostly papers on the warehousing industry were reviewed since no research is performed in the manufacturing industry on deep-lane storage configurations. The Closest-Open-Pure-Lane (COPL) policy seemed most applicable to the case study because forklift operators assign the coils based on their order identification number to minimize sorting operations. The policies were found to be highly dependent on the attributes of the entities in the system.

The synthesis of the challenges presented by the case and applicable theories leads to the following knowledge gap: *the need for an integrated analysis of flow path layout designs and their impact on material flow effectiveness in automated vehicle systems, considering vehicle scheduling and storage location policies*.

SQ2: Challenges of the Use Case

The 2nd sub-question aims to define the requirements and design environment of the case presented. Besides, based on TIMWOODS, a lean 6σ methodology, the wastes in the system are identified. The system analysis concludes with the performance indicators. The system analysis answers the following sub-question:

How is the solution space of the transport and storage system defined, and what challenges in its current operations require innovative changes?

The solution space is 'the multi-dimensional space limited by boundaries within which the solutions are to be found, determined by requirements and design environment' (Binsbergen, 2022, p. 42)[8]. A black box model for the process of scheduling vehicles to tasks, and coils to storage locations, and a black box model for the transport process define the design environment and system requirements. The inter-arrival time and buffer capacity of installations relate to what the maximum service time may be for a steel coil. The service time relates to the number of resources (forklifts) needed. The design environment revealed the presence of other modes of transport operating within the system boundaries of the to-be-implemented automated transport system.

Wastes in the system are found through the TIMWOODS methodology. Transport damages, employee shortages, inefficient storage assignment policies, safety incidents, and misplaced coils have led to the exploration of automated transport solutions. By analyzing the system several performance indicators were established. The right balance between the Total Costs of Ownership and the logistical performance which is based on the On-Time Performance should be obtained. The **key** performance indicators of the system are:

KPI 1 Performance = $\frac{\text{OTP delivery}+2*\text{OTP retrieval}}{3}$
KPI 2 Costs = Total-Cost of Ownership

Other performance indicators are the average and maximum service time and the utilization rate. These performance indicators give a better understanding of how certain designs influence the performance, however, they are not the key performance indicators of the system.

SQ3: Design Alternatives

Through the synthesis of an expert opinion, previous automation studies and a process analyses, the main functions, sub-functions and means were identified. Based on these means, several alternatives and experiments were generated answering the following sub-question:

What feasible design alternatives for the implementation of automated transport can be developed considering the solution space?

The chosen AGV supplier, as stated in section F.3, matched best with the solution space. Following this, the main and sub-functions of the system were identified. The main functions are the transport of material and the scheduling process. The scope clarified which sub-functions were excluded and established that the storage location assignment, unit-load selection and battery management would remain consistent across all alternatives. The storage location is assigned based on the order number and, otherwise, on the fill percentage of a storage park. Several vehicle dispatching methods were tested on all alternatives in the experiments. The design alternatives and experiments will test different means for the sub-functions of in-plant transport (which considers the material handling device), the flow path design, idle-vehicle positioning, and vehicle dispatching. A FFBD defines how the sub-functions relate to the process.

For each of the sub-functions, several means were identified. Three alternatives were generated by testing the combination of means on the requirements and constraints.

Alternative 1 considers a conventional bi-directional flow path layout design, with a fleet of forklift AGVs. The fleet of vehicles uses the same parking if they are idle (P1).

Alternative 2 considers a zone-based flow path layout. A transfer station between the O- and S-hall is used to transfer the material between the zones. A manual forklift serves the zone in the O-hall, while one or more forklift AGVs serve the other zone. Both zones have their own idle-vehicle parking spot (P1 and P2).

Alternative 3 is similar to alternative 2. The only difference is the use of one or more forklift AGVs in the O-hall instead of a manual forklift.

SQ4: Simulation Modelling

The generated alternatives were modelled using a Discrete-Event Simulation (DES) model. Chapter 6 addresses the following sub-question:

How can the system design alternatives that integrate the scheduling of automated vehicles and the assignment of coils to storage locations be modelled?

After identifying the requirements and modelling assumptions, a conceptual model of the real-world systems was developed. This model, represented by a swimlane diagram, visualizes the baseline operations. It was implemented using Arena Discrete-Event Simulation software. To build the model, key input parameters such as inter-arrival times, downtime, material handling delays, order sizes, coil weights, and transport distances were quantified. Lognormal distributions were found to fit the inter-arrival times best.

The model was built to simulate one year of operation, with input parameters carefully selected to reflect real-world conditions. By running five replications, the model provides reliable insights. Finally, verification and validation steps confirmed that the model accurately represents the real-world and its processes. The design alternatives were modelled using the baseline model as a foundation.

SQ5 & Main Research Question: System Performance

In chapter 7, an experimental plan is developed to investigate what dispatching policy and fleet size results in the most effective performance. By testing many system design configurations, the chapter aims to answer sub-question five and the main research question:

Sub-question 5: *Which system design demonstrates the best results, and what is its impact on the performance metrics?*

Main research question: *What in-plant system design facilitates effective material flow by the implementation of automated transport in a steel coil manufacturing plant?*

The KPIs for the future case scenario are presented in Table 7.8. All alternatives are modelled with the 'combination' dispatching policy. The base case utilizes one manual forklift, alternative 1&3 two forklift AGVs and alternative 2, one manual forklift and one forklift AGV.

	Base Case	**Alternative 1**	**Alternative 2**	**Alternative 3**
Performance	96.0%	87.5%	89.9%	77.4%
Costs (TCO)	M€ 4.67	M€ 4.04	M€ 6.71	M€ 4.04
Preference Rank	1	2	4	3

Table 8.1: Key Performance Indicators, future state scenario

A Pareto front was established from the set of non-dominated solutions. All solutions corresponding to alternatives 2 and 3 were dominated. Alternative 2 is dominated due to its high costs, while alternative 3 is dominated by its lower performance. Therefore, alternative 1 demonstrates the most effective performance among the options that include automated transport. This answers the 5th sub-question.

Even though alternative 1 is a viable alternative with a lower cost than the base case, it is not a strong investment decision. According to the Internal Rate of Return (IRR) rule, the IRR rate should be greater than the Weighted Average Cost of Capital (WACC), to cover the cost of financing. With an IRR of 6.4%, this is not the case (**??**). The project costs are for a large part overhead costs, increasing the scope of the project could result in an investment opportunity that does cover the cost of financing.

Scientific Results

The **research gap** addressed the need for research on an integrated system analysis of flow path layout designs and their impact on material flow effectiveness. This integrated analysis involved decision-making on many topics related to the system design with automated transport. The flow path layouts under study are zoning and conventional flow paths. The case study presents relatively short distances, and the material handling time for the automated vehicles handling steel coils is relatively large. Zone-based flow paths are generally implemented to reduce the total distance and prevent deadlocks. System designs that use this approach have an additional trip, resulting in an extra pick-up and drop-off operation. In this case, the reduction in travel distance could not offset the significant increase in material handling time. Additionally, restricting forklift AGVs to specific zones reduced the flexibility to assist in other areas. Compared to a conventional flow path layout, this led to a deterioration in the service time and, thus, the system performance.

Secondly, Tata Steel's 'combination' dispatching policy performs well overall. Although the primary focus is on retrieval, the percentage of tasks performed on time on the delivery side also shows great results.

The answer to the **main research question** is hard to generalize. The system design facilitating effective material flow is case-specific. In the case of Tata Steel, where the material handling time is a significant portion of the operational time, a conventional bi-directional flow path layout is the most effective. Furthermore, a dispatching policy which prioritizes tasks by using a combination of policies that best represent the needs of the plant results in the most effective performance. In the most effective automated transport alternative, two forklift AGVs need to be deployed.

The **scientific goal** of this thesis was to provide new insights into the integrated system design process for in-plant transport and storage systems in a manufacturing environment. The literature review and sub-functions helped identify relevant decision-making processes. The study evaluated how various decision-making processes interact and how this relates to the system's performance by testing multiple configurations in a discrete-event simulation model. Limited studies address the storage location assignment problem in the integrated design process of deploying automated transport in a manufacturing environment. Although the deep-lane storage system could not be modelled in detail, the study did model the decision-making processes related to storage location assignment and unit-load selection on the storage park level. Integrating these processes offers new insights into workflow and system interactions. The proposed approach reduces simulation time compared to modelling each individual storage position while providing more realistic model dynamics than models that simplify in-process inventory to a single station. Additionally, Appendix H presents a simulation model that explores the storage location assignment problem (SLAP) in more detail. The first results of this model are discussed in Appendix H, due to time limitations a detailed analysis could not be included in this thesis.

8.2. Discussion

The discussion is organized into several sections, addressing the limitations of this research. First, the project's scope is examined, followed by a review of the design alternatives generated. Next, the model's implementation, experiments, and results are discussed.

Scope

The project scope does not encompass all material flows the forklift operator handles. The initial scope was to study the feasibility of implementing automated transport between the origins HW48 and DKG11 towards the destinations EV11, EV12 and EV13. Later on, the material flows around IB11 and from CA12 towards the EVs were also considered, as these installations supply material to the tinplating lines. While these additional flows were incorporated into the model, they were not analyzed in detail during the system analysis. It was later discovered that this information was based on outdated documentation. This forklift operator does not manage the material flow around IB11, but the flow around Laminating Line 11 (LL11) is within scope. As a result, it is not entirely accurate to claim a savings of 5 FTEs through automated transport implementation. This issue will be addressed further in future research.

Generation of Design Alternatives

Automated material handling systems are associated with several topics in the literature. One of these topics is modelling deadlocks and collision avoidance. A control system should be in place to model deadlocks, leading to a higher utilization rate of the AGVs in alternative 1. One of the benefits of the zone-based flow path layout (alternative 2 & 3) is that deadlocks won't occur. However, the increased performance in service time and utilization rate compared to alternative 1 were not quantified or included in the results. Additionally, routing and failure management were not considered, as these topics were less relevant to the scope of this research.

Another limitation is the location of the transfer station where the load is transferred between zones in alternatives 2 and 3. While this location is the most logical, as it allows for the separation of material flows, it does not effectively balance the workload between the two zones. Choosing a different buffer location that better distributes the load between the AGVs in alternative 3, could potentially enhance the performance of this alternative.

Model Implementation

The main research question addresses the storage location assignment problem (SLAP) as one of the main topics considered. An expert opinion advised that modelling the SLAP would not be possible in the limited time of my research. According to the expert, each storage position would need to be modelled as an individual station, with distances between each station explicitly defined, leading to an extremely high number of modules and an overly complex model. As a result, the SLAP was performed on the storage park level and not based on the individual positions. A reliable estimate of the frequency at which coils needed to be repositioned to access coils deeper in the lane could not be obtained. As a result, the simulation model in Arena does not account for the unit-load relocation problem, which would lead to higher vehicle utilization. The future research section presents a model that successfully implements the detailed SLAP and unit-load relocation problem for the case considered. Due to time limitations and an incomplete understanding of all model aspects, the results of these experiments are not included in the main research.

Additionally, the decision to implement idle-vehicle parking could be questioned. When 1 manual forklift was considered, the implementation of idle-vehicle parking led to an improved service time. No tests were conducted to determine if the same benefit applies to forklift AGVs.

Regarding the data-gathering approach, it was challenging to find reliable stochastic estimates for the downtimes of the installation. Numerous categories contribute to standstills, each with significant variability in both duration and frequency. This made it difficult to fit a probability distribution to the downtimes. Attempts were made to fit distributions to the entire dataset, to individual categories, and after splitting the data, on short, medium, and long durations for each installation. However, none of these approaches resulted in reliable fits, leading to a highly unstable model. As a result, downtimes were categorized into short and long durations, with an average frequency and duration determined for each installation. This model simplification reduced some of the stochastic variability, resulting in a more stable inventory level than visualized in the system analysis. Some other model simplifications and assumptions are addressed below:

- The utilization rate of the forklift driver does not account for activities such as bathroom breaks, exiting the vehicle for tasks like scanning, analyzing the task screen and deciding which task to perform, taking breaks, or changing the battery. As a result, the utilization rates of the manual forklift and the forklift AGV cannot be accurately compared.
- The range of a forklift AGV was initially implemented as 3 km, based on information provided by the supplier. However, the sales department later clarified via email that the range for these forklift AGVs is around 18-20 km. Unfortunately, this updated information could no longer be incorporated into the model.
- The disruption of scrap material collected by trucks in the S/U-hall is not accounted for.

Experiments and Results

The experiments indicated that the third alternative was not viable with only one forklift AGV in the O-hall if the number of buffer positions at the outfeed of HW48 remained at 2. The alternative became viable by increasing it to 4, which is a simple adjustment. Although modifying the experiment based on performance was not part of the original experimental plan, this adjustment resulted in a viable alternative and required only a minor change.

Another limitation is the number of experiments conducted. Only two experiments were performed, as each configuration required numerous simulation runs, making the process time-intensive. It is recommended to explore additional experiments, such as examining the impact of idle-vehicle parking, extremely high demand scenarios, or increased variability in the system.

Furthermore, cost estimation plays a significant role in the financial attractiveness of the first alternative. If the 30% unforeseen costs are excluded, the Total Cost of Ownership would be M€ 3.52, leading to an IRR of 14.6%. This would make the alternative an attractive investment according to the IRR rule.

Lastly, this thesis's results are highly case-specific, which limits the generalizability of the findings to other studies. However, the literature often emphasizes the need for more case studies on the topics considered within manufacturing facilities.

8.3. Recommendations

This section discusses the recommendations for both future research and Tata Steel.

Recommendations for further research

Based on this thesis, there are many possibilities for future research. The topics considered for future research are zone-based flow path layout, collision avoidance, storage capacity, vehicle dispatching policies, storage location assignment, and applicability to other industries.

The zone-based flow path layout did not perform well in the case considered. A larger zone could potentially shift the balance between distance savings and additional material handling time. In this case, the short distances resulted in an unfavourable ratio between these factors. Future research should explore the optimal zone size at which zoning is preferred over a conventional flow path layout design.

Secondly, collision avoidance should be modelled in future research. Studies on flow path layout design are closely linked to collision avoidance, as an effective layout can help prevent deadlocks from occurring.

Furthermore, the influence of the storage capacity on how often the system reaches full capacity or becomes empty should be investigated. Due to the simplifications made in modelling downtimes, these scenarios did not occur frequently, so no reliable conclusions could be drawn. Reaching storage capacity can pose a significant problem for forklift AGVs; if there are insufficient positions to efficiently organize the storage park, service times can increase substantially.

Regarding vehicle dispatching policies, this research used a combination of several policies to closely mimic the real system, resulting in the best performance. It would be interesting to investigate whether a standard combination of policies or priority rules could perform effectively in a wider range of cases, or even across multiple industries.

This thesis did not explore the storage location assignment and unit load relocation problem for deep-lane storage systems in detail. However, many industries face similar challenges and could benefit significantly from a warehouse management system that optimizes storage location assignment. The startup SLAPstack offers advanced software capable of running simulations under various policies and implementing it as operating software [44]. This particular case has already been implemented in their software, and the first results are available. No literature was found on storage location assignments for deep-lane storage configurations in the manufacturing industry. Future research could build on the findings from this simulation model. More information is available on this topic in Appendix H.

The literature review analyzed papers from various industries, including warehousing, food, flexible manufacturing systems, and container terminals, which share many common characteristics. It would be valuable to use a similar model to study the trade-offs in these industries and compare them. Comparing the results and different trade-offs can give conclusions on why certain transport systems perform better under constraints imposed for a particular industry.

Recommendations for Tata Steel

The recommendations for the client are case-specific. The commissioner was interested in whether forklift AGVs can be connected to the Warehouse Management System (WMS), which is possible. Furthermore, this section will discuss the scope of the project, failure management, additional experiments, vehicle utilization when LL11 is within scope, idle-vehicle parking and how to separate different transport modes.

The most notable recommendation concerns the project scope. According to the Internal Rate of Return (IRR) rule, investment in automated vehicles is currently financially unattractive as it does not cover the cost of financing. The small project scope results in disproportionately high overhead costs relative to the AGV prices. Expanding the scope would increase the IRR, making the investment more financially attractive.

An earlier study highlighted the necessity of having a spare forklift AGV available. Given the scope of this problem, it is recommended that a manual forklift be deployed in case one of the forklift AGVs fails.

In such an event, the second AGV should also be taken out of operation. While it may be challenging to find a forklift operator on short notice, there are numerous pools of operators available, making it likely that someone can be called in to cover the shift.

As discussed in the conclusion, additional experiments are recommended to assess the impact of extreme high-demand scenarios, situations where one forklift AGV fails and the other must perform all tasks, and increased system variability. Furthermore, experiments can be performed with alternative idle-vehicle parking policies, such as having the vehicle remain at its current position or basing parking decisions on demand forecasts or a schedule.

The buffer capacity of production line HW48 should be increased from 2 to 4 positions if forklift AGVs are implemented. This adjustment is simple, inexpensive, and minor, yet it significantly reduces the likelihood of the production line being stopped due to a full output queue.

Regarding Laminating Line 11 (LL11), which is located above EV13, there are two material flows which need transport. Coils arriving from other facilities must be placed in the unpacking positions before they can go to LL11. Secondly, the material at the outfeed of LL11 needs to be put into storage. Table 8.2 gives an indication of the assumptions and additional utilization. The distance is estimated based on starting the trip from parking P1 and ending the trip at parking P1. The results are based on an average between 2-8-2022 and 16-8-2024, a total of 744 days. The time per trip is estimated based on the distance with an average speed of 55 m/min, the pick-up and drop-off time. The additional forklift AGV utilization is estimated at 15.7% for one forklift AGV.

Material flow	**Estimated distance**	**Frequency**	**Time per trip**	**Additional utilization**
Unpacking positions V-hall (ECCS)	480 (m)	9.7/day	645.2 (s)	7.2%
LL11 to storage (all material)	380 (m)	13.7/day	536.1 (s)	8.5%
Total				**15.7%**

Table 8.2: AGV utilization Laminating Line 11

Finally, recommendations will be provided for managing routes where other modes of transport may interfere. Table 4.7 presents data on the frequency of transport crossings at the intersection near IB11. The primary recommendation is to separate the transport flows. While forklift AGVs are programmed to stop for other vehicles and resume movement once the obstruction is cleared, encounters with other vehicles could create ambiguous and potentially unsafe situations.

AGVs are equipped with sensors to detect people, but these sensors typically scan a specific field along one axis and at a set height. Manual forklifts, for instance, may not be fully visible across the entire front length of the forklift AGV unless additional, costly sensors are installed. Due to these limitations, the preferred solution is to install automatic barriers that close when a forklift AGV needs to cross.

When scrap material is transported by trucks in the forklift AGV operating area, manual control of the forklift AGVs, such as temporarily stopping them, should be sufficient to ensure safety and operational efficiency. Pedestrian crossings can remain at the same locations. If the vehicle reaction time is too slow, automatic barriers are recommended to ensure a safe passage.

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A
Scientific Paper

The scientific paper starts on the next page.

Design of an In-Plant Transport System: A Case Study at Tata Steel

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***Abstract*—Traditionally, studies on in-plant transport system design for the manufacturing sector are limited to a specific subject. This paper attempts to integrate flow path layout designs with vehicle dispatching policies and decision-making related to the in-process inventory. A series of complex decisions are addressed related to the implementation of automated forklifts, resulting in an integral system design aiming to achieve an effective material flow. This paper introduces a case where steel coils must be transported in an in-plant manufacturing facility. The coils are transported between production lines and in-process inventories. The proposed design alternatives are analyzed through a discrete-event simulation model. The quantified costs and performance metrics of the tested configurations result in a Pareto front. The dominant solutions present that conventional flow path layout approaches outperform zone-based flow approaches under case-specific system constraints. A combination of dispatching policies that most closely resemble the current operations of the case resulted in the highest performance of all studied dispatching policies.**

This paper presents a conceptual process flow for a simulation study addressing integrated decision-making in AGV system designs and performance estimations for a manufacturing facility with in-process inventory.

