Data-Driven Transportation Planning for a Large Manufacturing Plant

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MSc Thesis

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Data-Driven Transportation Planning for a Large Manufacturing Plant

Analysis and development of a planning support tool for the internal transportation at Tata Steel IJmuiden

by

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Abstract

Planning the on-site transportation of Tata Steel IJmuiden is a complex process. Currently the plans are made by the on-site logistics planners, based on the on-site logistic constraints rather than on KPIs. Current research has been narrowly focused on either analysis of system parameters or generally on key performance indicators and this thesis aims to bridge that gap by taking both system analysis and KPI development into account in developing a working planning tool that can assist planners in a real-life situation. The goal of this thesis is to gain insights in the on-site transportation planning of large manufacturing plants and their performance measurement. These insights are used to determine to what extent improvements can be made in the on-site transportation plans by adding data-driven decision support. This research is focused on the question: How can the on-site transportation planning at a large manufacturing plant be improved, by 1.) adding company KPIs and 2.) data-driven decision support based on the parameters of the locality and its constraints? Through the application of the DMADE framework, this research question is answered. System Analysis tools are used to define the on-site logistics system and its transportation planning. The SCOR performance measurement framework is used to determine the KPIs of the on-site transportation plans. The performance indicators are on-time delivery, costs of planned actions, workload and robustness. These are modeled operationally as locomotive usage, workforce usage and wagon usage. The developed planning model, classified as a Resource Constrained Multi-Project Scheduling Problem, is formulated as a Mixed-Integer Linear Program. This planning model optimizes the on-site transportation plans for the KPIs and proves the correctness of the KPIs and the potential higher performance of on-site transportation plans if constructed by the planning model. The optimal plans lead to more effective and efficient logistics operations. Planning moves from being time and people intensive towards fast, consistent, less resource intensive and quantitative KPI-based.

Preface

This report is the final work for obtaining the MSc. degree in Transport, Infrastructure and Logistics at the Delft University of Technology. The original assignment of this thesis project was commissioned by ORTEC B.V., who have given me the opportunity to conduct this research as a graduate student in their organization.

Thesis project execution is like a roller coaster ride: highs, lows and sometimes you do not know you got yourself into, but in the end when the dust settles and you look back it was worth the ride. The addition of a global pandemic, resulting in working from home in the same setting for the bigger part of eight months, did not make it easier but it did make the ride even more unforgettable.

I would like to thank Rudy Negenborn, Jaap Vleugel and Frederik Schulte for their guidance and useful remarks. You have helped me get through the process of writing my thesis and raised the bar of the end-result.

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Furthermore I owe a debt of gratitude to all those helping me in completing this thesis and my studies as a whole. From fellow project members, friends and housemates, but in particular my sister, girlfriend and parents, whose continuing support throughout my studies has been essential in getting to this final achievement.

Finally I wish you enjoyment in reading this thesis work!

Peter Joon
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Contents

Nomenclature

API	Application Programming Interface
APS	Advanced Planning System
BBT	Break Bulk Terminal
CT	Consolidation Terminal
DMADE	Define, Measure, Analyze, Design, Evaluate
DMAIC	Define, Measure, Analyze, Improve, Control
DOTIF	Delivery On-Time In Full
DSS	Decision Support System
GHUIF	Gele Huif
IDEF0	Integration Definition for Function
IRS	Industrial Railway System
ITT	Inter Terminal Transport
KPI	Key Performance Indicator
MILP	Mixed-Integer Linear Programming
OSL	On-Site Logistics
OSP	On-Site Planning
OTB	Outbound Department
OTD	On-Time Delivery
PLWG	Platte Wagen
PMS	Performance Measurement System
RCMPSP	Resource Constrained Multi-Project Scheduling Problem
RCPSP	Resource Constrained Project Scheduling Problem
S&W	Stevedoring & Warehousing
SCOR	Supply Chain Operations Reference
SCP	Supply Chain Planning
VBIT	Vehicle Based Internal Transport
VWWG	Vaste Wiege Wagen

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1
Introduction

The topic of this thesis is the on-site transportation planning of large manufacturing plants. Large manufacturing plants, such as the steel manufacturing facilities of Tata Steel IJmuiden, have internal departments responsible for transporting large volumes of goods around the facility. The scale of these facilities and the accompanying amount of to-be transported volumes result in complex logistic processes and efficient and effective planning of these transports has a big impact on the surrounding processes. On-site transportation planning is a part of industrial logistics, defined as: "*all activities which allow the physical inflow and outflow of goods and associated services which link the firm to the external world before and after production takes place*" (Barros, 1997).

To assess on-site transportation planning and logistics processes, a use case has been found in the steel manufacturing facilities of Tata Steel IJmuiden. Located in Velsen, the Netherlands, Tata Steel IJmuiden is one of the largest steel production facilities in Europe. Its 9000 employees produce yearly more than 7 million tonnes of steel. The IJmuiden plant is known for its production of high-quality steel and fabricating this at one location: the 750 hectares size facility with its own (sea)port and rail yard (Tata Steel, 2020). The facilities in IJmuiden consist of many factories and warehouses spread over these 750 hectares. Transportation between these locations across the site is done using an industrial railway network of nearly 100 kilometers of rail tracks, locomotives and wagons (Pro Rail, 2013).

The industrial railway system is used for transport of inbound raw materials, outbound (semi-) finished products to customers by train or ship and on-site repositioning of the steel. Transports range from finished coils being transported from the warehouses or production facilities directly to the seaport or rail yard, but also include re-allocating the products around the plant area. The transports are planned by the On-Site Logistics (OSL) department, based on the arrival and departure plans of the outbound vessels and trains. While making the planning, the OSL planners need to take into account various parameters such as wagon types, driving times, loading capacity, loading speeds and locomotive availability. Planning the transports results in the on-site transportation plan. There being many constraints, parameters and variables to consider whilst making the planning make this a complex process. The planning is made using a software package named *Planwise*, which assists the planners in their tasks by providing them with e.g. information on the duration of specific tasks or transports. Planwise is developed by ORTEC, one of the world's leading supplier of mathematical optimization software and advanced analytics (ORTEC, 2020).

Currently planning of the on-site transportation is done based on the departure planning of outbound trains and vessel arrivals and departures in the seaport. The planning is fixed for the next 4 to 8 hours and is defined 24 hours in advance. During the day the "regisseurs" (dispatchers) adjust the planning to respond to the many possible disturbances, such as the malfunctioning of equipment, weather or faulty loading of a train resulting in delays.

1.1. Problem statement and knowledge gap

Based on the literature study of chapter 2, there is high potential in the application of decision support in planning on real-life use cases. Combining both human and automated planning creates an integrated planning approach that finds system optimal solutions and allows human planners to make more funded decisions, as described in e.g. Li and Tian, 2015. Including proper performance measurement by using a suitable performance measurement system is expected to result in improvements and is highlighted as relevant for further research. Current research has been narrowly focused on either analysis of system parameters or generally on key performance indicators (KPIs) and lacks the combination of both in light of real-world problems. This thesis aims to bridge that gap by taking both system analysis and KPI development into account to develop a working planning tool that can assist planners in a real-life situation. The development of this decision support system and application of a performance measurement system to a real world case with multiple objectives on multiple planning levels, in the on-site logistics sub-field, is a contribution to the current body of knowledge.

Tata Steel IJmuiden management, planners, ORTEC consultants and previous studies expect that there are gains to be made in the performance of the on-site transportation planning of Tata Steel IJmuiden, through the application of data-driven decision support for the planners. However, before such support can be applied, there are currently too many unknown constraints and requirements and the on-site transportation planning is not yet fully quantifiable. It is unclear what a better or worse plan is, as profitability is not the main driver. Furthermore it is not known to what extent automation of such a planning process can improve the performance of the on-site transportation plans. By assessing and using the Tata Steel IJmuiden on-site transportation planning as use case in this research, key insights are gained in on-site logistics and transportation planning in real-life. This includes the important considerations made at these facilities and the core characteristics of on-site logistics. Furthermore this provides a realistic use case to evaluate the found potential from literature.

1.2. Research goal

This research has a focus on performance measurement of on-site logistics. Emphasis is on expressing and determining the quality of on-site transportation plans. The evaluation of on-site transportation plans is done through a developed planning model which will allow planning to be done using quantitative prescriptive analysis with data-driven decision making.

The goal of this thesis is to gain insights in the on-site transportation planning of large manufacturing plants and their performance measurement. These insights are used to determine to what extent improvements can be made in the on-site transportation planning by adding data-driven decision support.

Enhancements in the planning process by the added decision support will provide opportunities for evaluation of specified alternatives, i.e. what-if scenarios and system configurations and policies can be assessed based on the performance metrics. In the end this will lead to optimal plans and more effective and efficient logistics operations.

1.3. Research questions

Based on the earlier presented research goal and steps towards achieving this goal, the following main-research question has been drafted:

How can the on-site transportation planning at a large manufacturing plant be improved, by 1.) adding company KPIs and 2.) data-driven decision support based on the parameters of the locality and its constraints?

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

1. What are the characteristics of on-site logistics and industrial railway systems?
2. How are on-site transportation plans created at large manufacturing plants?
3. What data is required for the application of data-driven decision support to on-site transportation planning?
4. How can the performance of on-site transportation plans be assessed?
5. How can on-site transportation planning be modeled?
6. What is a suitable solution method for on-site transportation models?
7. To what extent can increased decision support improve on-site transportation planning?

1.4. Scope

The scope of this thesis is limited to the on-site logistics sub-field and in particular on-site transportation planning of large manufacturing plants. Large manufacturing sites have costly resources and resource types and high operational cost levels. Furthermore in on-site logistics decision support is often based on historical procedures and not yet data-driven.

The use case scope is limited to the warehouse plan of the On-Site Logistics department of Tata Steel IJmuiden, responsible for logistics and transport operations of the distribution side of the IJmuiden site. This entails the transportation of inbound raw materials by train and outbound (semi-)finished products, i.e. steel coils, by truck, ship, train, and internal repositioning of steel coils by train. The warehouse plan and on-site logistics system of Tata Steel IJmuiden are discussed in-depth in chapter 4.

1.5. Structure

This thesis report is structured as follows. Firstly in chapter 2 the current body of knowledge on (on-site) transportation planning and logistics, performance measurement, planning and decision support and other relevant studies are examined. Based on this knowledge the methodology and approach for this study are discussed in chapter 3. Thereafter in chapter 4 the on-site transportation planning, process and industrial railway system in place at Tata Steel IJmuiden are analyzed.

The quantitative and qualitative performance indicators are determined and the on-site transportation planning process is made quantifiable in chapter 5. These performance indicators are evaluated by modeling the on-site transportation planning, generating optimal plans, comparing these to historical plans and assessing their differences. The model component of an optimization Decision Support System for use in on-site transportation planning is developed in chapter 6. Using the planning model results, the plans based on the performance indicators are analyzed and the performance is evaluated in chapter 7. Finally in chapter 8 the conclusions, discussion and recommendations are presented.

2

Literature Study

In this chapter the background on on-site logistics, planning and Decision Support Systems, performance measurement and relevant studies for this research are presented. This is done to provide the foundations from literature and to map the current literature gap. Furthermore the literature serves the purpose to find the research leads and methods to be used in this research. This chapter ultimately answers the first research question of this thesis:

SQ 1: What are the characteristics of on-site logistics and industrial railway systems?

Answering the above presented research question is done by covering the following literature topics:

2.1 On-site logistics at large manufacturing sites
2.2 Planning and Decision Support Systems
2.3 Performance measurement in logistics
2.4 Relevant studies

In section 2.5 the answer to this chapter's research question is given and the found literature gap is discussed.

2.1. On-Site Logistics at large manufacturing sites

The logistics field has three functional distinctions of logistics systems based on the flow of goods phase of the system: procurement logistics, production logistics and distribution logistics (Gleissner & Femerling, 2013d). Procurement logistics is the transport and supply of input for the corporate process, such as raw materials. Production logistics is concerned with planning and controlling of internal material flow, storage and transport and connects procurement logistics with distribution logistics. Distribution logistics is the coordination and interaction of transport and storage processes in the phase where goods are send to their customer. The tasks of distribution logistics are split into three:

1. Order processing
    - Order conveying

    - Order processing
2. Storage
    - Transshipment
    - Storage
    - Retrieval
    - Picking
    - Packing
    - Stock control
3. Transport
    - Transshipment
    - Disposition for transport
    - Loading
    - Transport
    - Delivery

In distribution logistics *service levels* are defined to assess business performance. Service levels consist of delivery time (time between order placement and receiving of goods by the customer), delivery quantity (customer requirement fulfillment based on order characteristics and composition), delivery flexibility (the adaptability of order delivery to customer requirements) and readiness to deliver (probability of the total order processing time being within a given time span) (Gleissner & Femerling, 2013d).

Large manufacturing sites are described in literature as an example of complex freight nodes (Schönemann, 2016). The infrastructure at these nodes can be categorized as site infrastructure. Included in site infrastructure are the traffic facilities and transshipment and storage facilities (i.e. suprastructure). Examples of site infrastructure are train stations, inland ports and railports. Site infrastructure makes use of the transport infrastructure to connect factories and customers via widely branched (railway) networks. The rail yard, or industrial railway system, connects the national railway system and e.g. production facilities, which operate according to different timetables and schedules (Gleissner & Femerling, 2013a). In general these networks consists of links and nodes, where the links are the rail track and the nodes are yards, terminals, etc. Various network arrangements are possible, such as hub-and-spoke networks, point-to-point networks or combinations of both, illustrated in figure 2.1. Hubs in the hub-and-spoke network are used to consolidate transport flows and bundle loads. Making use of such hubs limits the amount of lesser-efficient direct links (Schönemann, 2016).

In distribution logistics, the logistics network usage is structured into three categories, where for the latter two the addition of one or multiple transshipments adds a level of complexity (Daganzo, 2005):

1. One-to-one distribution
2. One-to-many distribution
3. Many-to-many distribution

Many-to-many configurations are often found in airlines, postal carriers and railroads. Large manufacturing plants can also be many-to-many configurations, where multiple warehouses are connected to multiple destinations, on- and off-site. In many-to-many configurations transshipment

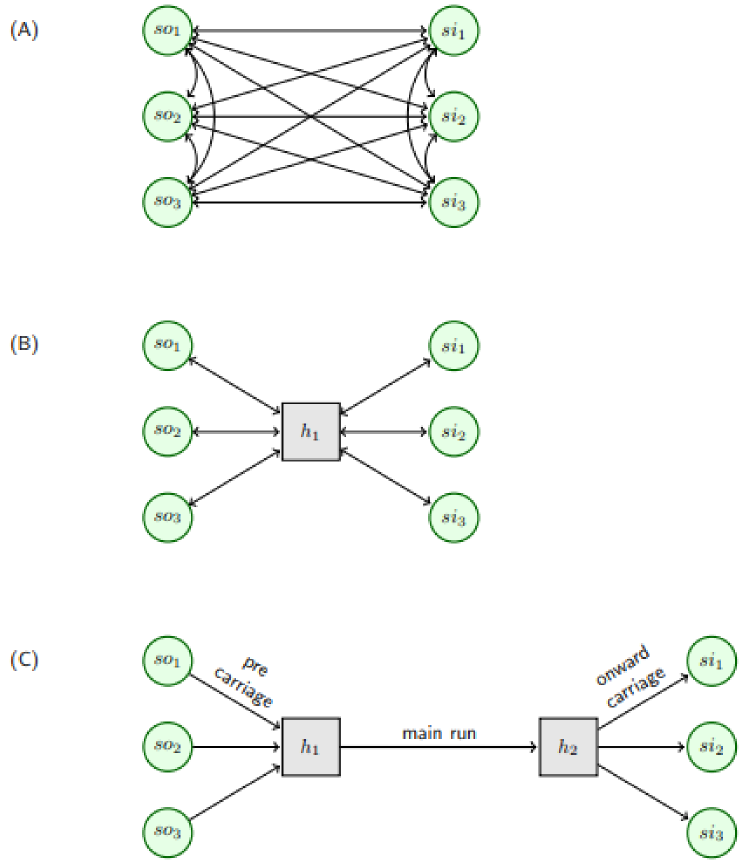


Figure 2.1: A: Point-to-point network, B: two-staged hub-and-spoke network, C: three-staged hub-and-spoke transport network, from (Schönemann, 2016)

take place if this results in performance improvements.