***Index Terms*—AGV, Block Layout, Flowpath, Forklift, In-Plant Transport, In-Process Inventory, Manufacturing, Scheduling, Steel Coil, Storage Location Assignment, System Design**

I. Introduction

Manufacturing environments try to maintain their competitive position by increasing cost-efficiency, especially in the steel industry. An in-plant transport system is a subsystem in the context of a larger production system. The goal of any production system is 'the pursuance of greater delivery capability and reliability with the lowest possible logistic and production costs' (Nyhuis & Wiendahl, 2009, p. 762) [1]. Automated Guided Vehicles (AGVs) are increasingly being applied in the manufacturing sector, allowing for the reduction of waste and cutting costs. An AGV is an unmanned, computer-controlled mobile transport unit [2]. Forklift AGVs allow for automation of the entire material handling process, including pick-up and drop-off. AGVs are popular in configurations where transport tasks are repetitive and for transporting extremely heavy loads, AGVs are commonly used as an alternative for manual forklifts [2].

The implementation of AGVs requires decision-making on the strategic, tactical and operational levels. To facilitate effective material flow through the implementation of AGVs in a steel coil manufacturing context, an integrated decision-making process is required. Traditionally, studies on in-plant transport system design for the manufacturing sector consider only a few decision-making subjects. Although manufacturing systems are often studied in the literature, integrating the storage location assignment for steel coils in the system design of the layout under study is a new approach. The study addresses the following research gap: *the need for integrated analysis of flow path layout designs and their impact on material flow effectiveness in automated vehicle systems, considering vehicle scheduling and storage location policies.*

The decisions integrated into the process of achieving effective material flow by automated transport are stated below. The configurations vary in the flow path layout design, vehicle dispatching, material handling system (manual vs automated forklifts), fleet size and idle-vehicle position. Other decisions are kept consistent among the studied configurations.

1) Flow path layout design: direction and layout of arcs that can be traversed for a vehicle [3]
2) Dispatching: assignment of vehicles to transport tasks.
3) Storage location assignment: allocation of products into a storage space [4].
4) Unit-load selection: choice of the unit to be retrieved from storage.
5) Material handling system: type of forklift.
6) Fleet sizing: minimum viable number of vehicles.
7) Idle-vehicle positioning: parking location when a vehicle is not engaged in a task.
8) Battery management: charging facility type and location.

A. Case Study

This integrated decision-making process is evaluated by testing multiple design configurations on a case presented by Tata Steel. The case presented is a brownfield project. There are four production lines where the material enters the system (DKG11, HW48, CA12 and IB11). The coils are stored in an in-process inventory between the production lines. There are multiple storage parks in the O- and S-hall. Coils are assigned to a storage position based on their order identification number. Finally, the coils leave the system if a production line retrieves

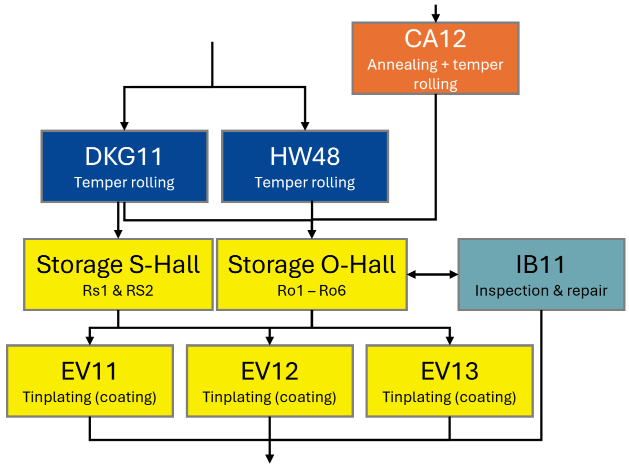

Fig. 1. Material Flow

the coils from its storage position (EV11, EV12, EV13 and IB11). The material flow is presented in figure 1. In current operations, the transport of these material flows is performed by one manual forklift.

A forklift has a capacity of one coil. The coils are stored in a deep-lane storage configuration, and the coils may not be stacked to prevent damage. The system is constrained by maximum queue sizes at the installations, the storage capacity, the availability of resources, the facility layout, and other characteristics. Two black box models are composed to gain insight into the physical transport process and the scheduling process of vehicles to tasks & assignment of storage locations. The purpose of the black box model is to show the input-output relations, disturbances, constraints and performance indicators. It emphasizes the lack of visibility into the internal workings of the system [5]. A system analysis consisting of studying previous AGV implementation documents, an actor analysis, system observations and an extensive data analysis on the transport and storage operations allowed to compose the black box models.

As in most human-operated storage systems, the driver assigns the coils to storage spaces based on experience and uses a set of rules. However, information is often lacking e.g. at shift changes [6]. AGVs controlled by Warehouse Management Systems (WMS) do not experience this, allowing them to optimize the storage locations assignment and reduce the number of sorting operations.

The case also presents other wastes and challenges which can be improved by the deployment of AGVs. Forklift operators make errors resulting in damage to the coils, infrastructure and forklifts. Forklift operators need to physically scan the coil and assign its storage position, which is non-value-added time. Besides, it causes safety-related incidents. The tight labour market presents the challenge of finding qualified employees [7].

B. Research Objective

The goal of this work is to obtain new findings on the in-plant system design process for a manufacturing facility. This involves the workflow and decision-making processes. The practical aim for the client Tata Steel is to present a minimum viable system design. By quantifying costs and performance indicators, a Pareto front can be drawn. The dominant solutions are discussed, resulting in a preferred configuration. The main research question addressed is:

What in-plant system design facilitates effective material flow by the implementation of automated transport in a steel coil manufacturing plant?

The word effective in the main research question is defined as 'the extent to which inputs do indeed lead to the desired outputs, without too much waste of resources' (Binsbergen, 2022, p. 5) [8]. This study makes the following contributions: (1) New findings on the integrated system design process through implementing automated transport in a manufacturing facility are presented, (2) provide and discuss the case study, a real-world use case with data provided by Tata Steel, (3) the influence of flow path layout designs (evaluating conventional and zone-based approaches), type & size of the fleet and vehicle dispatching policies on the system performance.

C. Structure

The paper starts with the methodology in section II, followed literature review on flow path layout designs, scheduling and storage location assignment problems in section III. The integral system design alternatives are presented in section IV. A Discrete-Event Simulation (DES) model evaluates the system design alternatives. The conceptual model, implementation, verification & validation and data gathering are discussed in section V. Section VI discusses the experiments and results. This is followed by a discussion in section VII. The conclusions are drawn in section VIII.

II. Methodology

A literature review was conducted to identify theories applicable to the case study and define a research gap. The system's current state was analyzed through interviews, data analysis, and insights from similar automation studies. Based on the challenges found in the system analysis, system design alternatives are generated through a functional analysis and the guidance of an expert opinion. The selection of the most suitable design is achieved through mathematical modelling.

Papers studied in the literature review indicate that (mixed) integer linear programming is by far the most applied mathematical modelling approach. Discrete-Event Simulation (DES) studies are hereafter the most applied approach. It is a simple and effective method for modelling the stochastic part arrival and processing times [9]. It increases the understanding of AGV system behaviour under various conditions [10]. This study considers DES as a modelling approach.

III. LITERATURE REVIEW

In literature, many in-plant system design problems are discussed. The reviewed papers presented that an integrated design process for transport and storage operations in the steel coil manufacturing industry seems to be lacking. Therefore a literature review is performed on flow path layout designs, scheduling and the storage location assignment in a separate manner. Common industries facing similar problems are warehousing, container terminals, logistics in general and (flexible) manufacturing systems. Besides a literature review, this section discusses applicable theories.

A. Flowpath Layout Design

A set of nodes and arcs creates a fully connected network. These arcs can be traversed in one or both directions, *unidirectional* or *bidirectional*. There are many flow path layouts. The review focused on conventional bidirectional and zone-based bidirectional flow path designs. Zone-based flow paths consist of mutually independent zones which do not overlap [11]. Buffer stations in between the zones can serve vehicles from both sides. According to Fragapane et al. (2021): 'The main objectives when designing zones and service points are to minimize travel distance, traffic, and throughput time while distributing the workload throughout the system, to increase and – ideally - maximize system throughput and resource utilization' (p. 413) [12]. In conventional designs, all vehicles are allowed to traverse all arcs in the system. The in-process inventory presented by the case causes additional complexity due to the high number of nodes and arcs. Limited studies consider this complexity and new methods for determining zones and handover locations need to be studied [12].

B. Scheduling

Scheduling involves allocating resources to tasks over time in a decision-making process based on an objective function. Objectives can be minimising travel time, cost considerations or service time improvement, given resource constraints, current operations and other managerial goals [13]. Studies on scheduling automated transport often considers conflict-free routing ([14] [15] [16] [17]) or simultaneous scheduling of vehicles and machines ([18] [19] [20] [21] [22] [23] [24]). A similar study on a brownfield project integrating a storage facility considers transport from production lines to a loading area. However, one main storage facility is considered instead of several facilities, and the number of positions to buffer material at load handling stations is significantly larger [9]. A study considering the scheduling of AGVs in very narrow aisle warehouses does consider multiple storage areas, however, only one input/output station is considered [25]. Performance indicators from these studies often addressed the service time and queue sizes at stations.

C. Storage Location Assignment

The Storage Location Assignment Problem (SLAP) concerns allocating products into a storage space, optimizing the storage space utilization and material handling costs. Parameters such as storage area design, storage capacity, product characteristics, storage availability and arrival times define the problem [4]. Optimization approaches include storage space utilization, the service time for material handling, and minimizing sorting operations under constraints such as order-picking resource capacities, and dispatching policies.

Studies on block storage and deep-lane storage configurations were only found in the warehousing industry. There is a clear gap regarding the assignment of storage locations in deep-lane configurations in a manufacturing context. Studies on assigning coils to storage locations utilize overhead cranes and present another type of problem [26]. Most studies in the warehousing industry use optimization to solve SLAP in a warehousing context ([27] [28] [29] [30] [31]).

One study presents SLAPstack, a simulation framework for autonomous block warehouses [6]. Based on the available product information, such as the Stock Keeping Unit (SKU) or due date, appropriate storage policies can be tested. The Closest Open Pure Location (COPL) policy is often considered the best policy when the material is assigned based on its SKU (i.e. order identification number). A significant difference between warehousing and manufacturing is the arrival rate. In warehousing, batches of units arrive or are retrieved from the storage, while in manufacturing, the arrival and retrieval pattern follows the takt time of the production lines. Moreover, the facility- and storage layout is notably different. A research gap on the SLAP in a manufacturing context for deep-lane storage configurations is evident.

This paper presents a simulation framework tailored for the case considering SLAP on the storage park level. A second simulation model is made by the developers of SLAPstack, who are able to assign a specific position for the presented case. The second model is not the main focus of this study and, therefore, not presented in this article. However, it presents an excellent possibility for future research and is further discussed in section VIII.

D. Knowledge Gap

Synthesizing the literature review findings indicated the need to develop a conceptual process for simulation studies addressing integrated decision-making in AGV system designs. Combined with the presented design issues, this led to the following knowledge gap: *the need for integrated analysis of flow path layout designs and their impact on material flow effectiveness in automated vehicle systems, considering vehicle scheduling and storage location policies.*

IV. DESIGN

The process of establishing effective material flow in a manufacturing environment by implementing AGVs requires a design approach. The problem has already been defined in section I. This section considers requirements, KPIs, a functional analysis and finally establishing AGV system design alternatives for the case study. The functional analysis discusses what main and sub-functions and associated means are

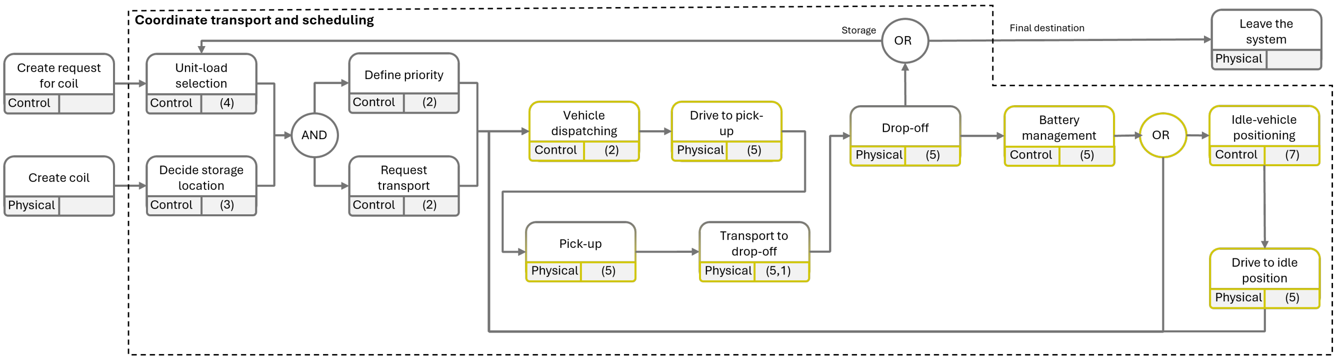

Fig. 2. FFBD

important for the case study. The advice of an expert opinion resulted in establishing design alternatives for the case under study.

A. Requirements

The goals, aims, and ambitions result in specific requirements for the design process. The requirements can be distinguished in constraints and objectives [8]. Constraints define what the system must comply with, while the objectives are requirements the design tries to comply with as much as possible. By establishing a black box model for the physical transport process and the Warehouse Management System with scheduling and SLAP as outputs, a list of requirements was established. A list of parameters, constraints, and disturbances were also identified. A black box model is used to gain insight into the process on the most abstract level and used to drive decision-making [32]. A list of requirements related to the WMS and vehicle requirements was established. A black box model is an abstraction of the processes and can, therefore, be seen as a requirement trawling technique. Other requirements are trawled by performing interviews, observations on real-time processes, similar AGV implementation studies, and by a historical data analysis.

B. Performance Indicators

Criteria can often be derived from the requirements. They are used in the design process to decide which alternative should be selected and in the operational phase to test whether the design functions as desired. Performance indicators reflect the functionality of the system. Many performance indicators are being tested and quantified:

1) Average service time: average duration from transport request till drop-off (min).
2) On-Time Performance (OTP): % of tasks performed within a 10-minute time frame from transport request till drop-off (%).
3) Average resource utilization (%).
4) CAPEX: Capital Expenditures (€).
5) OPEX: Operational Expenditures (€).
6) TCO: Total-Cost of Ownership (€).
7) IRR: Internal Rate of Return (%).

The service time and OTP can be estimated for the delivery and retrieval side. Delivery is from the production line to a storage park, and retrieval from the storage park to a production line. Inventory criteria such as the average turnover time and inventory level statistics were not assessed as they do not represent the effectiveness of the transport system but are unilaterally based on the arrival pattern of coils at the production lines. After discussions with stakeholders, the performance indicators were combined to the Key Performance Indicators (KPIs) cost and performance. Retrieval is more important in this case study due to the more limited buffer positions at the input of the production lines than the output.

KPI 1 Performance = $\frac{\text{OTP delivery}+2*\text{OTP retrieval}}{3}$

KPI 2 Costs = Total-Cost of Ownership

C. Functional Analysis

By considering the system as a whole, the physical transport process and scheduling by a WMS are considered the main functions. These are decomposed into sub-systems, which are the decision-making approaches discussed in section I. Decision-making aspects include the functions the system has to fulfil, the resources/technology needed and spatial sub-systems (i.e. functional, technical and spatial decomposition) [33]. After identifying the interrelations between the functions, a Functional Flow Block Diagram (FFBD) was established (fig. 2). The blocks and colours represent:

- Grey block: processes and flow of the coils.
- Yellow block: processes and flow of the vehicle.
- Grey & yellow block: the forklift handles the coil.
- Control or physical: in the bottom left of each process is defined whether it concerns a physical process, or a decision-making process (control).
- Sub-function: the number on the bottom right links to the sub-functions as defined in section I.

The means considered for the development of the design alternatives are indicated below. The numbers represent which means correspond to which system design alternative. The number 0 represents the current operations. For some decision-making approaches, experiments are performed to test the designs on all means, this is denoted by 'tested on all'.

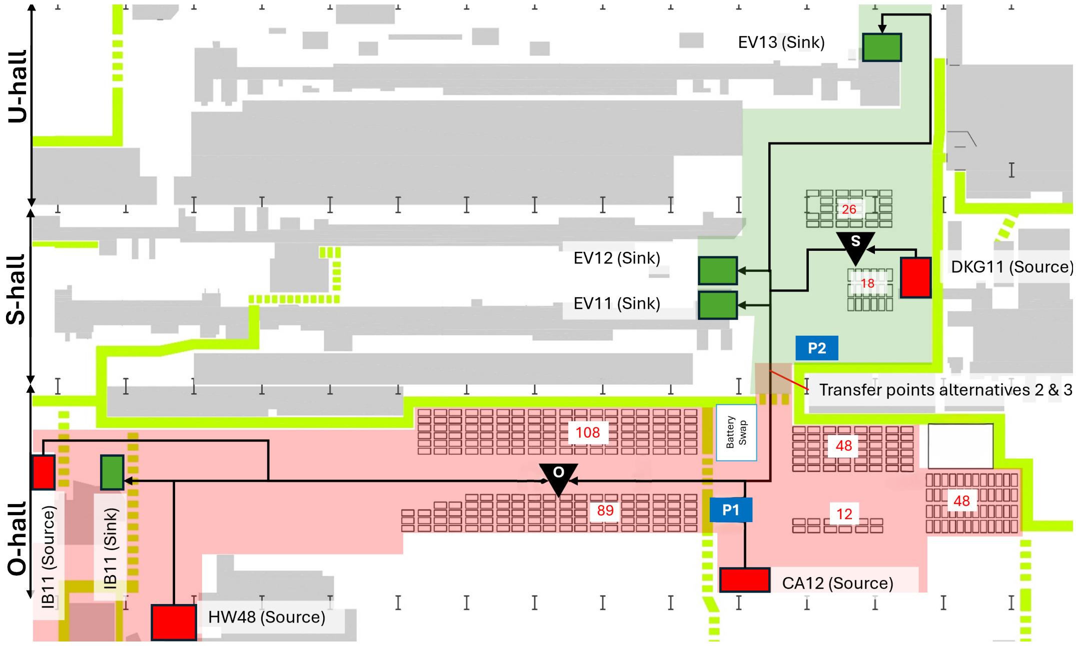

Fig. 3. Facility Layout for Automated Transport

1) Flowpath layout design: bi-directional conventional flow approach (0,1); bi-directional zone-based flow approach (2,3).
2) Dispatching (tested on all): random workstation; smallest distance (SD); minimum available storage positions (MASP); first-come-first-served (FCFS); a combination of policies representing the decision-making process of current forklift operators.
3) Storage location assignment: random-based; class-based; Closest-Open-Pure Location (COPL) (0,1,2,3)
4) Unit-load selection: based on order identification number and time in storage (0,1,2,3).
5) Material handling system: manual forklifts (0,2); counterbalance forklift AGVs (1,2,3); reach forklift AGVs; combination (2).
6) Fleet sizing (tested on all): 1; 2; 3; 4 vehicles.
7) Idle-vehicle positioning: Last station; fixed parking (0,1); zone-based fixed parking (2,3); demand forecast; schedule.
8) Battery management: battery swapping station (1,2,3); charging station.

The storage location assignment is a simplified version of COPL as the model presented in section V could not incorporate it in detail. The design assigns coils to one of the storage parks based on their order identification number. Battery management for manual forklifts is excluded from consideration due to their significantly larger battery capacity. After evaluating various transport methods against the requirements, counterbalance forklift AGVs were identified as the most suitable option for automated transport. Common system design issues not considered in this study are deadlock resolution, failure management, and routing.