In types of goods transported, the distinction is made between *single* and *multi-commodity* problems. Single commodity goods are those where a destination has a demand regardless of point of origin, e.g. water supply. In case of multi-commodity goods, destinations that have a demand related to a certain origin cannot be substituted by items from another origin. Terminals in one-to-many and many-to-many systems may also play the role of consolidation points, where smaller loads are combined into large loads. Such terminals are referred to as *Consolidation Terminals* (CT). Another type of terminal identified is the *Break-Bulk Terminal* (BBT), these are transshipment points where loads are 'broken' and subsequently reconstituted. Both CTs and BBTs intend to optimize the cost efficiency of the many-to-many network, combining loads and reducing travel distance for local carriers (Daganzo, 2005). Consolidation terminals and Break-bulk terminals in a many-to-many system are illustrated in figure 2.2.

Rail freight transportation distinguishes two loading types: wagon-load traffic and block train traffic (Gleissner & Femerling, 2013e) (Schönemann, 2016). In wagon load traffic the entire transport is carried out by rail but with several concentrated shipments, from multiple origins, which are later on combined into one train. Here marshaling yards are used to combine the wagons of several customers (or destinations). Block train services are complete trains without intermediate handling between origin and destinations. Block trains are sometimes deployed as shuttle services linking

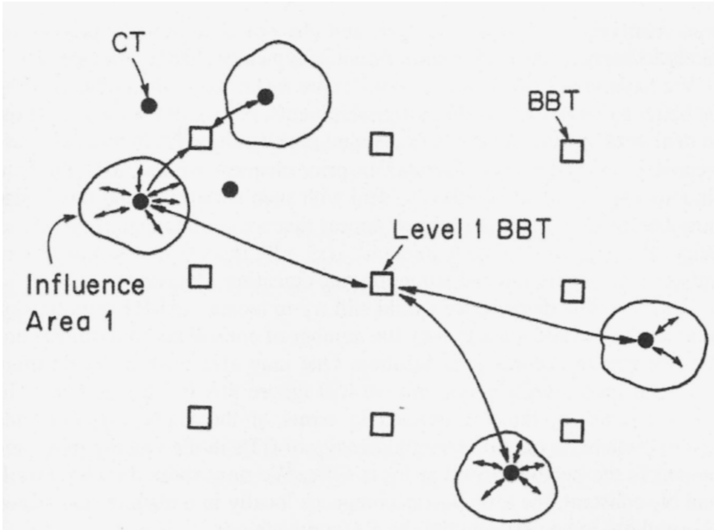


Figure 2.2: Consolidation and Break-bulk terminals in a many-to-many system (Daganzo, 2005)

various sites as point-to-point connections. Block train services have low transit times and limited (complex) shunting and sorting operations.

An example of many-to-many distribution is Inter Terminal Transport (ITT) as described by Duinkerken et al. (2006). ITT tasks are similar to that of on-site transportation at large manufacturing sites with multiple on-site locations: (1) Collect goods at the origin at the right time, (2) deliver the goods to the destination at the right time and (3) bridge mismatches by being a buffer on wheels or by using transport-stacks. The emphasis in ITT is on the punctuality of collection and delivery, this must neither be early nor late. Punctuality focuses on transit and handling at origin and destination. There are latest arrival times defined and if the transport is completed later this is classified as 'non-performance'. Non-performance is also the case where the subsequent mode of transport of the container has a delayed departure due to lateness of the ITT delivery. Other performance indicators include vehicle occupation rates, vehicle capacity percentage loaded, equipment utilization, number of empty trips and amount of vehicles waiting for loading and unloading.

In ITT there are two distinct goods flow types: push and pull. Push flow is when an origin terminal initiates transport to a destination terminal, and vice-versa is the case for pull flow (Duinkerken et al., 2006). The push and pull principles are used to describe logistic management strategies for presenting goods to market and for characterization of the logistics system. The ITT notion of push and pull is extended by Gleissner and Femerling (2013c): applying the push principle means the initiation in a logistic chain is by the manufacturer, i.e. this is seen as the start of the chain. Opposite to the push principle, the pull principle is the initiation of the logistic chain by customer order or demand.

In logistics of complex freight hubs warehouses play a key role as storage location or terminals. Storage is inevitable in a supply chain such as the steel industry as demand for products and the production process are hard to predict. Inventories are used to reduce overall logistic costs and increase customer service as the ability to supply the desired goods is enhanced. Warehousing consists of three basic functions: (1) movement (material handling), (2) storage (inventory handling) and (3) information transfer. The movement, or material handling, function includes four main activities: receiving and put away, order filling/picking, cross-docking and shipping. The storage function is categorized according to storage time. On the one hand there is inventory that is temporary in storage and on the other hand there is semi-permanent or long-term storage. In general the amount of temporary storage is determined based on the variability of both lead time and demand for specific goods. Finally the information transfer function in warehousing considers the information exchange on inventory levels, storage location of products and in- and outbound flow of goods. Furthermore information exchange is needed on non-inventory related elements such as workforce availability (Farahani et al., 2011).

On-site transportation systems are described by Le-Anh (2005) as vehicle-based internal transport (VBIT) systems. VBIT systems operate on a closed network in for instance warehouses or airport baggage handling environments. Vehicle scheduling problems in VBIT systems often have the goal to move loads as quickly as possible from pick-up locations to drop-off locations. In doing so the shortest path needs to be determined, but in for instance warehouses there might be congestion resulting in vehicles needed to take other routes. Two forms of vehicle dispatching are noted: centralized and decentralized. In decentralized dispatching, vehicles are independent agents who operate themselves. Centralized dispatching requires a system controller that operates all vehicles at the same time. Furthermore distinction is made in terms of vehicle guidance; either vehicles are guided (automatically or person-guided) or they are not. Figure 2.3 gives an overview of the full guide-path classification as discussed in Le-Anh (2005). Three categories to characterize VBIT systems are defined: flow topology, number of parallel lanes and flow direction. Flow topology concerns the network complexity, with conventional meaning a network consisting of paths, crosses, junctions and shortcuts and a tandem network being multiple loops together.

Flow topology	Number of parallel lanes	Flow direction
Conventional	Single lane	Unidirectional flow
Single-loop	Multiple lanes	Bidirectional flow
Tandem		

Figure 2.3: Guide-path classification, adapted from Le-Anh (2005)

2.2. Planning and Decision Support Systems

This section firstly covers more general literature on planning, followed by literature specifically on decision support systems in light of planning.

2.2.1. Planning

Planning supports decision making "*by identifying alternatives of future activities and selecting some good ones or even the best one*" (Fleischmann et al., 2008). Questions ranging from "Which job has to be scheduled next on a respective machine?" to deciding where to open a facility are part of planning. In planning and logistics three decision making levels are defined: strategic, tactical and operational (Crainic & Laporte, 1997) (Gleissner & Femerling, 2013b) (Fleischmann et al., 2008). Planning on the strategic level considers long-term decisions such as facility layout planning. Tactical planning focuses on efficient allocation of resources in order to improve system performance, data is in aggregated form and at freight terminals the cranes, machinery and staff are scheduled on this level. On the operational level, planning is real-time decision making by local operators, such as dispatchers. The operational decisions include load order of trains, shunting and redistribution of empty wagons (Crainic & Laporte, 1997).

Caris et al. (2008) identifies four types of decision-makers in freight transportation planning: dryage operators, terminal operators, network operators and intermodal operators. The dryage operators are responsible for planning and scheduling the vehicles between terminals, shippers and receivers. Terminal operators organize the transshipment between two modes of transport at a terminal. Network operators organize the rail and barge transports and make the infrastructure plan, whereas intermodal operators are seen as the users of the infrastructure and make the routing of shipments through the network.

Fleischmann et al. (2008) present two 'plan-control-intervention' structures: *rolling horizon* and *event-driven planning*. In a rolling-horizon structure, the planning horizon is split into periods and a frozen period (the first period) is determined. This frozen period is applied in practice and as the next period starts the plans for the subsequent periods in the planning horizon, which is now extended with one period, are updated based on the first period and forecasts. Rolling horizon planning is commonly used to handle the uncertainty of operational planning. A more efficient structure is event-driven planning. Here plans are updated following a significant event and not based on predefined intervals. To apply event-driven planning, all relevant data needs to be updated constantly to be able to update the plans at any given time.

In tactical planning the distinction between long-distance goods transportation and short-distance multiple pick-up and delivery transportation is made (Crainic & Laporte, 1997). The output of tactical planning is the transportation plan. This is used for determining the daily operations of the system at hand and contains the rules and policies of the operational level. The overall goal is to perform the transportation service as listed in the transportation plan and doing this rational and efficiently. Crainic and Laporte (1997) list the following key considerations when assessing short distance planning on the tactical level:

- Delivery characteristics: direct, indirect or both?
- Origin characteristics: distribution from a single or multiple depots?
- Vehicle characteristics: fleet size is a fixed amount or is it a decision variable, homogeneous or heterogeneous fleet composition, vehicle capacities, speed and operating costs.
- Driver characteristics: driver working conditions, pay structure, workday length, overtime conditions and workload permissions.
- Demand characteristics: is demand known in advance or dynamic over time?
- Customer or destination characteristics: How often or when must each customer be visited and must customers be visited within specific time windows?

2.2.2. Decision Support Systems

Decision Support Systems (DSS) are defined as "computer technology solutions that can be used to support complex decision making and problem solving" (Shim et al., 2002). DSS are divided into three components: (1) the data component for gathering and storing the data required in the DSS; (2) the model component for analytically solving the decision problem; and (3) the user-interaction component through which the user interacts with the DSS (Yazdani et al., 2017). Furthermore there are six categories of DSS: file drawer systems, data analysis systems, accounting and financial systems, representational systems, optimization systems, and suggestion systems (Mar-Ortiz et al., 2018).

Mar-Ortiz et al. (2018) list key steps that are important to run through before development of the DSS to determine key design elements of the DSS:

1. Problem and decision making scope identification
2. Determining the expectations of the decision-makers or end users. Possible uses are:
    - Monitoring
    - Diagnostic
    - Descriptive analysis
    - Prescriptive analysis
    - Predictive analysis
3. Requirement analysis of the DSS users and developers, based on the type of to-be-made DSS

Higher levels of integration between various levels of planning is expected to improve planning performance. Decision Support Systems are a way for planners to achieve higher levels of integration in planning. DSS are intended to alleviate planners from standard tasks and optimize for specific performance indicators, in order to let the planners have more time for the cognitive tasks requiring flexibility, communication and intuition. Planners will have less basic tasks, such as updating inventory levels or requesting updates from locations around the site and have more time for data interpretation and making improvements to the plan. Combining human and automated planning leverages the computational strength of computers and experience and judgment of human planners (McKay & Wiers, 2003).

Fully automated planning uses algorithms to generate optimal solutions. Oftentimes in these algorithms all the variables and constraints are assumed to be known a priori. However in real life and dynamic situations, these might change and could invalidate the solution on a daily or even hourly basis. These limitations of automated optimal solutions are solved by using human planners in conjunction with automation. Especially if the human operators are allowed to conduct sensitivity analysis on the parameters of the automated planner, system performance improvement is expected (Cummings & Bruni, 2010). It is however important to note that the trust of operators in the decision support tool is a key influencing factor in system performance. If trust in the automated planning system is low the human operator will be biased towards the resulting plans (Cummings & Bruni, 2010). Therefore decision support systems should be designed as such that they do not purely intend to reduce planner workload but rather allow for sensitivity analysis and collaborative planning. Too much automation has negative effects ultimately on performance if human planners are still required to interact with the planning system. DSS can also be used for 'what-if'-scenario generation and preparation of multiple planning variants. Such plans may for example have differing planning horizons or personnel allocation. These allow the planners to check several plans, select or combine plans and achieve optimal performance and act accordingly (McKay & Wiers, 2003). Research is to be done into examining what a proper design is of a *collaborative resource allocation decision support tool*, combining human and automated planning, handling competing objective functions of multiple stakeholders and one that achieves good results (Cummings & Bruni, 2010). Integration of DSS in different planning levels (strategic, tactical, operational) and applicability of research to real life cases lacks. Furthermore evaluation systems should be considered and DSS for planning with multiple-objective functions are to be researched, as most research is limited to one or two objectives, according to Ardjmand et al. (2016).

2.3. Performance measurement in logistics

This section firstly covers more performance measurement definitions. This is followed by the difficulties experienced in performance measurement as described in literature. Furthermore best practices for formulating performance metrics are discussed and lastly methods for finding the performance indicators of a system are covered.

2.3.1. Definitions

Performance measurement, measures and measurement systems are defined:

- Performance measurement can be defined as the process of quantifying the efficiency and effectiveness of action and evaluation of performance relative to a defined goal (Neely et al., 1995) (Rose, 1995), or as "*the assessment of efficiency and effectiveness of accomplishing a given task*", with the subsequent evaluation on how well a goal is met (Mentzer & Konrad, 1991).
- Performance measure can be defined as a metric used to quantify the efficiency and/or effectiveness of an action and determine subsequent action (Neely et al., 1995) (Rose, 1995).
- A performance measurement system can be defined as the set of metrics used to quantify both the efficiency and effectiveness of actions (Neely et al., 1995).

The notions of efficiency and effectiveness are the economic measure of a firm's resource utilization given a level of customer satisfaction and to the extent to which customer requirements are met, respectively (Neely et al., 1995). Mentzer and Konrad (1991) define effectiveness as *the extent to which goals are achieved* and efficiency as *how well resources are used for achieving the goals.* It is stated that effectiveness can be measured as the ratio between realized output and the nominal level of output, whereas efficiency is the ratio between realized input and nominal input. As the performance is defined by both how the realized output achieves the desired goals and how much input was used for the respective output, performance measurement requires an assessment of the complete process.

Three main functions for performance indicators are listed by Surie and Wagner (2008): informing, steering and controlling. It is important to make sure the indicators of use are correctly interpreted and that the variations the indicators observe have a causal link to the element of the operations that is measured. Furthermore it is noted that the strategic goals and indicators have to be aligned to prevent conflicting goals. This is closely related to using *cross-functional and process-oriented* measures, which will ensure the pursuing of shared goals.

Besides the considerations in supply chain performance measurement and indicator assessment, Surie and Wagner (2008) list four KPI-categories and examples that are often applicable:

1. Delivery Performance, e.g. service levels, on-time delivery, forecast accuracy and order lead-time.
2. Supply Chain Responsiveness, e.g. flexibility measures and planning cycle time.
3. Assets and Inventories, e.g. asset turns, inventory turns and inventory age.
4. Costs, e.g. value-added drivers.

2.3.2. Difficulties

Mentzer and Konrad (1991) discuss the difficulties in performance metric establishment. One is the incompleteness (or 'underdetermination') in measuring the full aspects of the inputs and outputs. Measurements often are only taking into account a part of the full process. Furthermore comparability is an issue, as it may happen that metrics are not fully comparable to each other. Errors in performance measurement might form a problem due to faulty data collection and/or faulty identification of the contribution of certain steps. Besides this, after having established the performance indicators, the adjustment of (human) behavior based on the indicator values might occur. This behavioral change may not necessarily be beneficial. Finally one should be careful when assessing the performance metrics to industry standards or other external benchmarks as the realized performance must be compared to the prior set desired level that is in line with the company or department's goals.

A number of common mistakes trying to measure non-financial performance are discussed by Ittner and Larcker (2003):

1. Not linking metrics to strategy: Oftentimes companies measure too much because there lacks a link to the strategy and goals and therefore they do not know what to measure exactly. Consistent with what Mentzer and Konrad (1991) discuss, it is therefore key in performance measurement to firstly define the overall goal of which the performance will be measured.
2. Not validating the links: What will happen with non-financial performance metrics is that the link to the resulting financial performance lacks. The proof of the usefulness of the non-financial performance metrics in achieving better financial results needs to be given and it needs to be determined that the defined metrics are the right metrics.
3. Not setting the right targets: When measuring performance companies fail to set (the right) targets for when achievement of a certain goal on a metric will pay off in the overall performance.
4. Measuring incorrectly: It is important to, before applying the performance metrics, assure the validity and reliability of the metrics. Here validity means that a metric properly captures what it is intended for, and reliability means that the measurements properly map the performance and do not introduce other 'errors'. Additionally it is important to think about how the metrics are computed. It will occur that different business units of the same company will be measuring the same performance indicator at the same time, but in a different way or on a different level. This is non-beneficial for the overall performance as these ways may be contradictory or capture un-relatable performance.
5. Akyuz and Erkan (2010) add the mistakes of having too many metrics at the same time, making it difficult to identify the most critical ones.