D. Design Alternatives

Three alternatives are generated, and the means for their decision-making processes are discussed in section IV-C. An expert opinion from the client of the case expressed the desire to study a zone-based flow approach with both a fully automated transport system and a partially automated transport system. The zones are separated into the O-hall (red area in figure 3), and the S/U-hall (green area in figure 3). A short description of the main differences are indicated below:

Alternative 1 considers a conventional bi-directional flow path layout design, with a fleet of automated vehicles. The fleet of vehicles uses the same parking if they are idle (P1).

Alternative 2 considers a zone-based flow approach as a flow path layout. A transfer station between the O- and S-hall is used to transfer the material between the zones. A manual forklift serves the zone in the O-hall, while one or more AGVs serve the other zone. Both zones have their idle-vehicle parking spot (P1 and P2).

Alternative 3 is similar to alternative 2. The only difference is the use of one or more AGVs in the O-hall instead of a manual forklift.

The storage requirements for implementing forklift AGVs necessitate a minimum clearance around the stored coils for safety reasons [34], reducing the total storage capacity from 408 to 349 coils. However, both the simulated baseline operations and alternative 2 maintain the original capacity of 408 coils, since manual forklifts are still deployed in the O-hall.

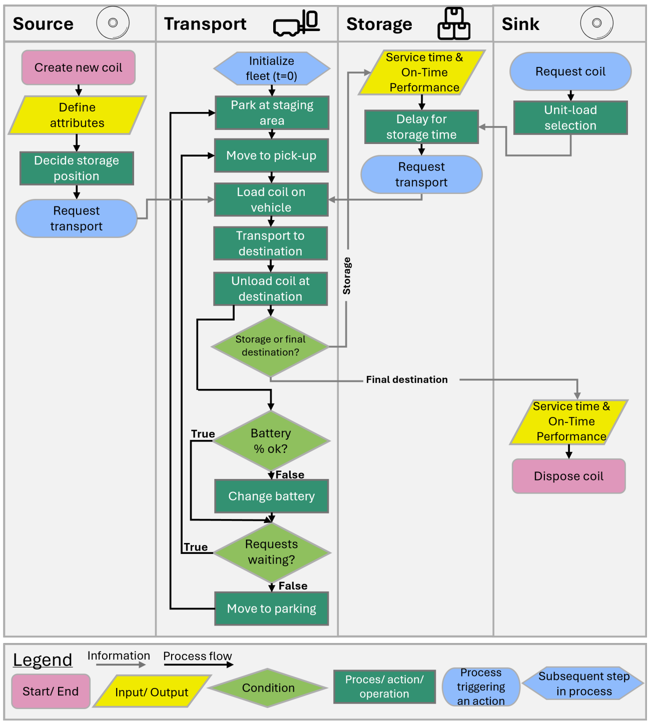

Fig. 4. Swimlane Diagram [35]

V. Simulation Model

Developing a discrete-event simulation model requires a step-wise approach. This section describes the abstraction of the real-world system, a conceptual model that is subsequently implemented as a DES model.

A. Conceptual Model

A conceptual model is the abstraction of a simulation model from the real-world system being modelled, capturing the system aspects and behaviour. Conceptual modelling is a crucial element of any simulation study, it should contain all necessary details to meet the objectives of the simulation study [36]. Furthermore, the implementation accuracy of the simulation model will be verified based on the conceptual model. Figure 4 presents the conceptual model in a swimlane diagram. Each swimlane represents a process, the diagram shows the relations between processes [37].

B. Software selection

A pugh chart for software selection indicated a preference for the DES software Arena and Simio over AnyLogic, FlexSim, Plant Simulation, and Python modelling [38]. Arena from Rockwell Automation was selected based on the client's preference and familiarity with the software.

C. Data Preparation & Implementation

The conceptual model has been implemented while adhering to a list of requirements and assumptions. Important assumptions are:

- A homogeneous fleet of manual forklifts and a homogeneous fleet of forklift AGVs are considered.
- Forklifts have a capacity of one coil.
- If a coil gets assigned a new position, it can't be reserved by other coils.
- Storage location assignment and routing are available before making vehicle dispatching decisions.
- Coils can be assigned to any storage park.
- Retrieval tasks prioritize DKG11 coils over 48h in the system. Hereafter coils with the same order ID as handled previously by the installation, followed by storage parks with the highest fill percentage.
- Urgent orders are not accounted for.
- Coils of the same order ID arriving consecutive after one another are sent to the same storage facility. Otherwise, the assignment is based on the facility with the lowest fill rate.
- Vehicles drive at a constant speed, acceleration and deceleration are represented in pick-up and drop-off.
- Delays of manual forklifts caused by human-related delays (e.g. breaks) are not accounted for.
- Production lines operate 24/7, with the exception of sales/logistics losses, planned losses and unplanned losses (i.e. real production time).
- Speed losses of production lines are captured in the arrival rate of the coils.
- Storage capacities and queue sizes at production lines constrain the model.

Two historical datasets were processed to obtain the arrival pattern of the production lines. One represents the date-time at which coils were produced by an installation. By matching the coil IDs with data on the production and downtime of installations, the duration of the production and downtimes could be estimated for each coil and downtime. With scipy.stats, a python package, the best fitting distribution for the inter-arrival rate of each production line was obtained. This resulted in lognormal distributions, which are frequently used to represent task times that have a distribution skewed to the right [39]. All inter-arrival KS statistics were below 0.1, which is considered a good fit. The downtimes could not be fitted on a distribution, for each installation the downtime was split up into short and long durations. The sum of standstills in both groups is equal. The average frequency and duration within these groups were estimated and provided as input to the simulation model.

Furthermore, material handling delays were estimated. Truncated normal distributions represent manual forklift pick-up and drop-off delays. For the forklift AGVs, these are constant values or uniform distributions if they take place in a storage facility. Coil 180° rotation delays and delays for battery exchange were added. The distances are estimated on a .dxf floorplan of the factory, and combined with the speeds of the forklifts, the model calculates the travel time. The weight of each coil is defined at the input and represented by a truncated normal distribution based on historical data. The size of an order is an integer estimated from a truncated log-normal distribution, defining the number of coils with the same order ID arriving consecutive after one another on a production line.

A crucial simplification of the real-world system is the assignment of coils to one of the storage parks and not an exact position. It is a new modelling approach, more advanced than considering the in-process inventory as one station, and easier to implement than considering all individual storage positions. This method allows to model the real-world system dynamics on a higher level while keeping the modelling time reasonable. Since simulation modelling of deep-lane storage location assignments in manufacturing environments has not been researched, a more advanced model is addressed for future work in section VIII.

D. Experimental Setup

The number of replications must be defined to obtain statistically reliable performance indicators. Since there is a high variability of transport operations being performed throughout the year, the run time is set to one year (i.e. 8760 hours). The number of replications relates to the statistical reliability of performance estimates. The number of replications n were estimated by [40]:

$$n \geq (\frac{z_{\alpha/2} \cdot \sigma}{\epsilon})^2 \tag{1}$$

Where ϵ is the desired margin of error, an error margin of 0.5% was used in this study, $\epsilon = \text{Error margin} * \mu$. An initial pilot sample of n_0, results in an average μ and a half width of the performance indicator. This allows to calculate the standard deviation needed to obtain the number of replications:

$$\sigma = \frac{\text{Half width} \cdot \sqrt{n_0}}{z_{\alpha/2}} \tag{2}$$

To achieve a confidence interval of 95% with a margin of error of 0.5% of the mean, $n = 5$ replications are considered. The simulation model does not include a warm-up period because the storage parks are filled with an initial storage level.

E. Verification & Validation

Through verification and validation, confidence in the model is obtained, and the procedure follows the structure proposed by Sargent [41] and Robinson [36]. Verification ensures that the conceptual model has been transformed into a computer model with sufficient accuracy [36]. The model was verified by entity tracing, discussions with a simulation expert, inspecting output reports and an animation (see figure 5) while continuously increasing the model complexity. White-box validation is performed in conjunction with the verification process to validate that the model represents the actual system.

Validation ensures that the model is sufficiently accurate for representing the actual system (i.e. building the right model) [36]. The conceptual model is validated by actors related to the system. The data was validated by performing a Measurement System Analysis (MSA), a 6σ methodology evaluating the variation inherent in every type of inspection or measurement. The simulation model has been black-box

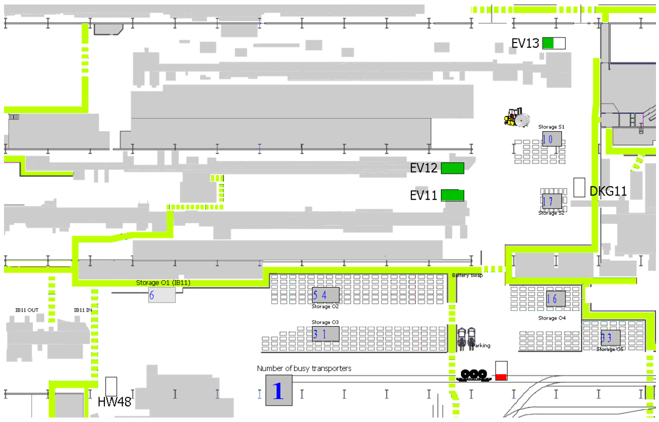

Fig. 5. Animation

validated by comparing the model outputs with real-world data on the number of coils flowing through the system and the turnover time percentiles. Besides, degenerate tests, extreme conditions tests and sensitivity tests explore the model behaviour.

VI. Experiments and Results

A. Experimental Plan

Two experiments were conducted, which resulted in many configurations. Each alternative is simulated with data representing the current situation based on historical data, and the future situation. In the future situation, EV11 will process more material, and the additional supply will originate from CA12.

The first experiment estimated which dispatching policy is preferred. The performance associated with all dispatching policies discussed in section IV-C are quantified. The 'combination' dispatching policy prioritizes the retrieval side. The priority assigned to the coils is based on the respective production line's queue size and capacity. A low number represents a high priority:

1) Output (EV11, EV12, EV13, IB11): 'Number of coils in queue'.
2) Input DKG11, HW48 & IB11: 1 + ('queue capacity' - 'queue size').
3) Input CA12 is assigned the lowest priority.
4) Tasks with the same priority level are prioritized based on the smallest distance.

The second experiment quantifies the effect of the number of forklifts on system performance. Fleet sizes of 1 to 4 forklifts are tested on all alternatives. For zone-based flow path layouts, the number of forklifts in a zone was at least one and at most two.

B. Results

Experiment 1 indicated the most effective performance on the 'combination' dispatching policy for all alternatives. Table I indicates the performance for all policies based on alternative 1 in the future state configuration. In general, the dispatching policy does not significantly influence the system's performance.

Policy	Performance
Random	86.1%
Combination	**87.6%**
SD	86.1%
MASP	86.5%
FCFS	85.5%

TABLE I
EXPERIMENT 1, ALTERNATIVE 1 FUTURE STATE DEMAND

The second experiment tested the performance of the alternatives and determined the minimum viable number of forklifts for each alternative. All configurations use the 'combination' dispatching policy. Table II indicates the performance and minimum number of viable forklifts. Alternative 1 and 3 use the same amount and type of forklift AGVs. A zone-based flow approach results in a performance deterioration. The savings in transport distance do not weigh up to the increase in material handling time from the additional trip from storage to the transfer location. Furthermore, by restricting the forklift to a zone, there is less flexibility to help out in the other zone, with more tasks queued at a particular moment. The performance of automated transport is lower than a human-operated transport system as indicated by the results, however, it is viable.

Configuration	Performance	Costs (TCO)
Baseline: 1 manual forklift	96.0%	M€ 4.67
Alternative 1: 2 forklift AGVs	87.5%	M€ 4.04
Alternative 2: 1 manual forklift; 1 AGV	89.9%	M€ 6.71
Alternative 3: 2 forklift AGVs	77.4%	M€ 4.04

TABLE II
EXPERIMENT 2, FUTURE STATE DEMAND

1) Cost Estimation: To estimate the Total Cost of Ownership (TCO), the capital (CAPEX) and operational (OPEX) expenditures, and the Weighted Average Cost of Capital need to be estimated. For a manual forklift, the OPEX are the salary for the forklift operators (5 FTE), lease of the forklift, maintenance, damages and fuel. The CAPEX of a forklift AGV are the cost for project management, basic & detailed engineering, AGV control system, IT, E&I, forklift AGVs, battery swapping station, erection & commissioning and a part unforeseen. The OPEX consists of a one-time production loss, maintenance, energy (charging) and IT support. To estimate the TCO, the following assumptions were made:

- An economic project life of 10 years.
- Expected year of commissioning is 2027.
- A WACC applicable to Tata Steel (confidential).
- Wages are increased by 1.5% annually.
- The reduced workload of the forklift operator in the 2^{th} alternative does not result in less FTE.

The costs (TCO) for the minimum viable configurations in experiment 2 have been added to table II. Alternatives 1 and 3 indicate the lowest TCO over the considered time frame of 12 years. However, the Internal Rate of Return (IRR) is

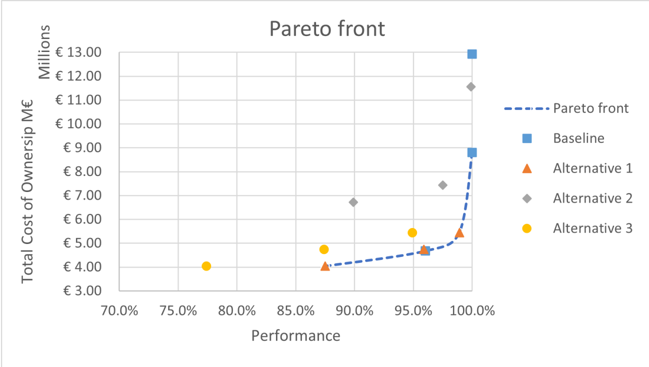

Fig. 6. Pareto Front

estimated at 6.4%. According to the IRR rule, suggesting that WACC≤IRR to accept the investment, an IRR of 6.4% does not result in an acceptable investment. It would suggest that the cost of financing is higher than the return on investment. Increasing the project scope likely results in an acceptable investment, as it would relatively decrease the project's overhead costs.

2) Pareto Front: In a multi-objective optimisation problem, there is a set of solutions that optimize the overall system if no solution dominates all other solutions on both objectives. A Pareto front can be established based on the non-dominated solutions, these are solutions of which an improvement in one objective comes only at the expense of the other objective [42]. Table III presents the metrics for the set of non-dominated solutions. Notably, alternatives 2 and 3 are excluded from the set of optimal system design configurations.

Configuration	Performance	Costs
Alternative 1: 2 forklift AGVs	87.5%	M€ 4.04
Baseline: 1 manual forklift	96.0%	M€ 4.67
Alternative 1: 4 forklift AGVs	98.9%	M€ 5.44
Baseline: 2 manual forklifts	100.0%	M€ 8.81

TABLE III
NON-DOMINATED SOLUTIONS

C. Conclusion

Alternatives 2 & 3 were outperformed on the costs and performance objectives. A zone-based flow path layout reduced the flexibility in the system and resulted in a decreased system performance. Alternative 1, a fully automated system, with a conventional bidirectional flow path layout and 2 forklift AGVs is selected as the most effective AGV system design. However, according to the IRR rule, the project is not financially attractive yet.

One of the objectives of implementing a zone-based flow path layout is to reduce travel distances. In this case study, the travel distances are relatively short, making the pick-up and drop-off times of the forklift AGVs a significant portion of the total material handling time. In industries or configurations where travel distances are longer and travel time is relatively large compared to pick-up and drop-off times, zoning may offer performance advantages. Nevertheless, the zone-based flow path layout in this study resulted in a decline in system performance compared to a conventional flow path design.

VII. Discussion

One limitation of this study is that not all aspects relevant to AGV system design are implemented. Routing and failure management did not seem important enough to the case study. Nevertheless, collision avoidance, which prevents deadlocks from occurring, is relevant to the case study. One of the benefits of a zone-based flow path layout is its ability to avoid deadlocks. However, the analysis did not account for the potential performance decrease in alternative 1 compared to alternatives 2 and 3 due to collision avoidance.

Another limitation involves the location of the transfer station. This location was chosen as it allows for the separation of material flows, however, it does not effectively balance the workload between the two zones. This caused the performance on the delivery side of alternative 3 to drop significantly with 1 forklift AGV, almost making the model unstable. Another transfer station location between the zones might balance the workloads more effectively, enhancing the performance of the AGV system design alternatives.

The decision to implement an idle-vehicle parking could be questioned. For baseline operations, this did enhance the performance. However, other approaches such as waiting at the last visited station were not tested for forklift AGVs. Further experiments on this topic and others should be conducted in future research to optimize performance.

Simplifying the storage location assignment does capture some of the real-world complexity. Nevertheless, as the exact storage position was not modelled, the delay for sorting operations could not be modelled either.

Another limitation lies in the modelling of production line downtimes. By simplifying downtime into constant values for frequency and duration (in both short and long categories), some of the stochastic variability inherent to a production system was lost. This simplification led to more stable inventory levels than those observed in historical data for the real-world system.

Regarding the cost estimation, an expense of 30% unforeseen project costs was included. If this expense were to be excluded, the IRR would be 14.6% resulting in a project return that does cover the cost of financing.

Lastly, the generalizability of the results poses a limitation. While the findings are highly case-specific, the overall process flow and new empirical insights within the manufacturing context offer valuable contributions to the literature.

VIII. Conclusion

This research presents the conceptual process for setting up a simulation study addressing integrated decision-making in AGV system designs for manufacturing facilities. The answer to the main research question of what in-plant automated transport system design facilitates effective material flow in a manufacturing facility is hard to generalize. A discrete-event simulation model is established, allowing multiple decision-making approaches related to AGV system designs to be incorporated. The results showed that a zone-based flow path layout performed worse compared to a conventional flow path layout. In this case study, the relatively short travel distances made the pick-up and drop-off times of forklift AGVs a significant part of the total material handling time. Zoning may provide performance advantages in industries or configurations with longer travel distances, where travel time constitutes a larger portion of the total time compared to pick-up and drop-off times.

The desired AGV system design configuration, a conventional flow path layout served by two forklift AGVs, could not be accepted based on the IRR rule. However, increasing the scope will likely result in a viable investment opportunity.

This paper's primary contribution is the presentation of new findings on the integrated AGV system design process in a manufacturing facility. An innovation is the integration of decision-making for storage location assignment and unit-load selection at the storage park level. The proposed approach reduces simulation time compared to modelling each individual storage position while providing more realistic model dynamics than models that simplify in-process inventory to a single station. Additionally, the design workflow and model implementation outlined in this study can be generalized for application in other research contexts.

This study opens many possibilities for future research. For example, a method for balancing the workload between zones in configurations with a high number of nodes and arcs due to an in-process inventory should be developed. Furthermore, a combination of dispatching policies resulted in the most effective performance for this system design. It would be interesting if sets of dispatching policies could perform effectively in a broader range of cases or across multiple industries.

This study presents a simplified approach to storage location assignment, focusing on the park level rather than the exact position. No simulation studies have been conducted on SLAP in the manufacturing industry for block or deep-lane storage facilities. The startup SLAPstack has demonstrated the ability to model SLAP for autonomous block-stacking warehouses [6]. One of the developers of SLAPstack successfully modelled the case for Tata Steel, where the Closest Open Pure Location storage assignment policy performed well. The first results revealed significant differences in system dynamics compared to the warehousing industry. In the case study, material arrivals followed the takt time of production lines rather than arriving in large batches to be stored or retrieved. These unique dynamics should be further explored to optimize the system operations for manufacturing facilities.

Acknowledgment

I would like to thank Ir. Mark Duinkerken and Dr. Ir. Arjan van Binsbergen of the Delft University of Technology for their guidance and valuable feedback. Although I had no previous knowledge on discrete-event simulation studies, they supported me throughout the process.

Moreover, I would like to thank MSc. Ewald Veenboer, my daily supervisor at Tata Steel IJmuiden, for offering me this opportunity and for his support throughout the project.