2.3.3. What makes a good performance metric

Apart from the difficulties of performance metric definition and formulation, Rose (1995) and Akyuz and Erkan (2010) provide the following on what makes a good performance metric:

- Performance metrics need to be customer-centered with a focus on what provides value for the customer.
- Performance metrics need to measure performance over time, showing trends.
- Performance metrics need to provide the information directly on the level at which they apply,

not requiring further processing.
- Performance metrics need to be linked to the organization's "mission, strategies and actions" and to strategic, tactical and operational levels of decision making and control.
- Performance metrics should be developed collaboratively with stakeholders, helping in their acceptance.
- Performance metrics need to allow for setting targets, aggregation and disaggregation.
- Overlaps between performance metrics needs to be avoided.
- Performance metrics need allow prioritization/weighting.
- Performance metrics need be simple and easy to use, preferably in the form of ratios rather than absolute numbers.
- Performance metrics need be specific and non-financial, rather than aggregate and financial, to be more actionable.
- Performance metrics need be determined through discussion with all the parties involved and serve the needs of people from all levels (not only upper management).
- Performance metrics need have a proactive approach, enabling fast feedback and continuous improvement.

Akyuz and Erkan (2010) list 'total quality', 'business process', 'fit' and 'excellence' as key notions in future performance measurement and 'supply chain business excellence' is said to "deserve further attention in any future research".

2.3.4. Methods for finding performance indicators

The following steps have been identified as most important for finding KPIs and developing a Performance Measurement System (PMS) (Mentzer & Konrad, 1991) (Rose, 1995) (Reddy et al., 2019):

1. Identify the company supply chain strategy and objectives
2. Establish the problem, goal and the context of what is to be evaluated
3. Identify the attributes (inputs, outputs) of what is to be evaluated
4. Identify the right performance measures and PMS based on the supply chain strategy and objectives
5. Prioritize the selected measures with the supply chain strategy in mind
6. Quantify the measures and provide proper (mathematical) formulation
7. Inter-relate the key performance measures with the supply chain strategy subsequent to discussions with the stakeholders
8. Analyze the measures based on the step above and make sure the measures to be used are satisfactory in this sense
9. Develop a suitable supply chain wide PMS and explain to the other members in the supply chain to evaluate the PMS

Over the years, many performance measurement systems have been developed, Estampe et al. (2013) present a framework for analyzing the various supply chain PMS in terms of applicability for the analysts' system. The framework differentiates 16 performance measurement models using the following characteristics to specify each model: "(1) the model's origin, (2) the type of analysis involved, (3) implementation conditions and constraints, (4) the degree of conceptualization, (5) the quantitative or qualitative indicators being used." The framework uses the following eight parameters for filtering of the PMS:

1. Decision level (strategic, tactical or operational)
2. Type of flows (physical, informational or financial)
3. Level of supply chain maturity
4. Type of bench-marking (internal or external)
5. Contextualization (type of company/industry)
6. Quality factors
7. Human capital
8. Sustainability

The most used performance measurement systems based on empirical data, by interviewing managers from various companies and industries, are the BSC (also in modified versions), process-based measurement and SCOR model (Piotrowicz & Cuthbertson, 2015). Akyuz and Erkan (2010) and Surie and Wagner (2008) advocate the use of the SCOR model for supply chain analysis due to its suitability in terms of various levels of consideration in light of performance measurement.

2.4. Relevant studies

This section is summarized in literature table 2.1 at the end of the section.

Railyards of complex freight hubs are oftentimes, due to complexity, slow and inefficient. This influences the performance of the complete hub (Schönemann, 2016). The low performance of the rail-element of complex freight hubs is in part due to sub-optimal scheduling. Based on observations and interviews with experts, Schönemann (2016) concludes there is poor coordination in tactical infrastructure utilization planning and the process coordination quality depends on individual actors' optimization strategies. This is due to a lack of coordination among actors of the freight handling process, resulting in actors mainly planning and optimizing their part. Secondly, there is poor coordination between the logistic and railway-specific processes, resulting in local optimization rather than global optimization. And thirdly, there is too little consideration for the medium-term capacity planning, with trains being scheduled in real-time rather than some time beforehand. This results in more idle time and less productivity. It is expected that the use of a "superior coordinator", or making use of a collaborative yard planning approach, has high-efficiency improvement potential in short-term planning and dispatching in rail freight hubs. This superior coordinator could be a freight hub manager, aiming for optimization of the complete planning process (Schönemann, 2016).

Clausen and Rotmann (2014) seek to find the relevant performance indicators of industrial railway systems of complex freight hubs. This is done using the theory of measuring performance in terms of efficiency ('doing the things right') and effectiveness ('to do the right things') from Neely et al. (1995), where the effectiveness of IRS is interpreted as "quality of scheduling". Regarding effectiveness the authors do not go more in-depth, but they do specify the performance in terms of efficiency. Figure 2.4 shows the performance categories and goals as determined by Clausen and Rotmann (2014). The performance is split into three categories: quality, time and productivity, adapted from Weber (1995). Where using the term productivity as a category is better for IRS as these systems do not control the volume as this is determined by customer demand (Clausen & Rotmann, 2014).

As Clausen and Rotmann (2014) mainly focus on the efficiency side of the performance and not on the effectiveness and the planning side of IRS, Clausen and Rotmann (2014) lack to link the effi-

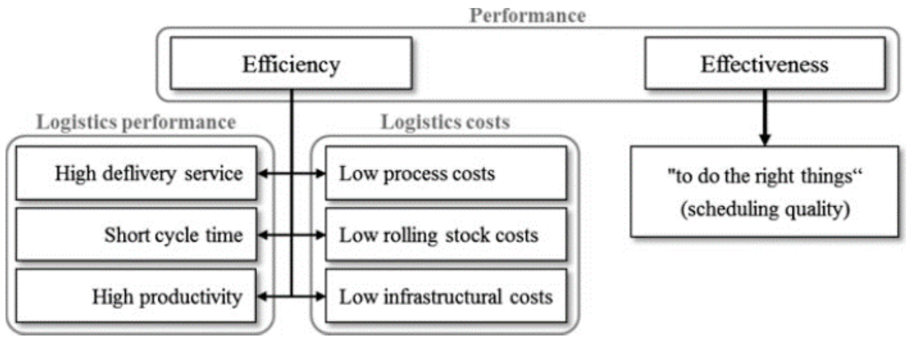


Figure 2.4: Performance categories and goals of IRS (Clausen & Rotmann, 2014)

ciency and relating logistics performance to the level of effectiveness. However, both efficiency and effectiveness should be pursued simultaneously for reinforcement (Fugate et al., 2010).

The MSc thesis from Van der Linden (2018) studying the industrial railway system (IRS) of Tata Steel IJmuiden notes that in the IRS the planning of the transports and the railway operations are separated. Planning results in orders in form of transport tasks, which in turn are performed by the railway operation department. Van der Linden (2018) recommends further investigation of the planning process as there is performance to be gained here. Currently detailed knowledge of the planning processes and accompanying performance is lacking. Information flows need to be mapped and performance parameter assessment of the planning needs to be made. It is suggested as a first step to mapping the planning process to track the original planning and its performance.

Crainic and Roy (1988) study the tactical planning process as an optimization problem which is modeled and solved using mathematical modeling and programming. Their study is proof of the ability to solve such planning problems using mathematical programming and optimization. The various possible applications of the developed tactical planning show the potential improvements compared to strictly manual planning, as planners are assisted by the program by e.g. presenting several possible plans. Díaz-Madroñero et al. (2015) state there needs to be more focus on applying these models of tactical transportation planning to real use cases.

Li and Tian (2015) study finished product logistics in the iron and steel industry. There is much research done into logistics optimization, but little into finished product logistics optimization. In the iron and steel industry, the various types of finished products are stored separately in different warehouses on-site. These products need to be transported, in case of the study of Li and Tian (2015), to the dockyard using vehicles only capable of loading a fixed number of products leading to single stop trips (visiting only one warehouse at a time) for the vehicles. Based on ship arrival at the dockyard schedulers determine which coils from which warehouse needs to be transported. Furthermore the schedulers need to consider inventory levels in the warehouses, preventing reaching capacity, called *consolidation planning*. Following the determination of the consolidation plan the schedulers formulate the transportation plan, which allocates vehicles to warehouses and prescribes loading sequences at the warehouses. Within the process as described by Li and Tian (2015) two main objectives are determined: maximizing ship loadage and maximizing logistics efficiency. In practice however these objectives contradict oftentimes. The manual method of sequencing the formulation of first the consolidation and then the transportation plan does not guarantee optimality and is expected to be inefficient. To address this, Li and Tian (2015) study the potential of integrated optimization of these planning decisions by formulating a mixed-integer programming model and solving this using a *two-layer multi-objective variable neighborhood search (TLMOVNS)* algorithm. What lacks with their study is the human planner aspect and consideration of Decision Support in the planning. Furthermore no details are given into the KPI determining nor are the determined KPIs evaluated for appropriateness.

It is furthermore noted in Caris et al. (2008) that real-world planning and operational management are heavily influenced by uncertainty in processes and operations. There is a reported limited number of scientific publications on intermodal planning problems on operational decision level and a need for more integration of planning problems on multiple decision levels. Later Caris et al. (2013) published a research agenda on decision support in intermodal transport. Here the trends in decision support systems are discussed. It is noted that there is a lack of understanding of all the actors involved in the various levels of the DSS, which leads to sub-optimal usage and solutions. Furthermore the objectives of the various actors should be integrated better. The decision support system in planning is also discussed in Beyer et al. (2016). In their article the potential of such planning support systems is emphasized as the planning of intra-logistics has increased in complexity over the years. Planning decision support systems aid the planner in reacting to changing conditions and uncertainty in a flexible manner and reduce the duration of making the planning, whilst increasing the systematization of the intra-logistics planning.

Bouchard et al. (2017) study the combination of strategic and tactical level planning decision making in the forestry industry. The decision problem is dissected into a two-stage formulation and solved by two solvers in an integrated iterative manner. Profit gains are made by applying integrated planning. Planning performance of the integrated plans is higher than the non-integrated plans.

Mostafa and Eltawil (2016) review literature on the integration of production planning, inventory management, distribution planning and routing scheduling, or the PIDRP problems, resulting in vertically integrated supply chains. It was concluded that there is an increased interest in literature in recent years into such integrated problems. However these are mostly constrained to less complex situations, considering e.g. only a single plant or homogeneous fleets. Furthermore there is a gap between research and industry due to the limited use real-life studies.

McKay and Wiers (2003) study the '*integrated planner*'-approach used in *focused factories*. The integrated planners perform planning, scheduling and dispatching, resulting in decisions with all relevant levels in mind. Such plans and decisions reduce the amount of finger-pointing and increase the speed and accuracy of plans. Hierarchical and integral planning are two of the three characteristics of *Advanced Planning Systems (APS)*, with the third being 'true optimization' (Fleischmann et al., 2008). True optimization is achieved by correctly finding and defining the alternatives, objectives and constraints of the planning problems and using either exact or heuristic optimizing planning methods. Advanced Planning Systems visualize the information, lower overall planning time and apply optimization methods. This computerization and possible automation of the planning leads to fear of substitution for human planners, however the APS modeling will be a simplification of the real-world systems. Therefore the experience, knowledge and skill set of human planners will still be required and APS will remain decision support systems for human planners. In the case of event-driven APS, human planners will define when an event is a trigger to re-plan.

Shipment Consolidation and Dispatching problems are discussed by Ghiani et al. (2004). In the Shipment Consolidation and Dispatching problem, the shipper "has to choose the best way for timely delivery of orders to customers during a time horizon divided by T" (Farahani et al., 2011). Shippers are to find the optimal mode of transportation (in the case of Tata Steel IJmuiden: which wagons) for each shipment and the best way to consolidate shipments and the start time of dispatching the shipments. This problem is a minimization model of the objective function being the total cost of delivery. Oftentimes the objective is to achieve a pre-defined service level whilst operating at minimal total cost. Ghiani et al. (2004) give three reasons for the application of quantitative analysis to planning systems:

1. If a logistics system already exists, one may wish to compare the current system design (or operating policy) to an industry standard.
2. The wish to evaluate specified alternatives (what if ...) to the existing system.
3. The wish to generate a configuration or a policy that is optimal or at least good for a given performance measure.

Finally Ghiani et al. (2004) advocate the use of benchmarking for comparison of performance to the best-practice current standard, i.e. use of internal benchmarking. For this performance evaluation the SCOR (Supply chain operations reference) model is advised for both its high and low-level KPIs.

Table 2.1: Relevant literature overview, number of checkmarks per source indicate the focus areas of this thesis in terms of the presented research opportunities

Source	Focus	Lacking	Opportunities	This study
Schönemann (2016)	Performance complex freight hubs	Coordination among actors & processes.	Collaborative yard planning approach	✓
Clausen and Rotmann (2014)	Performance measurement of IRS	Linking efficiency and logistics performance to effectiveness	Both efficiency and effectiveness should be pursued simultaneously	✓
Van der Linden (2018)	Capacity of the IRS of Tata Steel IJmuiden	Detailed knowledge of the planning processes and accompanying performance	Performance improvement of the planning process by mapping the planning process	✓✓✓
Crainic and Roy (1988)	Tactical planning process as an optimization problem	-	Potential improvements of added automation compared to strictly manual planning	✓✓✓
Li and Tian (2015)	The potential of integrated optimization	Human planner aspects and consideration of Decision Support elements. KPI determination and evaluation.	Extend the scope of what they did with the considerations of DSS, human planner and focus on performance measurement	✓
Caris et al. (2008), Caris et al. (2013)	Research agenda on decision support in intermodal transport	Understanding of the actors on multiple levels of DSS, leading to sub-optimal usage and solutions	Integrating objectives of the various actors better	✓
Bouchard et al. (2017)	Combination of strategic and tactical level planning decision making	Human planner aspects and consideration of Decision Support, KPI determining and evaluation	Application of integrated planning with higher planning performance	✓✓
Díaz-Madroñero et al. (2015)	Tactical transportation planning	Focus on application of these models to realistic use cases	Application of these models to realistic use cases	✓✓✓
Mostafa and Eltawil (2016)	Literature review on PIDRP problems	Research limited to less complex situations, considering e.g. only a single plant or homogeneous fleets. Limited use real life studies	Application on real life use case	✓✓✓
McKay and Wiers (2003), Fleischmann et al. (2008)	Integrated planning approach	-	Optimizing by finding and defining the alternatives, objectives and constraints of the planning problems and using either exact or heuristic optimizing planning methods	✓✓
Ghiani et al. (2004)	Shipment Consolidation and Dispatching problems	-	Evaluate specified alternatives, generate optimal configuration or policy with respect to a given performance measure and use benchmarking for performance comparison.	✓✓

2.5. Conclusions

This chapter firstly discussed relevant background literature on on-site logistics, planning and decision support, performance measurement and finally relevant studies. Apart from providing relevant background and mapping the knowledge gap in on-site logistics and transportation planning, one of the intentions of this chapter is to answer the first research question:

SQ 1: *What are the characteristics of on-site logistics and industrial railway systems?*

Based on paragraph 2.1 the following is given as the answer to the first research question: Depending on the focus of the on-site logistics system, its functional operations can either be categorized as procurement logistics, production logistics or distribution logistics, with agreed service levels with customers. For its operations on-site logistics makes use of site infrastructure consisting of traffic facilities, transshipment and storage facilities. Site infrastructure can be structured in various network arrangements and distribution structures, such as hub-and-spoke networks and many-to-many distribution. Furthermore the characteristics of on-site logistics depend on the type of goods that are transported, the type of terminals in the network and the way the network is used. This study in particular addresses rail-based on-site transportation. In rail-based on-site transportation loads can be transported in either wagon-load or block train configurations, having implications on yard types required for shunting and load consolidation. Key tasks of on-site transportation systems are collection and delivery of goods and being a buffer for the previous and subsequent systems. The flow in an on-site logistics system is either push or pull, depending on the surrounding systems. These surrounding systems also influence the storage functions found in the system and finally guide-path classification is presented, analyzing the IRS network structure.

Important is to note that much literature can be found on distribution planning, production planning, warehouse design and planning in general. However, when considering the on-site logistics of large manufacturing sites or on-site logistics of (large) complex freight hubs, there are many similarities to be drawn but also key differences. Some of these differences include the importance of one major stakeholder having ownership of the full site and part of the supply chain. Service level agreements are made within the same company between departments, and costs and competition are very different from 'regular' supply chains. For instance a conventional external customer-supplier relation lacks in the use case of the warehouse plan of Tata Steel IJmuiden. In chapter 4 the use case of Tata Steel IJmuiden is characterized based on this literature study.