Lastly, I would like to express my gratitude to MSc. Alexandru Rinciog from the startup SLAPstack for adjusting his simulation software to model the case presented by Tata Steel, as discussed in the future research section. I greatly appreciated our conversations and his enthusiasm for supporting thesis projects.

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B

Actor Analysis

B.1. Stakeholders

B.1.1. Production Manager Temper Rolling

Name: S. Nguyen
Date: 22-3-2024
Department: Production Manager Workarea 3 (Temper Rolling)

Processes workarea 3: Both the DKG11 and HW48 are located in work area 3. Regarding the DKG11, it has a buffer storage of four coils at the exit on the walking bean. This walking bean makes sure the coils are positioned in a way that the forklift operator can grab the coil at the same position. Almost all coils coming from the DKG11 are stored in the S-hall. Regarding the HW48, a buffer storage of 2 coils is present. The N-hall crane positions the coils on a mat, so the forklift can reach it. In the past year the HW48 was often not in operation. One of their largest clients did not place any orders.

Data on coils which are being sent towards the IB11 from the DKG11 and HW48, is a bit harder to acquire. Sometimes coils contain multiple mistakes and only the last one is accounted for, which makes the data on the amount of coils being sent towards the IB11 unreliable. This data is available in a report of 'P. Runhardt'. However, 'A. Westendorp', a process engineer, may have much more reliable data on the number of coils being send towards the IB11. Sang mentioned that this is not a large number.

Recommendations: If the transport flows should be separated, the largest challenge would be the crossing in front of the HW48. It would be interesting to check the business case of using a O-hall crane to transport the coils exiting the HW48 over this crossing. In that case, the automated transport area can be a restricted area.

B.1.2. Production Manager Electroplating

Name: M. Mathot
Date: 26-3-3034
Department: Production Manager Workarea 4

Work area 4 contains the EV11, EV12 and EV13. The tinning process is a continuous process, therefore there are two unwinders and two winders for the steel coils. This allows for welding the coil that is being processed to the coil that is in line afterwards, and cutting them at the end. There is a buffer storage of two coils at the entrance of each EV. He mentioned that about 7% to 8% of the steel coils exiting the EV11, EV12 and EV13 are sent towards IB12. This causes a lot of additional storage and should be reduced. One way of doing this is by reducing damages from transport operations.

Regarding the transport flows mainly the scrap material was discussed. There are three types of scrap material:

1. Edge scrap (NL: kantschrot): This is in tonnage by far the most. Some clients want to reduce the width of the coil, an edge scissor (NL: kantschaar) cuts a strip of the coil. A pressing machine presses the scrap material to a dense package after which it is placed in a container by a magnet.
2. Remainder of the coil: The last part of the coil often contains damages, therefore this is thrown away along with the carton tube. This is picked up by a forklift.
3. Sheet metal scrap: The first part of the coil often contains damages, or the client requests less meters than the standard size, this causes scrap material. This is thrown away in a large container and picked up by a truck.

R. Pitstra, one of the team leaders in work area 4 will gather data on how often scrap material is gathered. Other transport flows that were discussed is the gate next to the entrance of EV13. There are a lot of golf carts and some forklifts that drive trough this gate. One of the alternative routes trough workarea 7 can't be taken since this is a HARA area, and contamination from the tires of the vehicles to the coils in the storage park is too big of a risk. The other alternative route for golf carts is around DKG11, which is quite a big detour, however it is possible. This would be a great option if all transport flows need to be separated from the to be implemented automated vehicles.

Recommendations: If I am not able to acquire the correct data, or want a better understanding of the process, than just looking at the process for several hours and making notes can help. Furthermore, coils exiting the DKG11 are often transported directly towards the EV lines, this saves transport movements to and from the storage area and should be taken into account.

B.1.3. Production Manager Transport and Storage Operations

Name: R. van der Haag
Date: 14-3-2024
Department: Production Manager Workarea 6

Current state analysis: Ron explained the process and logistics in the factory:

- The IB11 has a lot of backlog. The maximum amount of backlog should not increase 400 coils, however currently there are 650. This provides a large amount of storage in the O-hall in work area 4.
- The coils coming from the DKG11 and HW48 have priority to be stored in the O-hall for workarea 4, over the coils that are in line for IB11. So there can be assumed that all coils from DKG11 and HW48 can be stored in workarea 4.
- The operations of IB11 consists mainly of inspection and repair. Additional operations consist of black plating (applying an oil film to the sheet metal) and coils that go on 'arf', which means that the coil is coming from HW48 and needs to follow the renovation route. Black plating takes relatively a large amount of time, since the machine needs to be cleaned afterwards, this results in large stocks that are waiting for the IB11.
- Forklift operators receive their tasks via a screen on the forklift, this is that is linked to BLITS.
- Steel coils are often re-positioned, when a coils must be obtained that is not in the front row. However, data on this is hard to find, the coils that are temporarily re-positioned are put back afterwards. This data is not saved in the system, since the location of those rolls does not change in the end, so the operators do not scan those coils to assign their temporary location in the system.
- Input capacity for the EVs:
  1. In total PAC runs around 16kt per week.
  2. **CA12:** should run around 10kt per week. The goal is to achieve this objective every week.
  3. **HW48:** 5kt per week.
  4. **DKG11:** 4kt per week.
- The DKG is often put on OC, which means over capacity. Then the machines does not run because their is no supply, or because the storage parks are full.

- Steel coils coming from DKG11 must be sent to the EV12 or EV13 within **72 hours**, otherwise corrosion will take place.
- Data on the EV's
  1. **EV11:** The EV11 will only be supplied by the CA12, and coils coming from Trostre and Hartelstein (Maastricht) in the future situation. There wont ba any material flow between the DKG11 and HW48 towards the EV11. Capacity $\approx 250t/shift$. A shift is 8 hours, the machines run three shifts per day.
  2. **EV12:** The EV12 is supplied by the DKG11, HW48 and CA12. The DKG11 supplies approximately 70% to the EV12. Capacity $\approx 250t/shift$.
  3. **EV13:** The EV12 is supplied by the DKG11, HW48 and CA12. Capacity $\approx 350 - 380t/shift$.
- The exit of the DKG11 has a 'walking bean', this is a buffer that can store upto 4 coils and places them to the front so a forklift can reach it. The exit of the HW48 has a buffer of 2 coils, this can be expanded if needed. For the exit of the HW48, the coil needs to be lifted by a N-hall overhead crane for only several meters. If the automated transport to be implemented is able to do this, it would safe a significant amount of time and transport operations.

Recommendations and challenges:

- Check RM reports, contains data on throughput's and amount of storage between processes at the current moment.
- Check KnowledgeNet for more data on logistics.
- For the implementation of automated transport, investigate if it is possible to make it a 'protected' area. To make this happen, there needs to be a transshipment/storage area for the rolls coming from CA12. This flow is quite large and will otherwise hinder the operations of the automated transport.
- A challenge is the storage location assignment, a plan was proposed that every machine has one storage park. Since the fluctuations in stock may differ a lot, this plan was not implemented.
- Other challenges are to untangle the transport flows to the EVs (mainly the coils from CA12) and where to put the coils coming from the DKG because in the S-hall there is not a lot of storage area. Around 100 coils coming from the DKG can be waiting in line for the EVs, this can't all be soted in the S-hall of workarea 4.
- The intersection in front of the HW48 is the busiest in the entire factory, all coils from EV11, EV12, EV13 and EV14 that are stored in the U-hall go trough here towards the W- and T-hall. In addition, the transport towards IB11 crosses this intersection.
- Ask one of the teamleads of workarea 6 (Jeff Ranjit, Ruud Zwanepol, Pim de Zeeuw) to speak to one of the forklift operators.

B.1.4. Head of Supply Chain Planning

Name: T. Keetlaer
Date: 19-3-2024
Department: Supply Chain Planning

T. Keetlaer's department (Supply Chain Planning), plans which coils need to enter the machine. They don't plan the location of the coils in the storage facilities, nor the transport. The conversation lead to the following findings:

- When planning the machines, a minimum stock level is kept to be able to supply the machines downstream. If a storage park is full, no new order will be planned on the machines upstream.
- Coils coming from the DKG11 must be inserted into the EV12 or EV13 within 72 hours. For coils of which the DKG11 reduces the thickness less than 7%, the coils need to be inserted into the EV12 or EV13 within 24 hours, since these are very sensitive to corrosion.
- Work issues are made by the plannings tool RSP, which is connected to MOMS. In MOMS the forklift operators can see the work issues, so which coils need to be transported.
- A work issue states which roll needs to be transported to where, but does not indicate a time frame when the machine is available for that specific coil. The work issue states which orders need to be handled, and does not indicate a specific coil. Forklift operators will handle it as soon as there is capacity available at the machine.

- Orders that are scheduled on the DKG11 are planned on the EV lines at the same time. This makes sure there is enough capacity on the EV's so the coils won't corrode. When there is only 24h left before the coil from the DKG needs to inserted on the EV's a notification will pop up in MOMS.
- The intention is that orders got trough the EV's as one batch. In practice this does often not happen. The order in which the coils of one order are placed on the EV's is not important. The only condition is that two small coils can not be processed consecutively. This would cause the line to stop operations, since it is a continuous process and the coils need to be welded together at the beginning and grinded apart at the end.
- The forklift operator assigns a storage location himself. He tries to place rolls of the same order together as much as possible. It often happens that there are several orders in one row. If an order has to be inserted into the EVs which has other coils in front of it in the same row, relocations are necessary. This is called 'digging out'. There is no specific focus on minimizing these transport movements.
- The annual revision of an EV line takes about 10 days, with a maximum of 3 weeks.
- There is space for one coil as buffer storage, in addition to the coil being processed at that moment.

Challenges: Positioning of the coils in the storage park and safety regarding other modes of transport.

Recommendations: Make a plan B for when the automated transport option does not perform well. Production must not come to a standstill. Think about how the software and maintenance process will look like.

B.1.5. Infra

Name: W. Klijn
Date: 27-3-2024
Department: Infra

The infra department manages the roofs, the floors, cellars, pedestrian paths and more. The conversation with Wouter lead to the following findings:

- Most floors in the workarea 4 are in good condition. The floor in the O-hall has been renovated in 2005. The floors are made of 30cm double reinforced concrete. This can hold the manual operated forklifts. The only part that may cause problems is where the two concrete pourings join at the height of column 40 in the O-hall.
- Regarding the roofs, there are some leakages between columns 30 and 34 in the O-hall. There is a storage park underneath, leakages can result in corrosion on the coils.
- Automated vehicles have a way lower pressure on their axes than a manual operated forklift which results in less damages to the floors. However, small height differences in the floor may cause a problem for automated vehicles. The current manual operated forklifts are about 34T and their carrying capacity is 26.5T.
- EV11 will fall under workarea 7 which is a HARA area (restrictions relating to food safety). This may cause additional challenges and will be further discussed with Lydia van Mourik.
- Changing the current layout of the storage park is possible as long as this does not go beyond the current boundaries.

B.1.6. Commissioner

Name: E. Veenboer
Date: several dates
Department: Teamleader ODS
Commissioner and daily supervisor of this project

E. Veenboer, is the commissioner of the project and has given valuable support throughout the project.

Weekly conversations were held to discuss the progress and the setup of the project. The key decisions in which he played a significant role were formulating the alternatives and the decision to simplify the inclusion of the installation downtimes.

B.2. Employees ODS

B.2.1. K. Klijnsmit

Date: 14-3-2024
Department: ODS

Recommendations: Try to get as much data possible on the flow of transport movements. This are is one of the busiest areas in the factory, so really make sure it is feasible. Furthermore visualising the flows, with a **spaghetti diagram** for example would be really useful. EV11 which is now under maintenance will fall under workarea 7 when operations will start. This causes that the AGVs will go through many work areas:

1. Workarea 1: To reach storage park Ro6 the automated transport goes trough a small part of workarea 1.
2. Workarea 2: Not within scope. However, the CA12 which is in workarea 2, will cause many transport movements towards EV11, EV12, and EV13.
3. Workarea 3: Both DKG11 and HW48 are situated in workarea 3.
4. Workarea 4: The storages Ro1 - Ro6, Rs1 and Rs2 and the machines EV11, EV12 and EV13 are situated in workarea 4. Furthermore, the to be implemented automated transport happens almost only in workarea 4.
5. Workarea 5: Not within the scope, however, IB11 stores many coils in the O hall of workarea 4. The high number of transport movements towards IB11 and coils stored in the O-hall that are destined for IB11 cause, must be taken into account.
6. Workarea 6: Workarea 6 manages the transport, purchase of new vehicles/means of transportation, and storage of the products that are ready to be shipped.
7. Workarea 7: This part of the factory contains the LL11 and FL12, soon EV11 will be part of this area as well.

The production managers of the different work areas all have their own ideas on feasibility studies like this. It might be hard to reach consensus. To increase the likelihood of implementation, communication and inclusion of their input must be properly managed.
Data warehouse which can be reached through business objects in service now contains a lot of relevant data.

B.2.2. R. Somers

Date: 13-3-2024
Department: ODS

Current projects: Provide insight in how to improve PAC. He uses methods such as PPS (Practical Proble Solving), six sigma, **advanced analytics and data driven methods**. PPS solves the problem with a 7 step approach. PPS is event driven, and the method used for most projects. Six sigma is used when there are fluctuations/variations in the system. For larger problems a SWOT analysis is performed, during 14 weeks project-team works on this topic.

Bottlenecks in the operations: There is a lot of work for both IB11 and IB12, around 250t per shift (8h) of supply. The current BLITS system can only memorise 7 lanes deep, if an 8^{th} coil is placed in front, the location of the coil in the 1^{st} row is unknown in the system. This causes coils that are lost and need be searched for manually, for this 2FTE is needed. Furthermore a RFID system would be better than QR codes, then the position of a coil in a certain lane can be directly identified instead of the need to scan the QR code of every roll in that lane to know which on the operator needs. In addition coils have different weights, a coils of 20T and of 3T have other processing times, on which the transport must be based. Lastly, both the IB11 and IB12 have a lot of backlog. The routing of the rolls destined to these machines is difficult due to the narrow corridors and roller doors.

Data systems: There are many systems, R. Somers mainly works with Data Warehouse. Blits and Blits+ are older systems, it contains data on the entire coil history. MOMS contains data on specific topics. The data systems are divided into 4 levels.

Recommendations: Is there a shorter transport route to the IB11 and IB12? Base the study on travel times, not on transport distance, a fixed transport route is preferred. Another recommendation is to look at the bigger picture to identify the cause of problems.

Feasibility: Determine in which time frame a coil should be delivered to the next machine. Making assertions regarding costs/ROI requires hypothesis formulation in advance. Utilizing a project charter guides the inquiry process: what are the lead times, creating a tentative schedule. This provides a fixed reference point. Besides iterating between several alternative designs.

B.2.3. T. Pie

Date: 14-3-2024
Department: ODS

AGV feasibility study work area 1: T. Pie mentioned the following things about the feasibility study he did for the implementation of AGVs in workarea 1:

- The area is from the pickling lane to 3 storage areas and then to the KW11 and KW12.
- There are huge fluctuations in inventory levels. The pickling lane supplies both the narrow and wide routes. If there is maintenance on one route it causes a lot of inventory. His inventory study was based on the data from 2021 and 2022.

Recommendations and challenges: For my project the mentioned challenges were order completeness, it is challenging to determine the individual accessibility of certain positions and then there is the trade-off between inventory capacity and available space. Regarding their data management systems, the WMS is offered by different vendors (konecranes and 3tn). This is not well integrated, take the integration with current warehouse management systems into account. Furthermore, the option of storing the coils in the height on a cantilever racking system was discussed.

B.2.4. L. van Mourik

Date: 19-3-2024
Department: ODS

L. van Mourik continuously improves processes regarding food safety and contamination of the coils. Food safety is often referred to as HARA (Hazard Analysis and Risk Assessment). Her recommendations were the importance of being able to track the coils. Furthermore, in storage park Ro1, there are coils that have finished all processes besides the IB11. These are highly sensitive to contamination. In addition the transport from the U-hall towards the W and T hall, is also a point of attention. Transporting the coils from the U-hall through the upper part of the factory could be a solution for both problems. The by-catch for this project is less transport that intersects with automated transport from the HW48.

B.2.5. S. Kleijn

Date: 14-3-2024
Department: ODS

Current projects: S. Kelijn works at Tata Steel for several months, one of her main projects is investigating possible alternatives to the narrow tracks that run trough the factory of Packaging. The Transport Vision which has been set up in October 2016 states a vision for 2025, where both AGVs and automatic cranes will be deployed [64]. The current state as stated in the vision of 2016 states:

1. The transport operations take 113FTE

2. It is inefficient and it is not well directed (when which task has to be performed)
3. There is a lot of transport damage (pick up and put down, unfavorable layout, human action)
4. There are too many different transport options (AGV, narrow tracks, forklift, overhead cranes, industrial trailers, cross transport)
5. Modes of transport are outdated, high sensitivity to malfunctions, high maintenance

The transport vision indicates to deploy AGVs almost everywhere to have one robust system. Automated overhead cranes in the receiving and shipping halls (H2BA, E, W and T hall) will be used as well. Both should be scheduled by the Warehouse Management system. However, due to the large amount of costs and downtime, the plan was not implemented.
Momentarily, Sarah's study indicates that forklifts are not the best alternative to the narrow tracks since forklifts need maintenance often, it damages the floor, forklift drivers have a high workload already, it will increase the amount of lost steel coils and it will bring additional transport damage.

Method: S. Kleijn follows the steps current situation, problem definition, possible additional benefit, option selection and recommendation. By separating additional benefits from the main problem, it is easier to choose an alternative.

C

Previous Studies

Previous studies on AGVs are discussed in this section. This inclusion aims to identify opportunities for implementing automated vehicles, describe potential bottlenecks, and gather insights on the implementation process. Only the project at koudband 2 was realized.

C.1. Transport Vision for 2025

In 2016 a transport vision for the year 2025 was made for Packaging IJmuiden [64]. The study sorted out the current transport, the routes, trajectories, vehicles, occupation, costs, and other aspects. This resulted in a future state proposal where 20 AGVs would be deployed and automated cranes in the arrival and departure hall (E, W- and T-hall) and for the transport around the batch annealing (H_2BA) process. This would result in an expected cost reduction 47.2%. From €12.500.00/year (of which €8.000.000 is personnel), to €6.600.000/year. The implementation of automated transport would reduce the personnel from 113FTE to 33FTE.

Some processes have been automated, however, major transports, planning, logistics and their optimization are still taking place largely by hand. By applying an intelligent WMS, it is possible to reduce the amount of transport operations. The document states that the clustering of coils for batch transport is not economically interesting, not even for long-distance transport due to the additional organisation, planning, different maintenance and handling of coils. Therefore the one-piece flow with automated forklifts is preferred.

A characteristic of AGVs are their slower speed than manual forklifts, however, they do operate according to the schedule made by the WMS. Other advantages with regard to the AGV include safety, emissions, noise, steering load, energy consumption, stability and operational costs. The manual forklift only scores better on flexibility and investment costs. Based on the speed of installations the amount of handling operations were calculated, which resulted in 1 or at most 2 automated forklifts for the scope of this project. This has not been validated with a quantitative model.

The conclusion states the need for a robust coil tracking system, RFID is recommended. Another requirement for the implementation of AGVs is control by the Warehouse Management System. The recommendations indicate to implement AGVs in 6 phases, where there are clear take-over locations between manual and automated forklifts. Besides, the separation of transport for production and maintenance is recommended, by using overhead cranes for maintenance. Investments can be limited by operational lease contracts.