There is a high potential, based on literature, in the application of decision support in planning on real-life use cases. Combining both human and automated planning benefits and creating an integrated planning approach that finds system optimal solutions and allows human planners to make better and more funded decisions. Highlighted for further research, and expected to result in performance improvements, is the inclusion of proper performance measurement by using a suitable performance measurement system. Development of a decision support system and application of a performance measurement system to a real-world case with multiple objectives on multiple planning levels, in the on-site logistics sub-field, will be a contribution to the current body of knowledge. Literature highlights these research opportunities but does not yet fully fills the gap.

3
Methodology

To answer the research questions and achieve the goal of gaining insights into the on-site transportation planning of large manufacturing plants and their performance measurement, a methodology has been drafted. This methodology is discussed in this chapter. The main goal of this chapter is to present and discuss the steps, tools and methods used in this research to answer the main research question:

How can the on-site transportation planning at a large manufacturing plant be improved, by 1.) adding company KPIs and 2.) data-driven decision support based on the parameters of the locality and its constraints?

The methodology used for this research consists of a combination of process analysis methods and tools from the System Analysis field and the DMADE design framework. Furthermore a combination of quantitative and qualitative analysis is used. This combination of fields and analyses is used due to the characteristics of the system and problem. The tools from the System Analysis field, as described in Veeke et al. (2008) and Duinkerken and Schulte (2019), are useful for defining the current (planning) process at Tata Steel IJmuiden. The DMADE framework is an adaptation of the better known DMAIC lean six sigma method for finding improvements in processes. The letters of DMADE stand for: Define, Measure, Analyze, Design and Evaluate (Vleugel, 2019). DMADE represents the five key steps from first assessing the processes to designing the right solutions and evaluating these with the original situation.

The methodology follows the steps towards proper performance measurement system formulation in terms of the right KPIs for on-site transportation planning. Thereafter the development of a mathematical model that is capable of generating on-site transportation plans is done. The results of this model, i.e. the generated plans, are compared to historic plans to evaluate the KPIs and determine the potential performance improvement resulting from data-driven decision making in planning.

3.1. Used framework

Each element of the DMADE framework has corresponding sub-research questions and tools, models and steps in the methodology. In this section these are listed based on the categorization of the DMADE framework. In figure 3.1 the methodology is graphically represented, here each step of the DMADE framework is linked to the corresponding sub-research questions and chapters.

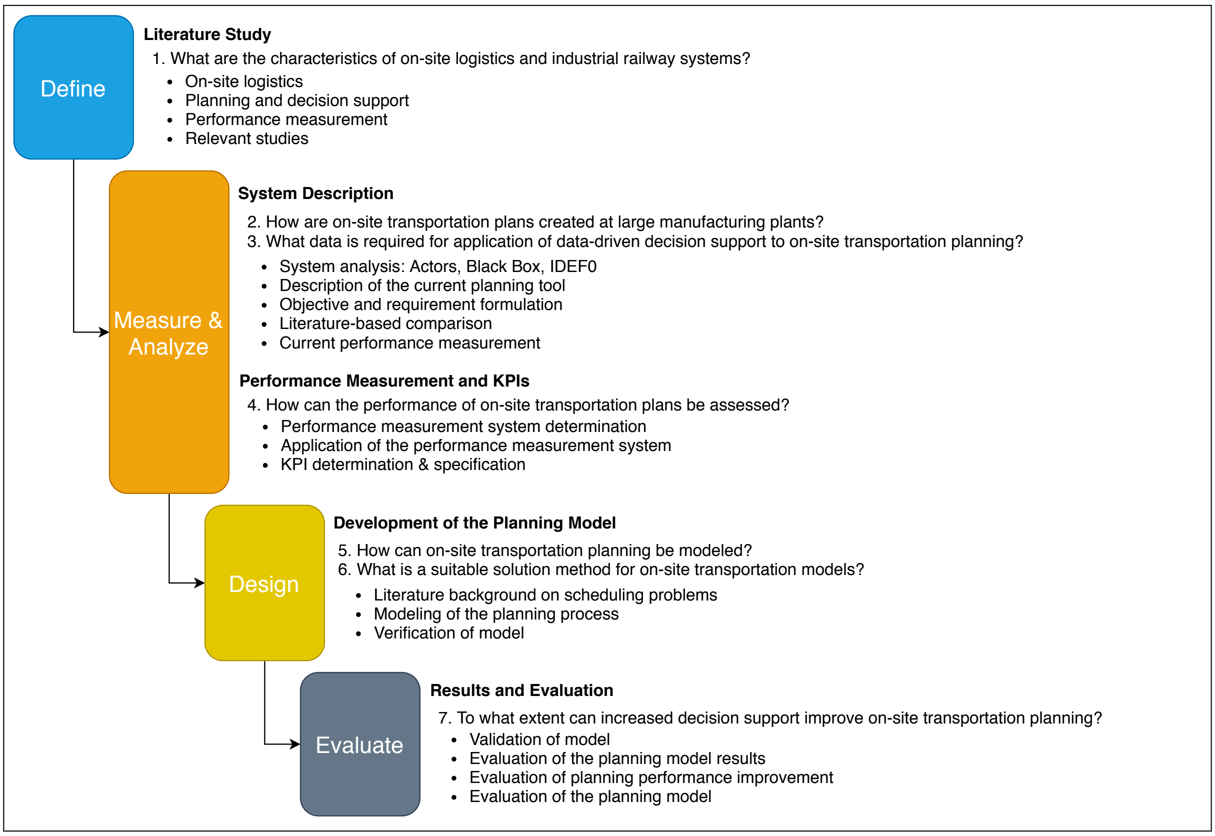


Figure 3.1: Graphical representation of the methodology, linking the DMADE steps to the sub-research questions, chapters and intermediate steps.

D: Define - Define the problem, background and foundation

In this first step of the DMADE framework, the background and foundation in terms of literature is made. Literature study is done into the field of on-site logistics and industrial railway systems, decision support in planning, performance measurement and relevant studies. This is done to provide the foundations from literature and map the current literature gap. Furthermore methodological leads and best practices are found. This part of the methodology is covered in chapter 2, which answers the first sub-research question:

1. What are the characteristics of on-site logistics and industrial railway systems?

M & A: Measure and Analyze - Map and analyze the system

The measure and analyze steps are often intertwined in the DMADE framework. In this combined step the Tata Steel IJmuiden use case is analyzed. This is done using System Analysis tools such as the *black-box model* and *IDEF0 (IDEF-Zero) diagram* to formulate a comprehensive system description and analysis. Interviews are done to map the process and determine the objectives and requirements of the on-site transportation plans. Furthermore documentation from Tata Steel IJmuiden is used as a source of information on the processes and objectives, requirements and performance indicators.

The M & A step is split into two chapters; chapter 4 and chapter 5. Chapter 4 is the system description of Tata Steel IJmuiden, intended to answer the second and third research questions:

2. How are on-site transportation plans created at large manufacturing plants?
3. What data is required for the application of data-driven decision support to on-site transportation planning?

The following tools and models are applied in this step of the methodology:

1. Actor analysis & Black box model of the planning process
2. Description of the current planning tool
3. IDEF0 diagram of planning process Tata Steel IJmuiden
4. Goal and requirement formulation of the on-site logistics process and warehouse plan
5. Literature comparison of Tata Steel IJmuiden
6. Current performance measurement of the warehouse plan

Actor analysis and the black box model are used in the system description chapter to describe the actors in the process and to illustrate the planning process at the use case in terms of input, output, parameters, constraints, requirements, disturbances and Key Performance Indicators. Furthermore the current planning tool is described to give more insight into the current practices. An IDEF0 diagram is made of the process from plant activities to on-site logistics to on-site planning to the warehouse plan. Using IDEF0 the data flows and functional flows become clear.

The following requirement techniques are used in this research to determine all three requirement types: interviewing, brainstorming and systems archaeology. These are chosen for their suitability, current research possibilities and the expected results of their combination. More details on this are discussed in appendix B.

Based on the literature study of the Define step, chapter 2, functional attributes of the Tata Steel IJmuiden use case are discussed. This links the use case system description to the supply chain and logistics typology found from literature. Finally the current way of measuring the performance of the on-site logistics and warehouse plan at Tata Steel IJmuiden is discussed.