C.2. AGV Study Work Area 1

The scope of this research is to implement automated vehicles in work area 1 between the pickling and cold-rolling installations. This study was ultimately not carried out. In between the installations, three storage parks are present with a combined storage capacity of 420. The forklifts have to cross the same ’highway’ as presented in Figure 4.2 and additionally a track. Therefore, the challenges are

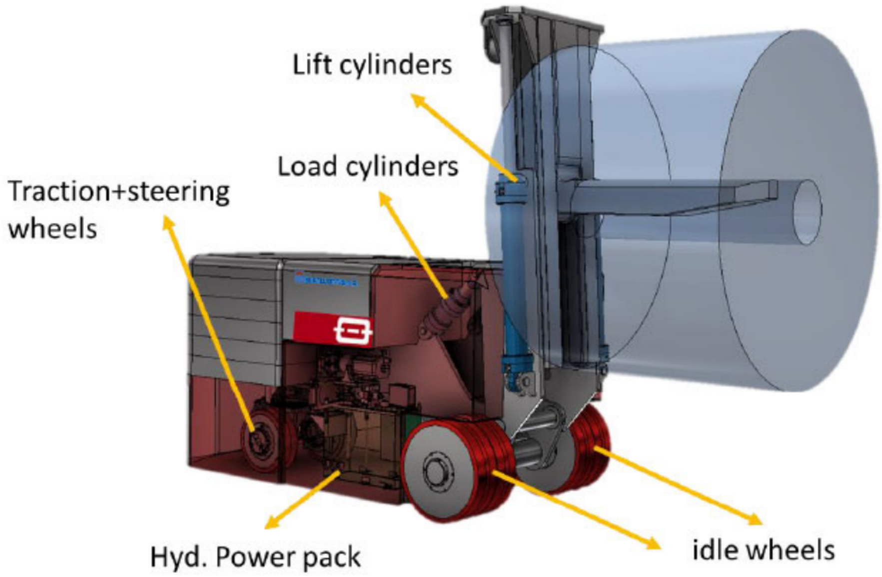

Figure C.1: Proposed AGV for workarea 1: Bertolloti [45]

similar. The proposed AGV has the same technical characteristics (turning radius, lifting height etc.) as the manual operated forklifts. It drives autonomously and is electrically powered. A figure of the AGV is presented in Figure C.1.

Indicated disadvantages are the high floor load (due to the counterweight); low speed, the relation between the number of manual operated forklifts and AGVs needed is about 1:2; the AGV stops automatically when other traffic or objects are in the vicinity which could lead to high down-time if not sufficiently included in the scope. The investment costs of this project are €3.400.000 including 30% unforeseen expenses. Relevant design criteria for the implementation of AGVs have been included in section 5.1. The project would result in a reduction of 5FTE's. However, due to the small scope of this project the overhead costs in relation to the price of one AGV are high. Automating the transport for an additional workarea would significantly increase the profitability.

Furthermore, the study indicates options for reducing down-time of the AGVs by crossing traffic. Some of the options are reducing crossing traffic by letting them take detours and avoiding the intersection, a crossing with traffic lights and/or barriers and separating pedestrian flows. Besides, the impact on the choice of the Warehouse Control System is discussed as well. The focus should be on strategic decision making to enable the implementation of the same system in subsequent projects.

C.3. Koudband 2 - Confidential

D

Data Analysis

This appendix first describes, the MSA (Measurement System Analysis). Furthermore data analysis on the size of orders and how many coils of the same order arrive consecutive after one another at the same installation is presented. Finally, data on the pick-up and drop-off duration's for AGVs are calculated.

D.1. Measurement System Analysis

D.1.1. Data obtained from Data Warehouse

This data below indicates the reliability for the data obtained form data warehouse for the period April 2022 till April 2024. The data indicates that about $\frac{1}{3}$ of the data is unreliable. Therefore there has been decided to obtain data from level 2, the database.

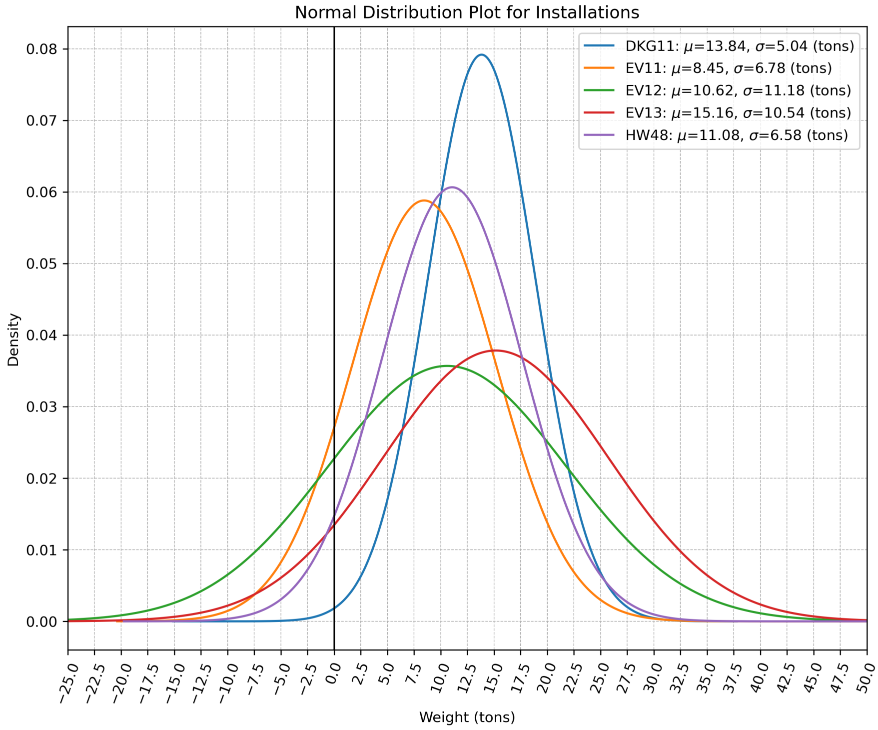

Figure D.1: Normal distributions of the weight. Data obtained from DataWarehouse for the past 2 years.

Installation	Mean, μ	Median	Mode	Mode Count	Min	Max	σ	μ + σ	μ + 2σ	μ + 3σ
DKG11	13.84	14.18	0.00	449	0.00	22.67	5.04	18.88	23.92	28.96
EV11	8.45	9.70	0.00	2018	0.00	41.68	6.78	15.24	22.02	28.81
EV12	10.62	9.62	0.00	11723	0.00	122.62	11.18	21.80	32.98	44.16
EV13	15.16	11.20	0.00	2883	0.00	51.60	10.54	25.71	36.25	46.80
HW48	11.08	10.64	0.00	4297	0.00	46.39	6.58	17.66	24.24	30.81

Table D.1: Statistics for installations, weight in tons. Data obtained from DataWarehouse for the past 2 years.

D.1.2. Transport operations data from the database

The data to measure the transport operations has been filtered first based on the following observations:

- There are duplicate coil ID's present in the data.
  - Most of the coils with duplicate ID's are saved twice, where one of the weights is less than 1 ton. The coils with the least weight which was handled was processed at almost the same time is therefore removed from the dataset.
  - Some duplicate ID's indicate that a coil has been processed by the DKG11 or HW48 twice, or that a coil has been processed by both of these installations. These transport operations are not within the scope of being automated. Therefore, these duplicate ID's have been removed as well.
- Some coils (less than $0.4 \cdot 10^{-3}\%$) have values above 26.5kt. This is not possible in reality, however, for counting the amount of transport operations these values have been saved in the data.
- After removing duplicates with the least weight, there were still some coils with a weight less than 1kt (less than $2 \cdot 10^{-3}\%$). These coils were kept due to the possibility of inaccuracies in weight determination, although they likely still prompted transport operations.

After the data was filtered, a normal distribution was drawn based on the weight of the coil as presented

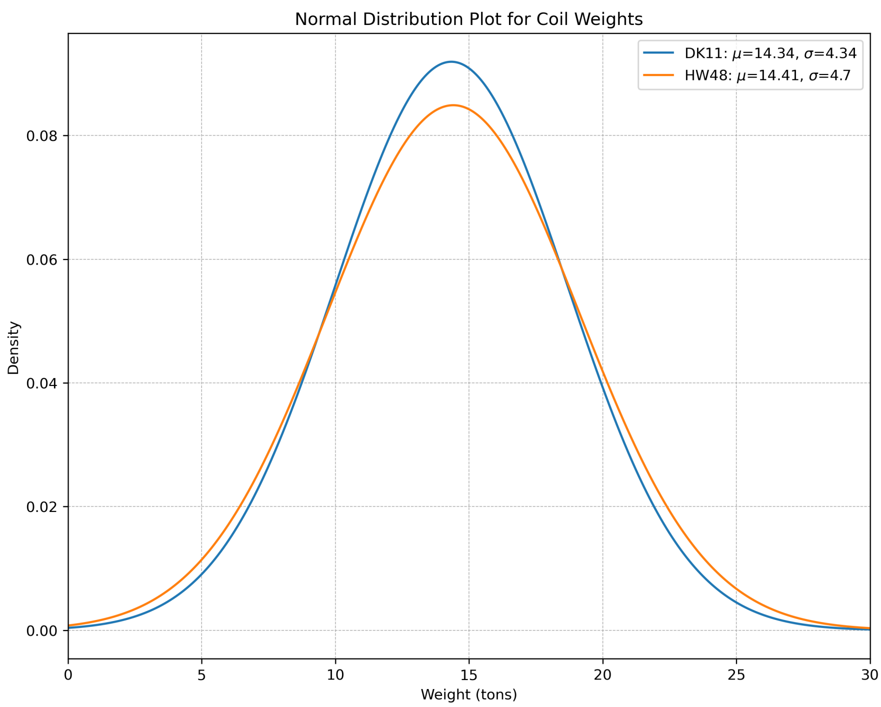

Figure D.2: Normal distribution w.r.t. weight based on database/mainframe data

Table D.2: Statistics of Coil Weights by Origin in tons

Origin	Mean, μ	Median	Mode	Mode Count	Min	Max	σ	μ + σ	μ + 2σ	μ + 3σ
DK11	14.34	14.30	0.0	30	0.0	22.80	4.34	18.68	23.02	27.36
HW48	14.41	14.57	0.0	18	0.0	46.39	4.70	19.11	23.81	28.51

The statistics indicate a reliability of at least 95.45% based on μ + 2σ. The μ + 3σ, or 99.73% of the data is not accurate anymore. This analysis suggests that the present approach yields more robust results compared to data from Data Warehouse, and appears to be sufficiently reliable for drawing conclusions.

D.2. Coil batching

The number of coils in an order varies. Supply chain planning aims to schedule coils from the same order consecutively on a single installation, allowing them to be shipped as one batch. This strategy also reduces the need to dig out coils in storage parks, as filling a specific lane with coils of the same order becomes more feasible. Based on the retrieved data there can be examined whether consecutive coils are from the same order or if their sequence is random. For the period from 1-2-2022 to 31-7-2022, the data was grouped by installations. The order sizes were then determined (Table D.4), as well as the number of consecutive coils processed through the same installation (Table D.3). Findings show that the size of consecutive coils going trough the same installation is way smaller than the order sizes. Therefore it is quite random. The data clearly indicates that coils are scheduled according to their orders. This has been incorporated into the simulation model.

Number of coils from the same order consecutive trough the same installation	Occurence	Number of coils from the same order consecutive trough the same installation	Occurence
1	3212	28	8
2	1600	29	5
3	1069	30	3
4	841	31	5
5	535	33	2
6	374	34	2
7	277	35	2
8	206	36	4
9	138	37	1
10	125	38	6
11	80	39	7
12	92	40	1
13	44	41	2
14	44	42	4
15	37	43	2
16	40	44	1
17	33	45	3
18	26	46	1
19	25	47	2
20	24	48	1
21	13	53	1
22	6	56	1
23	9	61	1
24	8	62	1
25	8	74	4
26	7	77	2
27	10		

Table D.3: Number of coils from the same order consecutive trough the same installation

Size of order	Occurrence	Size of order	Occurrence	Size of order	Occurrence
1	635	42	7	100	2
2	611	47	7	116	2
3	570	24	7	144	2
4	493	37	7	135	2
5	389	27	6	45	2
6	296	48	6	57	2
7	219	39	6	61	2
8	213	28	6	143	1
9	163	34	6	111	1
10	107	50	5	83	1
12	75	29	5	269	1
11	68	75	4	242	1
13	65	54	4	174	1
14	58	41	4	56	1
17	45	35	4	224	1
16	38	33	4	53	1
15	32	74	4	65	1
19	29	38	3	69	1
20	23	46	3	113	1
21	22	31	3	125	1
18	21	79	3	173	1
22	15	43	3	177	1
25	14	73	3	189	1
30	13	52	3	309	1
26	13	67	2	62	1
23	12	40	2	66	1
32	9	44	2	82	1
36	7	72	2	90	1
49	7	70	2	491	1

Table D.4: Order size

D.3. Pick-up and drop-off durations

Table D.5: AGV pick-up at installation & pick-up at storage minimum duration

Path length (m)	Radius (m)	Speed (m/s)	Time (s)	Type
0.0	0	1 to 0.4	2.6	Acceleration
3.9	2.5	0.4	9.8	Elbow
0.0	0	0.4 to 0.3	0.4	Acceleration
3.0	0	0.3	10.0	Operating Hazard Speed
	0	0	8.0	Searching Hole
	0	0	10.0	Loading
0.0	0	0 to 0.3	1.3	Acceleration
3.0	0	0.3	10.0	Operating Hazard Speed
0.0	0	0.3 to 0.4	0.4	Acceleration
3.9	2.5	0.4	9.8	Elbow
0.0	0	0.4 to 1	2.6	Acceleration
			64.8	

Table D.6: AGV drop-off at installation & drop-off at storage minimum duration

Path length (m)	Radius (m)	Speed (m/s)	Time (s)	Type
0.0	0	1 to 0.4	2.6	Acceleration
3.9	2.5	0.4	9.8	Elbow
0.0	0	0.4 to 0.3	0.4	Acceleration
3.0	0	0.3	10.0	Operating Hazard Speed
	0	0	10.0	Unloading
0.0	0	0 to 0.3	1.3	Acceleration
3.0	0	0.3	10.0	Operating Hazard Speed
0.0	0	0.4 to 0.3	0.4	Acceleration
3.9	2.5	0.4	9.8	Elbow
0.0	0	1 to 0.4	2.6	Acceleration
			56.8	

Table D.7: AGV pick-up at storage park maximum duration

Path length (m)	Radius (m)	Speed (m/s)	Time (s)	Type
0.0	0	1 to 0.4	2.6	Acceleration
3.9	2.5	0.4	9.8	Elbow
0.0	0	0.4 to 0.3	0.4	Acceleration
9.0	0	0.3	30.0	Operating Hazard Speed
	0	0	8.0	Searching Hole
	0	0	10.0	Loading
0.0	0	0 to 0.3	1.3	Acceleration
9.0	0	0.3	30.0	Operating Hazard Speed
0.0	0	0.3 to 0.4	0.4	Acceleration
3.9	2.5	0.4	9.8	Elbow
0.0	0	0.4 to 1	2.6	Acceleration
			104.8	

Table D.8: AGV drop-off at storage maximum duration

Path length (m)	Radius (m)	Speed (m/s)	Time (s)	Type
0.0	0	1 to 0.4	2.6	Acceleration
3.9	2.5	0.4	9.8	Elbow
0.0	0	0.4 to 0.3	0.4	Acceleration
9.0	0	0.3	30.0	Operating Hazard Speed
	0	0	10.0	Unloading
0.0	0	0 to 0.3	1.3	Acceleration
9.0	0	0.3	30.0	Operating Hazard Speed
0.0	0	0.4 to 0.3	0.4	Acceleration
3.9	2.5	0.4	9.8	Elbow
0.0	0	1 to 0.4	2.6	Acceleration
			96.8	

Table D.9: Battery swapping duration

Path length (m)	Radius (m)	Speed (m/s)	Time (s)	Type
0.0	0	1 to 0.4	2.6	Acceleration
3.9	2.5	0.4	9.8	Elbow
0.0	0	0.4 to 0.3	0.4	Acceleration
5.7	0	0.3	19.0	Operating Hazard Speed
	0	0	10.0	Unloading
0.0	0	0	480	Battery Exchange
0.0	0	0 to 0.3	1.3	Acceleration
5.7	0	0.3	19.0	Operating Hazard Speed
0.0	0	0.4 to 0.3	0.4	Acceleration
3.9	2.5	0.4	9.8	Elbow
0.0	0	1 to 0.4	2.6	Acceleration
			554.9	

D.4. Transport Network

	Transfer	Battery	Parking	Parking 2	HW48	DKG11	CA12	IB11 in	IB11 out	EV11	EV12	EV13	O1	O2	O3	O4	O5	S1	S2
Transfer	-	20	25	15	155	55	40	145	165	20	25	98	110	60	60	40	55	38	30
Battery	-	-	10	25	135	70	25	125	145	35	40	113	90	40	40	20	35	53	45
Parking	-	-	-	40	135	80	15	125	145	45	50	123	90	40	40	20	35	63	55
Parking 2	-	-	-	-	165	65	55	155	175	25	30	103	120	70	70	50	65	23	15
HW48	-	-	-	-	-	205	150	85	105	170	175	248	50	95	95	145	160	188	180
DKG11	-	-	-	-	-	-	95	205	225	49	44	57	170	110	110	90	105	40	30
CA12	-	-	-	-	-	-	-	140	160	60	65	138	105	55	55	35	50	78	70
IB11 in	-	-	-	-	-	-	-	-	25	160	165	238	40	85	85	135	150	178	170
IB11 out	-	-	-	-	-	-	-	-	-	180	185	258	60	105	105	155	170	198	190
EV11	-	-	-	-	-	-	-	-	-	-	5	92	125	75	75	55	70	32	24
EV12	-	-	-	-	-	-	-	-	-	-	-	87	130	80	80	60	75	27	29
EV13	-	-	-	-	-	-	-	-	-	-	-	-	203	153	153	133	148	60	83
O1	-	-	-	-	-	-	-	-	-	-	-	-	-	50	50	100	115	143	135
O2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	50	65	93	85
O3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	50	65	93	85
O4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	15	73	65
O5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	88	80
S1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	15
S2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table D.10: Distance matrix in meters

D.5. Validation

The table below is a hand calculation of the utilization rate of the forklift. The ratio between the empty and loaded distance has been retrieved from the simulation model. The Arena simulation model indicates a value of 37.8%, which is 0.9% more than the analytical calculation of 36.9%.

Origin	Destination	Number of operations	Distance (m)	Distance on route (km)
Storage O-Hal	EV11	2408	72	173
Storage O-Hal	EV12	2115	77	163
Storage O-Hal	EV13	6998	150	1049
Storage S-Hall	EV11	993	29	29
Storage S-Hall	EV12	3639	28	101
Storage S-Hall	EV13	1351	69	94
IB11 Storage (Ro1)	IB11 in	1215	40	49
HW48	Storage O-Hal	7400,0	113	836
HW48	IB11 Storage (Ro1)	1162	50	58
DKG11	Storage S-Hall	5983,0	99	590
DKG11	IB11 Storage (Ro1)	53	170	9
CA12	Storage O-Hal	3995,0	52	207
IB11 uit	Storage O-Hal	126,0	131	16
				3373

Ratio distance unloaded vs loaded according to simulation model
1,56

Category	Distance (km)	Speed (km/h)	Duration (h)
Loaded	2912	7,2	404,4
Unloaded	4543	7,2	630,9
Total			1035,4

Operation	Duration (s)	Number of operations	Duration (h)
Pick-up	20,5	37438	213,2
Drop-off	25,3	37438	263,1
Rotation	40,4	8214	92,2
Total			568,5

Total duration (h)	1603,9
Lentgth data period (h)	4344
Occupancy rate forklift	36,9%

Figure D.3: Validation of the utilization rate

E

Vehicle Specifications - Confidential

F Results

This section shows the complete results of the experiments corresponding to section 7.2 and the cost estimation corresponding to section 7.3.

F.1. Simulation Model Experiments

The results for the simulation model are indicated in Table F.3 for experiment one and two, on the next page.

The first experiment is performed with the minimum viable number of vehicles. The second experiment is performed with the 'combination' dispatching policy. Meaning, 1 forklift for the base case, 2 AGV's for alternative 1, 1 forklift and AGV for alternative 2, and 2 AGV's for alternative 3.

The tables below indicate the main results for the current state with the 'combination' dispatching policy. Table F.1 indicate the KPIs, Table F.2 indicate the Performance Indicators (PIs). The results follow a similar pattern to those observed in the future state configuration, leading to consistent conclusions.

	Base Case	**Alternative 1**	**Alternative 2**	**Alternative 3**
Performance	98.6%	93.6%	94.1%	88.2%
Costs (TCO)	M€ 4.67	M€ 4.04	M€ 6.71	M€ 4.04
Preference Rank	1	2	4	3

Table F.1: Key Performance Indicators, current state configuration

	Base Case	**Alternative 1**	**Alternative 2**	**Alternative 3**
Average utilization rate (%)	38.2%	51.8%	36.2%	54.0%
Service time delivery <10 min (%)	95.9%	89.1%	94.0%	77.3%
Service time retrieval <10 min (%)	99.9%	95.8%	94.1%	93.6%
Avg. service time delivery (min)	3.9	8.1	4.6	12.6
Avg. service time retrieval (min)	2.7	6.5	5.9	6.7
CAPEX	-	M€ 2.26	M€ 1.72	M€ 2.26
OPEX	M€ 4.67	M€ 1.79	M€ 4.99	M€ 1.79
Total Cost of Ownership	M€ 4.67	M€ 4.04	M€ 6.71	M€ 4.04
IRR	-	6.4%	No project return	6.4%
Preference Rank	1	2	4	3

Table F.2: Performance Indicators, current state configuration

		Occupancy Rate (%)		Avg. Service Time Delivery (min)		Avg. Service Time Retrieval (min)		Max Service Time Delivery (min)		Max Service Time Retrieval (min)		Service Time Delivery <10 min (%)		Service Time Retrieval <10 min (%)	
		Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future
Base Case	Random	38.2%	46.7%	3.70	4.72	2.73	2.91	33.20	34.02	22.84	23.99	97%	93%	100%	99%
	Combination	38.4%	46.9%	3.92	5.23	2.66	2.74	36.82	51.54	12.38	12.99	95.9%	89.1%	100.0%	100.0%
	SD	38.1%	46.7%	3.71	4.71	2.73	596.90	27.48	34.59	22.64	24.36	97.4%	92.9%	99.8%	99.4%
	MASP	38.3%	46.8%	3.89	5.17	2.71	2.80	36.44	49.73	14.28	21.42	96.2%	90.2%	100.0%	99.9%
	FCFS	38.1%	46.6%	3.70	4.69	2.74	2.92	29.94	34.43	23.29	22.75	97.5%	93.0%	99.7%	99.4%
Alternative 1	Random	51.8%	63.4%	7.69	9.61	6.62	7.17	50.77	99.35	40.27	57.89	89.3%	76.2%	94.9%	91.0%
	Combination	51.9%	63.8%	8.15	10.96	6.47	6.82	80.91	161.77	27.34	32.96	89.3%	76.0%	96.0%	93.4%
	SD	51.8%	63.4%	7.69	9.60	6.62	67.19	60.93	94.85	40.90	57.67	89.3%	76.2%	94.9%	91.1%
	MASP	52.0%	63.7%	8.06	10.50	6.52	6.92	76.26	132.12	39.82	42.84	89.0%	75.1%	95.5%	92.2%
	FCFS	51.9%	63.5%	7.67	9.54	6.64	7.28	48.26	72.64	42.87	54.35	89.3%	75.8%	94.8%	90.4%
Alternative 2	Random	36.1%	44.8%	4.42	5.06	5.95	6.55	41.55	58.30	56.70	85.77	95.7%	91.4%	93.6%	90.7%
	Combination	36.2%	44.9%	4.61	5.58	5.89	6.46	62.73	138.95	45.38	54.28	94.0%	87.4%	94.1%	91.3%
	SD	36.1%	44.9%	4.41	5.07	5.93	6.57	43.90	72.19	55.88	83.64	95.9%	91.3%	93.7%	90.6%
	MASP	36.2%	44.9%	4.58	5.47	5.90	6.46	68.38	102.17	49.86	62.09	94.3%	88.8%	94.2%	91.2%
	FCFS	36.1%	46.6%	4.42	5.05	5.93	6.57	37.75	48.80	49.25	63.08	95.8%	91.1%	93.7%	90.3%
Alternative 3	Random	53.6%	67.8%	10.77	17.57	6.35	7.02	151.42	853.80	65.40	93.00	77.8%	52.8%	92.5%	88.8%
	Combination	54.1%	68.8%	12.61	23.60	6.17	6.70	386.86	697.02	38.85	63.84	77.3%	51.9%	93.5%	90.3%
	SD	53.7%	67.8%	10.75	17.54	6.33	7.03	150.98	726.36	61.15	83.16	78.1%	53.0%	92.8%	88.6%
	MASP	54.1%	68.7%	12.34	24.09	6.25	6.83	246.05	1173.00	90.59	105.84	76.9%	49.2%	93.2%	89.7%
	FCFS	53.7%	67.4%	10.66	16.13	6.36	7.13	91.17	119.62	58.96	79.92	77.9%	53.9%	92.4%	88.1%

		Occupancy Rate (%)		Avg. Service Time Delivery (min)		Avg. Service Time Retrieval (min)		Max Service Time Delivery (min)		Max Service Time Retrieval (min)		Service Time Delivery <10 min (%)		Service Time Retrieval <10 min (%)	
		Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future
Base Case	1 Forklift	38.2%	47.0%	3.9	5.3	2.7	2.7	36.8	43.7	12.4	11.7	95.9%	88.1%	99.9%	100.0%
	2 Forklifts	19.6%	24.3%	2.6	2.9	2.3	2.2	15.0	12.8	6.1	6.6	100.0%	99.9%	100.0%	100.0%
	3 Forklifts	13.1%	16.3%	2.4	2.4	2.2	2.2	7.2	8.4	5.5	5.1	100.0%	100.0%	100.0%	100.0%
	4 Forklifts	9.8%	12.1%	2.3	2.2	2.2	2.2	7.1	6.3	5.4	5.3	100.0%	100.0%	100.0%	100.0%
Alternative 1	1 AGV	-	-	41.0	61.1	11.6	14.1	1722.5	2560.8	148.4	546.5	38.5%	24.0%	51.6%	31.6%
	2 AGVs	51.9%	63.8%	8.1	11.0	6.5	6.8	88.1	121.6	26.5	34.8	89.1%	76.0%	95.8%	93.2%
	3 AGVs	35.1%	43.5%	6.3	6.9	6.0	6.0	37.5	40.1	18.8	2.1	96.0%	89.6%	99.6%	99.1%
	4 AGVs	26.3%	32.8%	5.9	5.9	6.0	5.9	26.9	25.3	13.1	16.4	99.1%	97.2%	99.9%	99.8%
Alternative 2	1 Forklift/ 1 AGV	36.2%	45.0%	4.6	5.6	5.9	6.5	63.2	144.6	45.0	59.5	94.0%	87.3%	94.1%	91.2%
	1 Forklift/ 2 AGV	24.8%	30.9%	4.0	4.7	4.7	4.6	26.4	29.9	19.1	20.6	97.2%	93.0%	99.9%	99.8%
	2 Forklifts/ 2 AGV	18.6%	23.3%	3.3	3.3	4.7	4.6	17.2	20.8	18.4	19.0	100.0%	100.0%	99.9%	99.8%
Alternative 3	1 AGV/ 1 AGV	54.0%	69.0%	12.6	23.6	6.2	6.7	267.0	596.8	53.7	51.1	77.3%	51.9%	93.6%	90.2%
	2 AGV/ 1 AGV	36.6%	46.9%	7.3	8.6	6.1	6.6	68.3	135.4	45.5	55.9	90.7%	79.7%	94.1%	91.2%
	2 AGVs / 2 AGVs	28.0%	35.9%	6.7	7.8	4.9	4.8	42.1	53.9	20.4	21.8	93.9%	85.0%	99.9%	99.8%

Table F.3: Results experiment 1 and 2 respectively

F.2. Costs Estimation - Confidential

F.3. Chosen AGV Supplier - Confidential

G

EV11 future situation - Confidential

H
SLAPstack

This appendix introduces SLAPstack, a block-stacking warehouse simulation able to model the material flow including the Storage Location Assignment Problem (SLAP) [44]. First the software will be explained in section H.1. Secondly the implementation of the conceptual model into SLAPstack software is discussed in section H.2. Finally, the first results are discussed (section H.3). The case has been implemented by the startup SLAPstack, through which results are obtained.

H.1. Background

SLAPstack is a discrete event simulation framework for Autonomous Block Stacking Warehouses (ABSW), wherein products are kept in storage on the ground and/or stacked on top of each other. The framework embeds the Storage Location Assignment Problem (SLAP), Unit Load Selection Problem (ULSP) and Vehicle Dispatching Problem (VDP) [44]. The software has been further developed to embed the Unit-Load Relocation Problem (ULRP) as well. This allows Autonomous Mobile Robots to perform reshuffle task. Besides, collision avoidance is implemented, resulting in an approach that comes close to reality.

Each product is assigned a Stock Keeping Unit (SKU). In the case of Tata Steel, this is the order number. SLAPstack divides the floor space into storage bays and aisles. Since a manufacturing environment has a different layout compared to warehouses, the functionality of the tool was modified in order to include manufacturing layouts. The software is capable of modeling a wide range of storage location assignment and dispatching policies. For storage location assignment, it supports strategies such as Class-Based (CB) storage, which minimizes travel time by assigning high-demand SKUs to high-turnover zones. Additionally, other policies like 'Random', 'Closest Open Location', and 'Pure Lane Delivery' can also be implemented.

The input to the simulation model are the warehouse layout, an order list, the number of AMRs together with their speeds, the warehouse unit distance and the initial SKUs in storage. Each event can be of the type delivery or retrieval. The events are added to the main event queue, wherein events are sorted by there arrival time. Therefore, dispatching is done in a FIFO fashion. Whenever a delivery events pops up, the closest available AMR is picked for the job. The AMR route and travel time are computed using the Dijkstra shortest path algorithm.

An agent controlling the simulation selects an appropriate open storage location during empty transport to the load it is picking up. The lane of the respective position gets locked by the agent whenever a position within that lane is selected to retrieve or deliver a product from/to. As a result, the lane cannot be used for retrieval or delivery until the locking event finishes. If upon a retrieval task the item is blocked by other items, the AMR incurs a time penalty for every item it shifts away to reach the desired position. The hole that results from such a retrieval is plugged by pushing the items lane inwards.

Regarding the Unit-Load Relocation Problem, this can be divided into unwanted relocation's, and sorting. This strategy will reposition units, such that the lanes are ideally homogeneous. Unwanted relocation's occur if the coil that needs to be retrieved from the inventory is blocked by coils in front of it. Each obstacle needs to be moved to another storage position until the target coil can be reached. Each move consists of, material handling time for pick-up, a storage decision, a routing decision, the calculation and traversal of the path and material handling time for drop-off.

Sorting relocation's can be divided into entropy breaking and lane filling. Sorting only occurs if there are no queued delivery or retrieval orders. So it is always done during off-times. This approach is especially useful since the chances are quite high that not only the targeted, problematic coil is going to get sorted, but all in front of it as well.

As long as there is entropy (lanes containing multiple SKUs), and there is at least one open lane, and no delivery order that needs to be processed, the reshuffling heuristic will run. The heuristic chooses the most problematic SKU in the lane, generating the most 'disorder'. If this SKU is deep in the lane, it follows that reshuffling will occur.

The lane filling scheme runs as long as there are pairs of homogeneous lanes containing the same SKU that are not full. However, this is not accounted for in the pallet shift metric, since the first coil is always the source candidate.

Another feature of SLAPstack is the synchronization parameter. Meaning that if the vehicles have chosen a set of lanes they are forced to commit to them, as long as the lanes stay pure. If a lane is assigned but currently locked, the AGV is forced to take on a lower priority order. The locking mechanism is in place to ensure storage consistency. In warehousing batches of 40 pallets may arrive with the same SKU. If a lane is locked by an AGV, other vehicles can't position their pallets in that lane. This would cause the pallets to be spread all over the warehouse. The synchronization parameter prevents this.

The results capture metrics on the average service time (s), total distance per AMR (km), maximum queue for delivery and retrieval, average lane-wise entropy (SKU amount in a lane), average turnover time and average hourly throughput. An animation visualizes which lanes are popular, indicated with a color when the lane is not pure (multiple SKUs in one lane).

H.2. Model Implementation

The layout for how the model is implemented in SLAPstack is visualized in Figure H.2. The locations of sources IB11 and CA12, as well as sink IB11, depicted in the layout, do not exactly match the Arena model. This discrepancy arises because the layout reflects an earlier version created during the initial stages of the thesis. Historical data from 1-2-2022 until 31-5-2022 has been used to run the simulation on. The simulation started with an initial fill level of 157 coils.

The model does not capture exactly the same dynamics as the one implemented in Arena. Therefore the models will not be compared. A black box model representation for the model is presented in Figure H.1. The bold requirements are varied in the experiments, the bold performance metric is relevant for the Arena simulation model.

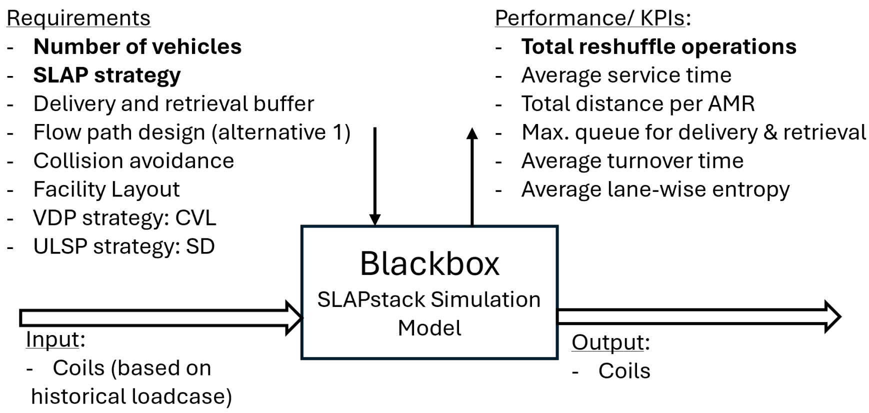

Figure H.1: Black box model SLAPstack

Some parameters were simplified for the model implementation. The model only considers alternative 1, a fully automated system, with a conventional bi-directional flow path layout. It is based on historical data, so it represents the system in its current state. To match the case as much as possible the following metrics were implemented:

Parameter	Value	Notes
AMR Speed	55 (m/min)	Based on 50 m/min loaded and 60 m/min unloaded
Material handing time	101.2 (s)	Based on 0.5*(pick-up) + 0.5*(drop-off) + (coil rotation penalty)
Retrieval buffer positions	8	2 per sink installation
Delivery buffer positions	12	On average 3 per source

Table H.1: Parameters SLAPstack model

The experiments conducted in the simulation model tested variations in the number of AMRs and the SLAP strategy. COPL, which stands for Closest Open Pure Lane, refers to a strategy where coils are placed in the nearest available lane that contains only coils from the same order number. COL, stands for Closest Open Location, which is also a pure lane delivery strategy. The abbreviation RND, is a random storage location assignment policy. This approach aims to optimize storage by minimizing travel distance while maintaining order consistency. The configurations tested are indicated below:

1. 2 AMRs, RND
2. 1 AMR, COPL
3. 2 AMRs, COL
4. 2 AMRs, COPL
5. 3 AMRs, COPL

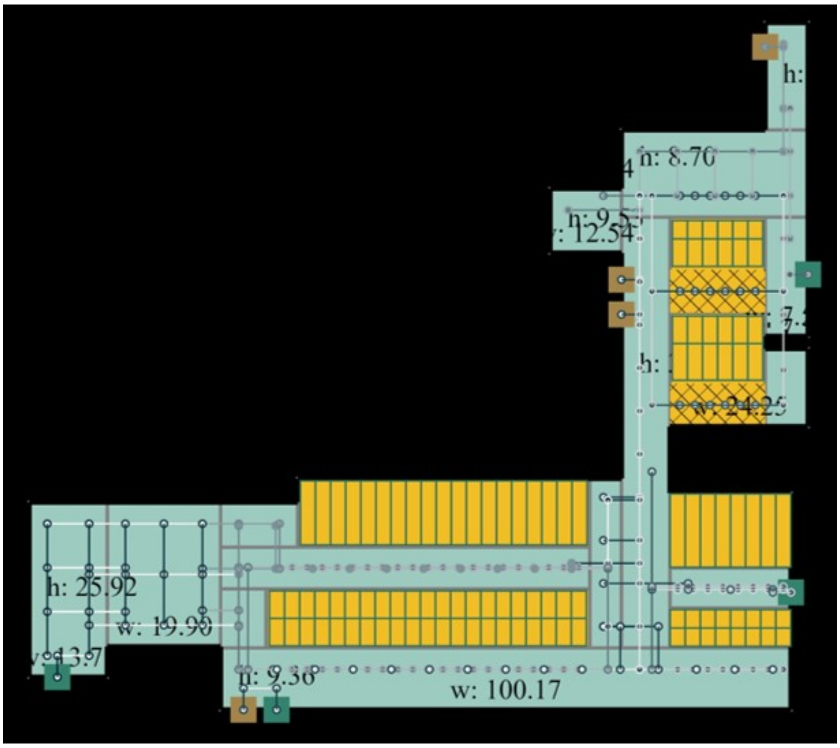

Figure H.2: Layout drawn in SLAPstack

H.3. Results

The first results indicate that in the passage between the O- and S-hall there are often confrontations between the vehicles. A heatmap visualizes the areas where deadlocks are most likely to occur. Therefore, in future research the influence on collision avoidance in this case should be further investigated. The entropy heat is visualised in Figure H.3, both for the aggregate and exact state representation. Lighter red colors indicate a higher entropy heat in the storage park.

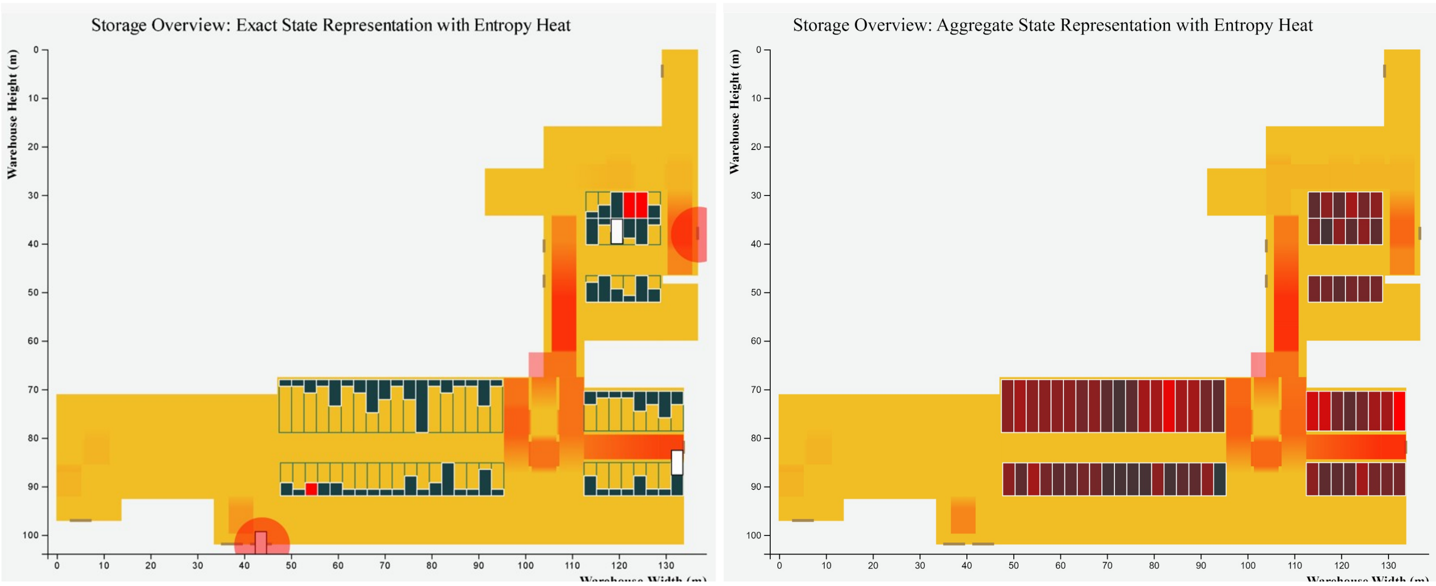

Figure H.3: Storage Representations with Entropy Heat

Figure H.4 visualizes an aggregate state representation of the storage park with Popularity Heat and Fill Heat. This indicates which lanes are used most often and which have the highest fill rate over the entire simulation run.

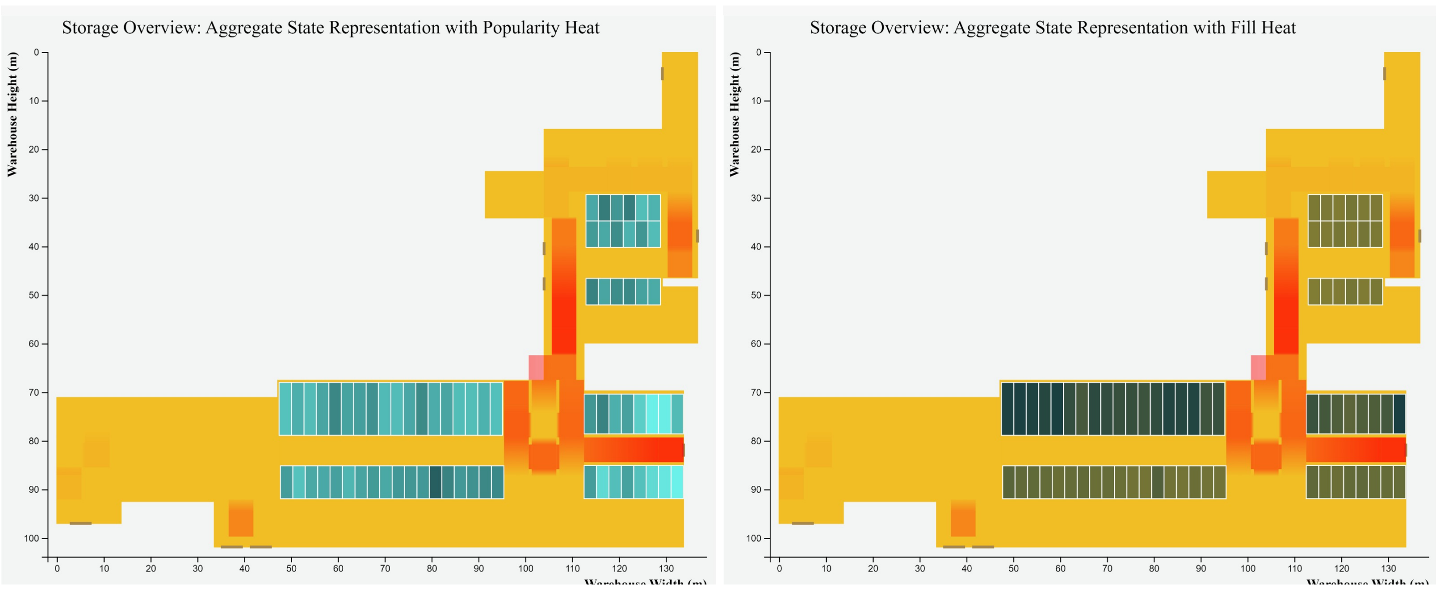

Figure H.4: Aggregate State Storage Representations with Popularity and Fill Heat

Figure H.5 visualizes the density plots for the average distance and travel time. There can be concluded that the mean of travel time when deploying 3 AGVs is lower than than for 1 AGV, while the mean for the travel distance is for both configurations the same.

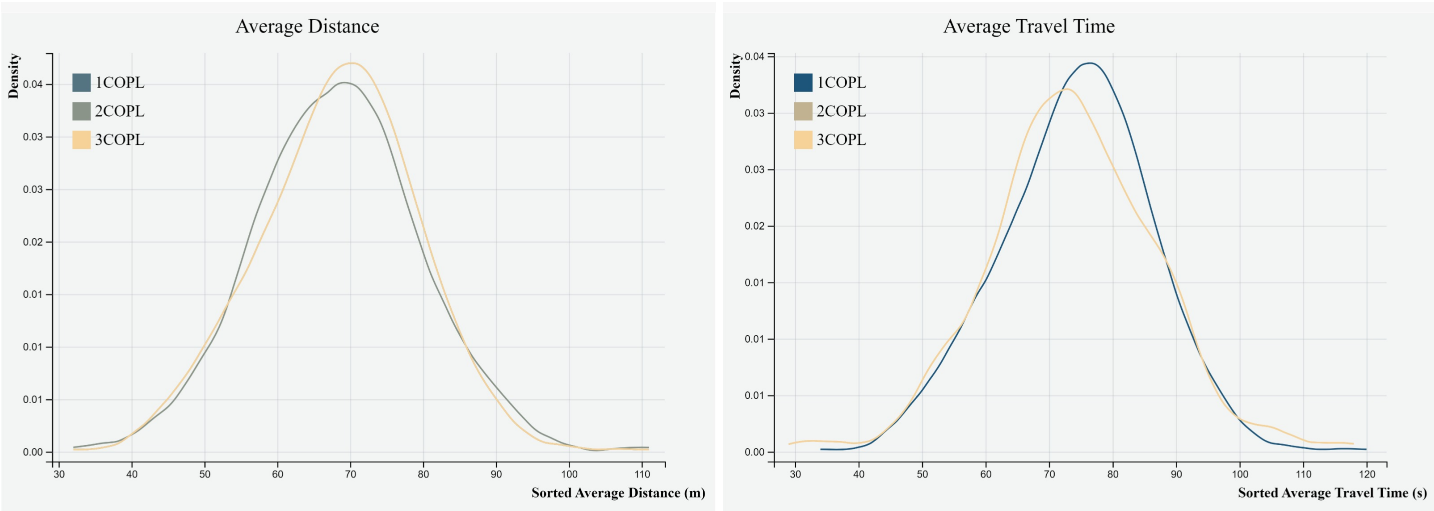

Figure H.5: Average distance and travel time

Figure H.6 visualizes the number of pallet shifts. Pallet shifts are the combination of unwanted shifts and sorting for entropy breaking. The figure shows that deploying more AGVs leads to more pallet shifts. By deploying 3 AGVs there are less delivery and retrieval tasks in queue. So there is more time to perform sorting operations.

Furthermore, the random storage location assignment policy indicates a higher number of pallet shifts in comparison to the other policies. This was expected since coils are often blocked by others.

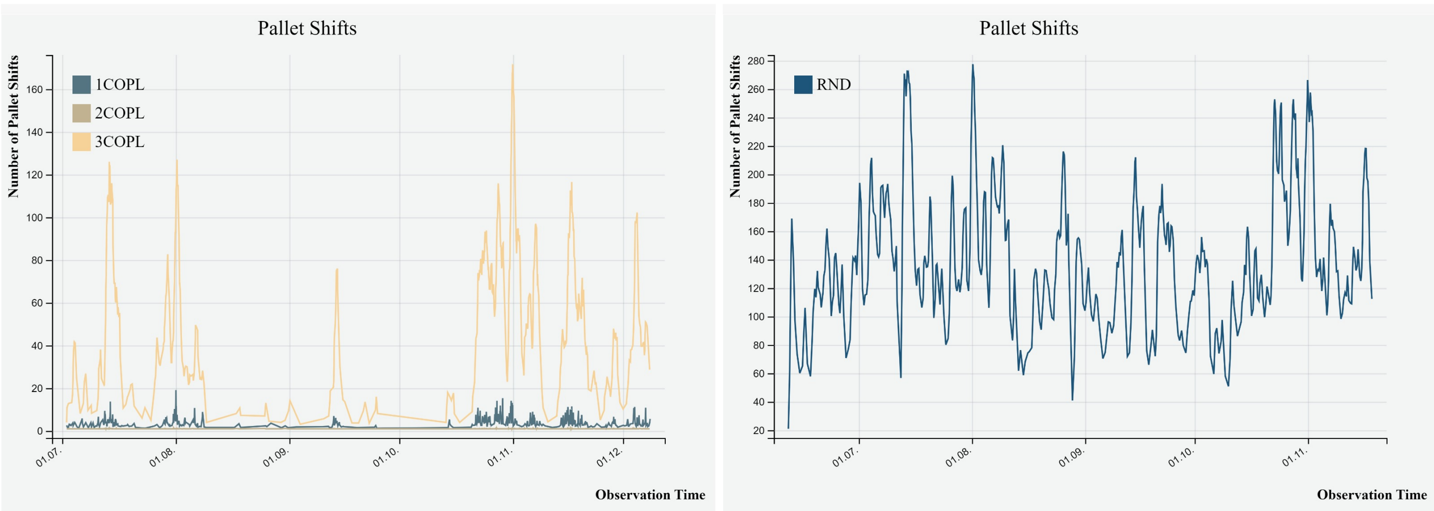

Figure H.6: Pallet shifts

Figure H.7 visualizes the execution duration and a density plot for the service time. The service time is about 380 seconds in general and increases a bit in the last month. Moreover, 3 AGVs indicate a lower service time, but the difference is not significant compared to 1 AGV.

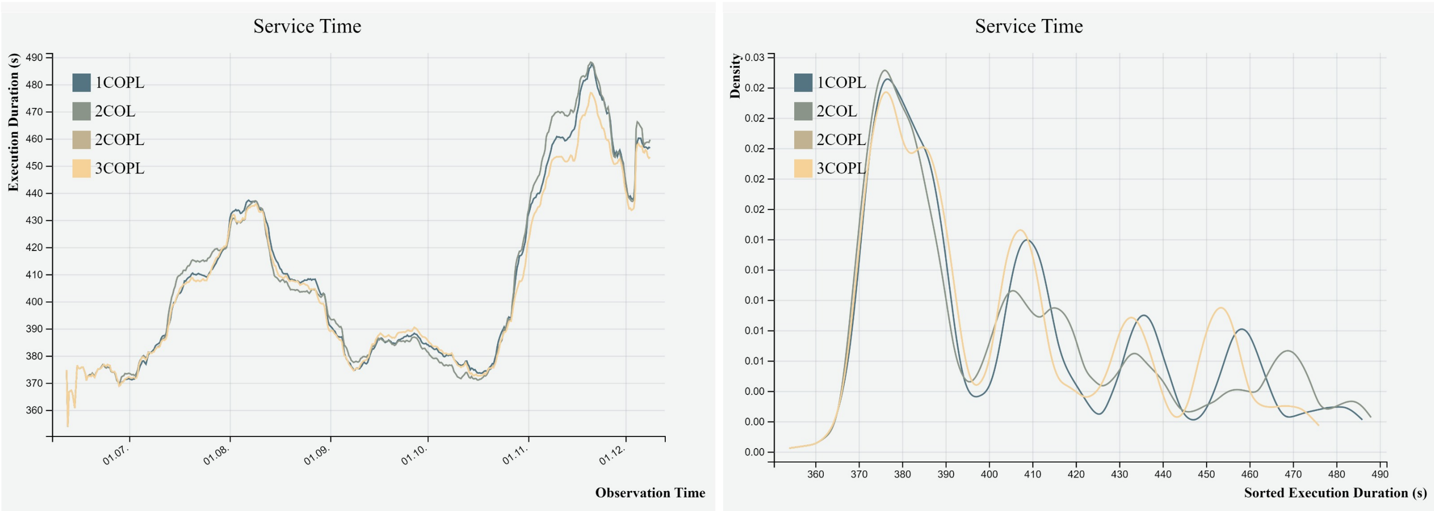

Figure H.7: Service time

Figure H.8 indicates that the service time of the random storage location assignment is about 2 to 3 times higher than the other strategies. However, the service time for the COPL strategy is almost independent of the number of AGVs. This shows again that according to this model and the current state demand, 1 AGV would suffice.

The cycle time in the second plot indicates that coils are stored about 2 days in the inventory before they are processed, there are outliers where 12 days are reached as well.

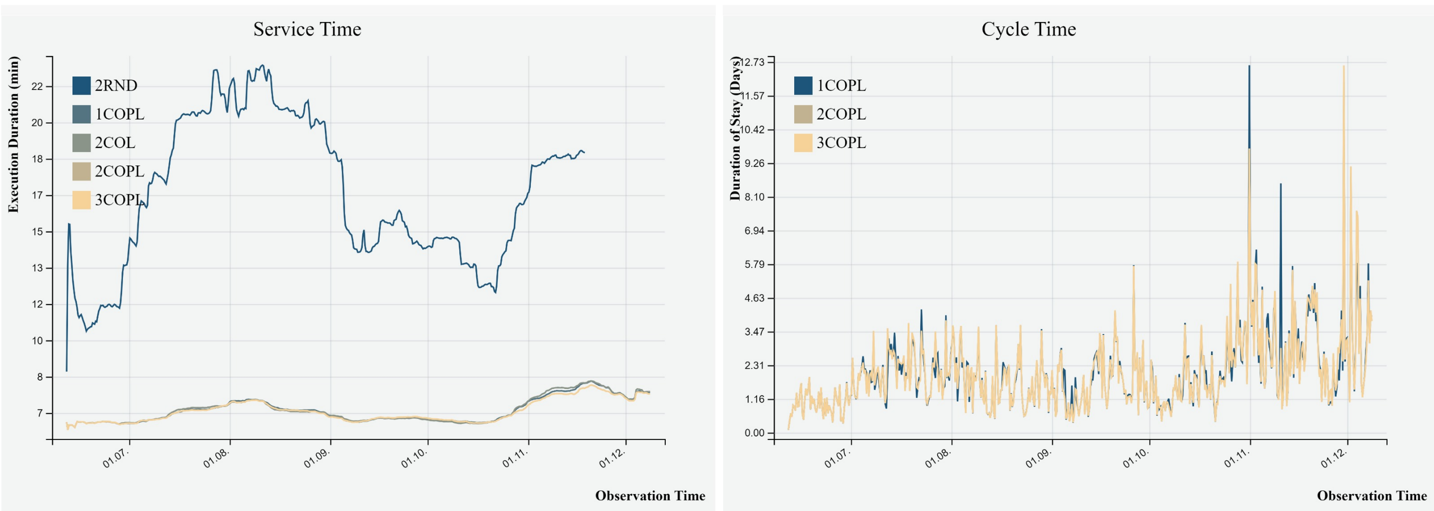

Figure H.8: Service and cycle time

According to the simulation model of SLAPstack, one AGV would be sufficient to handle the tasks. This alternative shows a total utilization of about 70%.

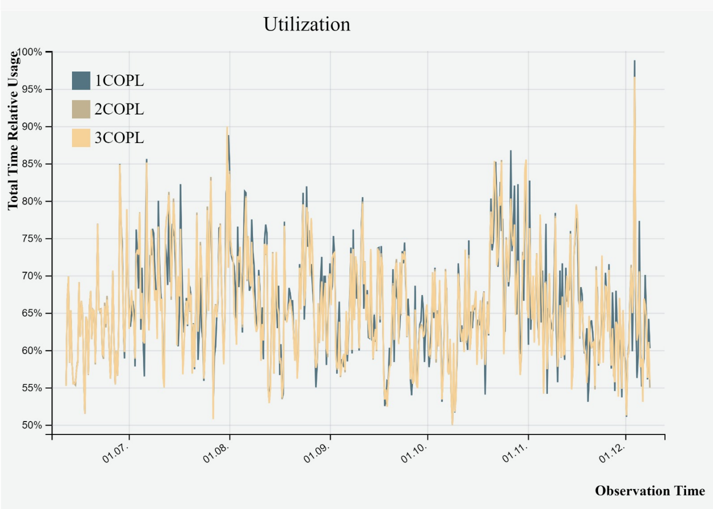

Figure H.9: Utilization

Lastly, the results indicated that the synchronization parameter, which in the warehousing industry does have the desired effect, had the opposite effect for the considered manufacturing facility. The difference is that coils arrive according to the takt time, instead of as a large batch. The synchronization parameter causes lane locking, to ensure storage consistency. However, if another AGV has to take on a lower priority order because of this, it can lead to a worsened service time.

I

Python Code: Data Processing

The data provided as input to the simulation model is based on two sources. J. Lagerberg provided data on the origin-destination pairs of the material flows within scope of this project. The origins include DKG11, CA12, IB11, HW48 and the destinations EV11, EV12, EV13 and IB11. The second source is on the production and downtime of installations. Each time period is logged under a category. The categories are net production time, speed loss, planned losses, unplanned losses and sales/logistic losses.

By linking the coil identification number from both files, a sixth category was created, the category 'out of scope'. Since CA12 produces material for EV14 as well, this is considered as out of scope. Furthermore, 0.45% of the material processed by EV11, EV12 and EV13 does not originate from DKG11, CA12, IB11 or HW48. This material is also considered out of scope.

The categories net production time and speed loss define the yield data per installation (interarrival time between steel coils). All other categories are considered as downtime. The downtime data has been cleaned, a subcategory in sales/logistic losses called 'external stagnation' is not included in the analysis. This subcategory identifies when the installation is put to a standstill due to no available coils, or a full storage park. This data must follow from the simulation model and can't be given as input. Furthermore yearly revisions are also left out of scope.

The duration and start date and time of each standstill were retrieved from the downtime excel. Since the duration's and inter-arrival time of the (sub)categories did not follow any type of probability distribution, the choice was made to calculate the mean duration and mean inter-arrival time. The consequence of this is that the inventory turnover is quite stable and does not contain large fluctuations. However, by using this method, the sum of all downtimes is the same as in the historical data for each installation. The use of statistically insignificant probability distributions would result in an unstable model, and would not represent the real-world well.

The python codes below have been developed with ChatGPT, and validated by checking the outcomes with excel techniques. The first code defines whether the material is within the scope of this project.

```python
import pandas as pd

# Load the Excel files
nieuwe_gegevens_df = pd.read_excel('OD␣pairs␣material␣flow␣within␣scope.xlsx')
stilstanden_df = pd.read_excel('Production␣and␣downtime␣data.xlsx', sheet_name=None)

# Step 1: Filter 'Nieuwe gegevens.xlsx' on 'EV_NR' for 'EV11', 'EV12', 'EV13', and 'IB11'
filtered_nieuwe_gegevens_df = nieuwe_gegevens_df[nieuwe_gegevens_df['EV_NR'].isin(['EV11', 'EV12', 'EV13', 'IB11'])]

# Ensure the IDs are strings and strip any whitespace
filtered_nieuwe_gegevens_df['NW_ROL'] = filtered_nieuwe_gegevens_df['NW_ROL'].astype(str).str.strip()

# Extract the first 6 digits of 'NW_ROL'
```

```
filtered_nieuwe_gegevens_df['NW_ROL_6'] = filtered_nieuwe_gegevens_df['NW_ROL'].str[:6]

# Step 2: Compare 'Materiaal ID' in '20240626 vraag joris 1 stilstanden.xlsx' with 'NW_ROL' from filtered data
main_df = stilstanden_df['Alle␣Data']  # Using 'Alle Data' sheet

# Ensure the IDs are strings and strip any whitespace
main_df['Materiaal␣ID'] = main_df['Materiaal␣ID'].astype(str).str.strip()

# Extract the first 6 digits of 'Materiaal ID'
main_df['Materiaal_ID_6'] = main_df['Materiaal␣ID'].str[:6]

# Create 'Match?' column with special condition
def determine_match(row):
    materiaal_id = row['Materiaal␣ID']
    materiaal_id_6 = row['Materiaal_ID_6']

    # Check for exact match
    if materiaal_id in filtered_nieuwe_gegevens_df['NW_ROL'].values:
        return 'Yes'

    # Check for match on first 6 digits
    elif materiaal_id_6 in filtered_nieuwe_gegevens_df['NW_ROL_6'].values:
        return 'Yes␣matched␣on␣first␣6␣digits'
    else:
        return 'No'

main_df['Match?'] = main_df.apply(determine_match, axis=1)

# Save back to the main dataframe
stilstanden_df['Alle␣Data'] = main_df

# Step 3: Create separate sheets based on unique 'Park Installatie' values
unique_park_installatie_values = main_df['Park␣Installatie'].unique()

# Initialize a dictionary to hold the separate dataframes
park_installatie_dfs = {value: main_df[main_df['Park␣Installatie'] == value] for value in unique_park_installatie_values}

# Save all sheets back to the Excel file, including the 'Alle Data' sheet
with pd.ExcelWriter('Production␣and␣downtime␣data␣within␣scope.xlsx') as writer:
    for sheet_name, df in stilstanden_df.items():
        df.to_excel(writer, sheet_name=sheet_name, index=False)

    for park_installatie, df in park_installatie_dfs.items():
        df.to_excel(writer, sheet_name=park_installatie, index=False)
```

The code used to define coil processing times for each installation is indicated below.

```
import pandas as pd

# Load the dataset
file_path = 'Production␣and␣downtime␣data␣within␣scope.xlsx'
data = pd.read_excel(file_path, sheet_name='Alle␣Data')

# Filter rows based on 'TIB Verlies Omschrijving' and 'Match?' column
verliezen_data = data[
    data['TIB␣Verlies␣Omschrijving'].isin(['Ongeplande␣verliezen', 'Geplande␣verliezen', 'Verkoop/Logistieke␣verliezen']) |
    data['Match?'].isin(['No␣went␣to␣IB11,␣matched␣on␣first␣6␣digits', 'No␣went␣to␣IB11', 'No'])
]

# List of Materiaal ID's to be dropped
list_ids_to_be_dropped = verliezen_data['Materiaal␣ID'].unique().tolist()

# Filter on 'Netto productietijd' and 'Snelheidsverlies' and exclude list_ids_to_be_dropped
filtered_data = data[data['TIB␣Verlies␣Omschrijving'].isin(['Netto␣productietijd', 'Snelheidsverlies'])]
filtered_data = filtered_data[~filtered_data['Materiaal␣ID'].isin(list_ids_to_be_dropped)]

```

```
# Function to calculate the duration for batch processes
def calculate_tussentijd_batch(group):
    start_time = pd.to_datetime(group['Begintijd␣Inzet'].iloc[0], format='%d-%m-%Y␣%H:%M:%S')
    end_time = pd.to_datetime(group['Eindtijd␣Stilstand'].iloc[-1], format='%d-%m-%Y␣%H:%M:%S')
    return (end_time - start_time).total_seconds()  # Tussentijd in seconden

# Function to calculate the duration for continuous processes
def calculate_tussentijd_continuous(group):
    start_time = pd.to_datetime(group['Begintijd␣Inzet'].iloc[0], format='%d-%m-%Y␣%H:%M:%S')
    end_time = pd.to_datetime(group['Eindtijd␣Inzet'].iloc[-1], format='%d-%m-%Y␣%H:%M:%S')
    return (end_time - start_time).total_seconds()  # Tussentijd in seconden

# Group by installation
installations = filtered_data.groupby('Park␣Installatie')

# Output dictionary to store dataframes for each sheet
output_data = {}

for name, group in installations:
    # Group by unique 'Materiaal ID' and 'Begintijd Inzet'
    if name in ['HW48', 'DKG11']:
        grouped = group.groupby(['Materiaal␣ID', 'Begintijd␣Inzet']).apply(
            calculate_tussentijd_batch).reset_index()
    elif name in ['EV11', 'EV12', 'EV13', 'CA12']:
        grouped = group.groupby(['Materiaal␣ID', 'Begintijd␣Inzet']).apply(
            calculate_tussentijd_continuous).reset_index()
    else:
        continue  # Skip if the installation is not in the specified lists

    grouped.columns = ['Materiaal␣ID', 'Begintijd␣Inzet', 'Tussentijd␣(seconden)']

    # Calculate the 1st and 99th percentiles to filter out outliers
    lower_percentile = grouped['Tussentijd␣(seconden)'].quantile(0.01)
    upper_percentile = grouped['Tussentijd␣(seconden)'].quantile(0.99)

    # Filter data to keep only values between the percentiles
    filtered_grouped = grouped[(grouped['Tussentijd␣(seconden)'] >= lower_percentile) & (
        grouped['Tussentijd␣(seconden)'] <= upper_percentile)]

    output_data[name] = filtered_grouped

# Output file path
output_file = 'Opbrengst.xlsx'

# Write to Excel
with pd.ExcelWriter(output_file, engine='openpyxl') as writer:
    for sheet_name, df in output_data.items():
        df.to_excel(writer, sheet_name=sheet_name, index=False)
```

The file below can be used to create the duration's for the planned losses and unplanned losses:

```
import pandas as pd

# Lees de Excel-file in
file_path = 'Production␣and␣downtime␣data␣within␣scope.xlsx'
data = pd.read_excel(file_path)

# Filter de gegevens op 'Geplande verliezen'
planned_downtime_data = data[((data['TIB␣Verlies␣Omschrijving'] == 'Ongeplande␣verliezen') &
        ((data['Match?'].isin(['Yes', 'Yes␣matched␣on␣first␣6␣digits'])) | (data['Materiaal␣ID'] == '-2')))]


# Functie om de stilstandduur te berekenen
def calculate_stilstandduur(group):
    start_time = pd.to_datetime(group['Begintijd␣Stilstand'].iloc[0], format='%d-%m-%Y␣%H:%M:%S')
    end_time = pd.to_datetime(group['Eindtijd␣Stilstand'].iloc[-1], format='%d-%m-%Y␣%H:%M:%S')
    duration = (end_time - start_time).total_seconds()  # duur in seconden
```

```python
    toelichting_stilstand = group['Toelichting␣Stilstand'].iloc[0] if 'Toelichting␣Stilstand' in group else ''
    return pd.Series([group['Stilstand␣uniek␣Id'].iloc[0], start_time, end_time, toelichting_stilstand, duration],
                     index=['Stilstand␣uniek␣Id', 'Begintijd␣Stilstand', 'Eindtijd␣Stilstand', 'Toelichting␣Stilstand', 'Duur␣(seconden)'])

# Verwerkingsresultaten opslaan in een DataFrame
output_data = []

# Voor elke installatie in de gefilterde gegevens
for installation, group in planned_downtime_data.groupby('Park␣Installatie'):
    # Groepeer op 'Stilstand uniek Id' en bereken de stilstandduur
    grouped = group.groupby('Stilstand␣uniek␣Id').apply(calculate_stilstandduur).reset_index(drop=True)
    output_data.append((installation, grouped))

# Maak een Excel-writer object
output_file = 'Ongeplande␣Verliezen.xlsx'
with pd.ExcelWriter(output_file) as writer:
    for installation, df in output_data:
        # Schrijf elke installatie naar een aparte sheet in het Excel-bestand
        df.to_excel(writer, sheet_name=installation, index=False)
```

For the sales and logistic losses the following code is used:

```python
import pandas as pd

# Lees de Excel-file in
file_path = 'Production␣and␣downtime␣data␣within␣scope.xlsx'
data = pd.read_excel(file_path)

# Filter de data op 'Verkoop/Logistieke verliezen'
filtered_data = data[data['TIB␣Verlies␣Omschrijving'] == 'Verkoop/Logistieke␣verliezen']

# Verwijder de rijen waarin 'TIB Categorie Omschrijving' gelijk is aan 'Externe stagnatie'
filtered_data = filtered_data[filtered_data['TIB␣Categorie␣Omschrijving'] != 'Externe␣stagnatie']

# Functie om de duur van de stilstand te berekenen
def calculate_durations(group):
    group = group.sort_values('Begintijd␣Stilstand')
    begintijd = pd.to_datetime(group.iloc[0]['Begintijd␣Stilstand'], dayfirst=True)
    eindtijd = pd.to_datetime(group.iloc[-1]['Eindtijd␣Stilstand'], dayfirst=True)
    duur = (eindtijd - begintijd).total_seconds()  # Duur in seconden
    return pd.Series({
        'Stilstand␣uniek␣Id': group.iloc[0]['Stilstand␣uniek␣Id'],
        'Begintijd␣Stilstand': group.iloc[0]['Begintijd␣Stilstand'],
        'Eindtijd␣Stilstand': group.iloc[-1]['Eindtijd␣Stilstand'],
        'TIB␣Categorie␣Omschrijving': group.iloc[0]['TIB␣Categorie␣Omschrijving'],
        'Toelichting␣Stilstand': group.iloc[0]['Toelichting␣Stilstand'],
        'Duur␣(seconden)': duur
    })

# Resultaten opslaan in een Excel-bestand met een sheet per installatie
output_file = 'Verkoop␣en␣logistieke␣verliezen.xlsx'
with pd.ExcelWriter(output_file, engine='openpyxl') as writer:
    for installatie, group in filtered_data.groupby('Park␣Installatie'):
        result = group.groupby('Stilstand␣uniek␣Id').apply(calculate_durations)
        result.to_excel(writer, sheet_name=installatie, index=False)
```

The code below states the duration for every moment that the installation was considered 'out of scope'. Based on the file earlier, which defined what material was not within scope, this file determines the duration.

```python
import pandas as pd

# Load the data
file_path = 'Production␣and␣downtime␣data␣within␣scope.xlsx'
data = pd.read_excel(file_path)
```

```

# Filter out rows where 'Materiaal ID' is '-2'
data = data[data['Materiaal ID'] != '-2']

# Define the "not in scope" values
not_in_scope_values = 'No'

# Function to process each installation
def process_installation(installation_data):
    results = []
    current_sequence = []
    for idx, row in installation_data.iterrows():
        if row['Match?'] in not_in_scope_values:
            current_sequence.append(row)
        else:
            if current_sequence:
                start_time = current_sequence[0]['Begintijd Inzet']
                end_time = current_sequence[-1]['Eindtijd Stilstand']
                if end_time == pd.Timestamp('1900-01-01 00:00:01'):
                    end_time = current_sequence[-1]['Eindtijd Inzet']
                duration = (end_time - start_time).total_seconds()
                material_ids = set(item['Materiaal ID'] for item in current_sequence)
                results.append({
                    'Begintijd': start_time,
                    'Eindtijd': end_time,
                    'Duration (seconds)': duration,
                    'Material Ids': ', '.join(map(str, material_ids))
                })
                current_sequence = []
    if current_sequence:
        start_time = current_sequence[0]['Begintijd Inzet']
        end_time = current_sequence[-1]['Eindtijd Stilstand']
        if end_time == pd.Timestamp('1900-01-01 00:00:01'):
            end_time = current_sequence[-1]['Eindtijd Inzet']
        duration = (end_time - start_time).total_seconds()
        material_ids = set(item['Materiaal ID'] for item in current_sequence)
        results.append({
            'Begintijd': start_time,
            'Eindtijd': end_time,
            'Duration (seconds)': duration,
            'Material Ids': ', '.join(map(str, material_ids))
        })
    return results

# Group data by 'Park Installatie'
grouped = data.groupby('Park Installatie')

# Create a dictionary to store dataframes for each installation
output_data = {}

# Process each group and store in the dictionary
for name, group in grouped:
    result = process_installation(group)
    result_df = pd.DataFrame(result)
    output_data[name] = result_df

# Output file path
output_file = 'Not in scope.xlsx'

# Write to Excel
with pd.ExcelWriter(output_file, engine='openpyxl') as writer:
    for sheet_name, df in output_data.items():
        df.to_excel(writer, sheet_name=sheet_name, index=False)
```

The 4 categories of donwtime (plannend-, unplanned-, sales & logistic losses and not in scope), were added to one list for each installation. The code below determines the downtime parameters for the installations:

```
import pandas as pd

```

```
# Laad het Excel-bestand
file_path = 'Combined_Installations_Data.xlsx'
xls = pd.ExcelFile(file_path)

# Initialiseer een lege lijst om de resultaten op te slaan
results = []

# Definieer de analyseperiode (in seconden)
start_date = pd.to_datetime('2022-02-01')
end_date = pd.to_datetime('2022-07-31')
total_seconds_in_period = (end_date - start_date).total_seconds()

# Verwerk elke sheet (installatie)
for sheet_name in xls.sheet_names:
    # Lees de sheet in een DataFrame
    df = pd.read_excel(xls, sheet_name=sheet_name)

    # Zorg ervoor dat 'Duur (seconden)' in float-formaat staat en 'Begintijd Stilstand' in datetime-formaat
    df['Duur␣(seconden)'] = df['Duur␣(seconden)'].astype(float)
    df['Begintijd␣Stilstand'] = pd.to_datetime(df['Begintijd␣Stilstand'])

    # Sorteer op 'Begintijd Stilstand' om chronologische volgorde te garanderen
    df = df.sort_values(by='Begintijd␣Stilstand').reset_index(drop=True)

    # Bereken de cumulatieve som om het splitsingspunt te vinden
    df['Cumulative␣Sum'] = df['Duur␣(seconden)'].cumsum()
    total_duration = df['Duur␣(seconden)'].sum()
    half_duration = total_duration / 2

    # Vind de index waar de cumulatieve som meer is dan de helft van de totale duur
    cutoff_index = df[df['Cumulative␣Sum'] >= half_duration].index[0]

    # Splits in 'Kort' en 'Lang' categorieën
    df['Categorie'] = ['Kort' if i <= cutoff_index else 'Lang' for i in df.index]

    # Bereken de gemiddelde duur en interarrival time per categorie
    mean_duration_kort = df[df['Categorie'] == 'Kort']['Duur␣(seconden)'].mean()
    mean_duration_lang = df[df['Categorie'] == 'Lang']['Duur␣(seconden)'].mean()

    mean_interarrival_kort = df[df['Categorie'] == 'Kort']['Begintijd␣Stilstand'].diff().dt.total_seconds().mean()
    mean_interarrival_lang = df[df['Categorie'] == 'Lang']['Begintijd␣Stilstand'].diff().dt.total_seconds().mean()

    # Bereken de totale stilstand en productie tijd
    total_stilstand_seconds = df['Duur␣(seconden)'].sum()
    productie_seconds = total_seconds_in_period - total_stilstand_seconds
    percentage_stilstand = (total_stilstand_seconds / total_seconds_in_period) * 100

    # Voeg de resultaten toe aan de lijst
    results.append({
        'Installatie': sheet_name,
        'Mean␣Duration␣Kort␣(s)': mean_duration_kort,
        'Mean␣Duration␣Lang␣(s)': mean_duration_lang,
        'Mean␣Interarrival␣Kort␣(s)': mean_interarrival_kort,
        'Mean␣Interarrival␣Lang␣(s)': mean_interarrival_lang,
        'Total␣Stilstand␣(s)': total_stilstand_seconds,
        'Productie␣Tijd␣(s)': productie_seconds,
        'Percentage␣Stilstand␣(%)': percentage_stilstand
    })

# Zet de resultaten om naar een DataFrame voor verdere analyse
results_df = pd.DataFrame(results)

# Sla de resultaten op in een Excel-bestand
output_file_path = 'Processed_Installations_Statistics2.xlsx'
results_df.to_excel(output_file_path, index=False)
```

I.1. Empirical Distribution Fitting

The code below is used to find the best fitting distribution, and the associated parameters. Furthermore, it plots the distribution over a histogram for validation.

```
import pandas as pd
import numpy as np
from scipy.stats import lognorm, norm, kstest
import matplotlib.pyplot as plt
import seaborn as sns

# Load the Excel file
file_path = 'Opbrengst.xlsx'
xls = pd.ExcelFile(file_path)

# Initialize a list to store results for each sheet
results = []

# Function to calculate lognormal parameters
def calculate_lognormal_params(data):
    # Fit a lognormal distribution to the data
    shape, loc, scale = lognorm.fit(data, floc=0)
    sigma = shape
    mu = np.log(scale)

    # Calculate mean and standard deviation for the lognormal distribution
    lognormal_mean = np.exp(mu + (sigma**2) / 2)
    lognormal_std = np.sqrt((np.exp(sigma**2) - 1) * np.exp(2 * mu + sigma**2))

    # Calculate KS statistic and p-value for lognormal
    ks_statistic_lognorm, p_value_lognorm = kstest(data, 'lognorm', args=(shape, loc, scale))

    return lognormal_mean, lognormal_std, ks_statistic_lognorm, p_value_lognorm, shape, loc, scale

# Function to calculate normal distribution parameters
def calculate_normal_params(data):
    # Fit a normal distribution to the data
    normal_mean, normal_std = norm.fit(data)

    # Calculate KS statistic and p-value for normal distribution
    ks_statistic_norm, p_value_norm = kstest(data, 'norm', args=(normal_mean, normal_std))

    return normal_mean, normal_std, ks_statistic_norm, p_value_norm

# Iterate over each sheet in the Excel file
for sheet_name in xls.sheet_names:
    df = pd.read_excel(xls, sheet_name=sheet_name)

    # Convert 'Duur (seconden)' to hours
    df['Duur␣(hours)'] = df['Duur␣(seconden)'] / 3600

    # Get the data for fitting
    data = df['Duur␣(hours)'].dropna()

    # Calculate lognormal parameters
    lognormal_mean, lognormal_std, ks_statistic_lognorm, p_value_lognorm, shape, loc, scale = calculate_lognormal_params(data)

    # Calculate normal distribution parameters
    normal_mean, normal_std, ks_statistic_norm, p_value_norm = calculate_normal_params(data)

    # Get minimum and maximum duration values
    min_duration = data.min()
    max_duration = data.max()

    # Format results
    formatted_result = f"MN(MX(LOGN({lognormal_mean:.5f},␣{lognormal_std:.5f}),␣{min_duration:.5f}),␣{max_duration:.5f})"

    # Append results
```

```
    results.append({
        'Sheet Name': sheet_name,
        'Lognormal Mean': lognormal_mean,
        'Lognormal Standard Deviation': lognormal_std,
        'KS Statistic Lognorm': ks_statistic_lognorm,
        'P-Value Lognorm': p_value_lognorm,
        'Normal Mean': normal_mean,
        'Normal Standard Deviation': normal_std,
        'KS Statistic Norm': ks_statistic_norm,
        'P-Value Norm': p_value_norm,
        'Formatted Result': formatted_result
    })

    # Plotting the data and fitted distributions
    plt.figure(figsize=(10, 6))
    sns.histplot(data, kde=False, stat='density', bins=30, color='blue', label='Data')

    # Generate the lognormal distribution based on fitted parameters
    x = np.linspace(min_duration, max_duration, 1000)
    pdf_lognorm = lognorm.pdf(x, shape, loc, scale)
    plt.plot(x, pdf_lognorm, 'r-', label='Fitted Lognormal PDF', linewidth=2)

    # Generate the normal distribution based on fitted parameters
    pdf_norm = norm.pdf(x, normal_mean, normal_std)
    plt.plot(x, pdf_norm, 'g--', label='Fitted Normal PDF', linewidth=2)

    plt.title(f'Distribution Fit for {sheet_name}')
    plt.xlabel('Duration (hours)')
    plt.ylabel('Density')
    plt.legend()
    plt.grid(True)

    # Save the plot
    plot_file_path = f'Fit_{sheet_name}.png'
    plt.savefig(plot_file_path)
    plt.close()

# Convert results to a DataFrame
results_df = pd.DataFrame(results)

# Save the results to a new Excel file
output_file_path = 'Distribution_Fit_Analysis.xlsx'
results_df.to_excel(output_file_path, index=False)
```