In the second part of the M & A step, chapter 5, a suitable performance measurement system for the on-site transportation planning is determined. This is done using the literature study of chapter 2, which found a framework for PMS determination. The following steps are done in this part of the Measure & Analyze step:

1. Determining the suitable performance measurement system
2. Application of the performance measurement system, resulting in fundamental KPIs
3. Determination of the use case specific KPIs
4. Specification of the use case specific KPIs

This answers the fourth research question:

4. How can the performance of on-site transportation plans be assessed?

D: Design - Develop the solution
In the Design phase a suitable planning strategy and solution algorithm for the on-site transportation planning is determined. This is firstly done through a literature study on scheduling problems. A mathematical model of the optimization problem is made and discussed in chapter 6, includ-

ing decision variables, objective function (goal), constraints, parameters (inputs) of the warehouse planning process. This model is solved and verified. The fifth and sixth research questions are answered in this step of the methodology:

5. How can on-site transportation planning be modeled?
6. What is a suitable solution method for on-site transportation models?

The following steps are taken during this part of the methodology:

1. Model conceptualization
2. Literature background: scheduling problem classification
3. Mathematical formulation of the planning model
4. Solving the model, discussing modeling simplifications, assumptions and parameters
5. Verification of the planning model

E: Evaluate - How does the solution perform
Finally in the evaluation step the performance of the developed planning strategy is assessed. This aims to answer the final sub-research question:

7. To what extent can increased decision support improve on-site transportation planning?

The following steps are taken during this part of the methodology:

- Validation of generated plans
- Comparing original plans to new plans based on determined PMS and KPIs
- Experimentation with the planning model
- Evaluation of the planning performance improvement
- Evaluation of the planning model

3.2. Available information & data acquisition

To apply the suitable performance measurement system and planning model, data needs to be available. This data is obtained from the Planwise logs and supporting systems Tata Steel uses. Required data includes past transports, port-planning and the rail-plan (which train leaves from where). Other data such as the speed of the trains and amount of wagons are known. Transit times are extracted from Planwise and personnel availability is known.

All required information is obtained from Tata Steel and ORTEC. There is a lot of knowledge within ORTEC on the Tata Steel processes and in the fields of optimization, programming, Operations Research and performance measurement. Furthermore Tata Steel has agreed to full co-operation and provides two unofficial supervisors, one of whom with direct access to the relevant data at Tata Steel IJmuiden and another senior on-site transportation planner, both considered experts on the on-site transportation plans and logistics. If the required data lacked or was not available, assumptions and experience-based data have been used to fill the gaps.

4
System Description

This chapter discusses the system description of the use case that is applied in this research: the on-site transportation planning process of Tata Steel IJmuiden. The system description is, as described in chapter 3 a large part of the Measure and Analysis phase of the methodology. The goal of this chapter is to describe the use case and the planning process this research considers and to answer the following two research questions:

SQ 2: How are on-site transportation plans created at large manufacturing plants?

SQ 3: What data is required for the application of data driven decision support to on-site transportation planning?

Answering the above presented research questions is done by covering the following points:

4.1 General description
4.2 Actor analysis
4.3 Black box model
4.4 Current planning tool: Planwise
4.5 Current planning process - structure
4.6 Current planning process - timing
4.7 Objective and requirement formulation
4.8 Characterization of the use case based on literature
4.9 Current performance measurement

Finally in section 4.10 this chapter is concluded and the answers to the research questions of this chapter are discussed.

4.1. General description

The process of making the on-site transportation plans that govern the logistics operations at the Tata Steel IJmuiden facilities is elaborate and complex. Tata Steel IJmuiden is one of the largest steel production facilities in Europe and over 100 kilometers of rails connect the various locations around the site. The steel products Tata Steel makes are transported between facilities such as the hot rolling mill and the packaging facilities, but also from storage locations to the export locations such as the transit hall and all-weather terminal for loading onto ships. Figure 4.1 shows the 750 hectares Tata Steel IJmuiden facilities. This thesis only considers transport movements and planning on the central network, i.e. to the right of the red line. Here mainly (semi-)finished products are transported between warehouses and production facilities and to and from the port and rail yard.

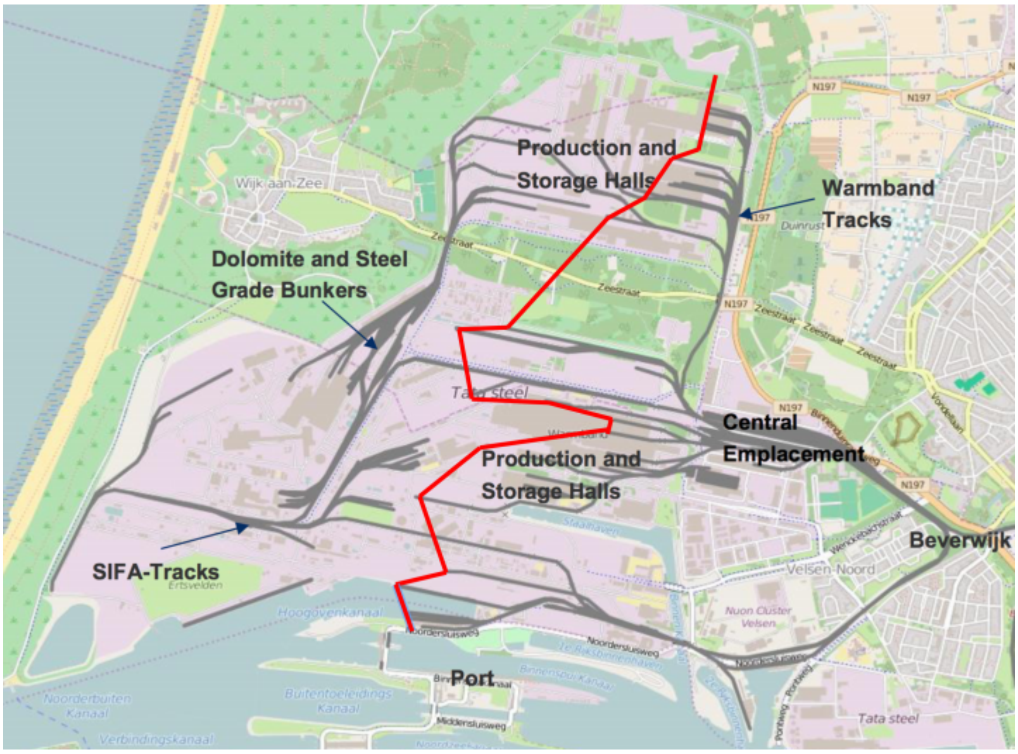


Figure 4.1: Map of the Tata Steel IJmuiden facilities, the red line is the non-physical separation of the west and central networks. On the west network (left) mainly raw materials and liquid steel are transported, on the central network (right) the various (semi-finished) steel products are transported. Source: Van der Linden (2018).

4.2. Actor analysis

Within the organization of Tata Steel IJmuiden, the OSL department of Tata Steel IJmuiden is responsible for the logistics processes between the facilities. The logistic processes range from the import of raw materials to crane movements in warehouses. The OSL department has several subdepartments with their separate responsibilities: Stevedoring & Warehousing (S&W), OSP and Rail. In figure 4.2 a chart is presented which illustrates the three sub-departments of the overarching OSL department. Furthermore the three major categorizations (Outbound, Inbound and Repositioning) of transports as operated by the OSL department are shown, along with the different modalities that are used in these transports. The warehouse plan, being the focus of this research, is governed by the warehouse planners and the dispatchers of the On-Site Planning (OSP) department.

4.2.1. OSP department

The OSP department has the role of planning the transports from warehouses towards the outbound terminals: inland and seaport, railyard and road transport. Besides this the OSP department schedules inbound transport and internal repositioning of goods between warehouses via rail. The OSP department consists of planners and dispatchers.

Planners
The planners (port, rail and warehouse) each have their own focus areas. Port planners plan the port operations, for instance assigning vessels to quays, and rail planners are responsible for incoming lime trains and outbound rail transport. The warehouse planner is responsible for all operational tasks concerning the warehouses at the IJmuiden site. They determine which load is transported using which wagon-subtype and at what time and govern the storage filling levels of the warehouses.

Dispatchers
Where port, rail and warehouse planners make the plan for the coming day(s), dispatchers govern the plan in real-time. The dispatchers adjust the warehouse plan if, for instance, disturbances cause disruptions in the operations. They supervise the plan and during weekends take over the planning task of the planners. Dispatchers are the only ones allowed to adjust the plan during the next 4 hours.

4.2.2. Stevedoring & Warehousing department

The Stevedoring & Warehousing department is responsible for operations at the warehouses and the port. This includes cargo loading and unloading on and off wagons in the warehouses and at the port. This means the crane operations, their drivers and the loading crews at the warehouses and port are under their control. For the OSP department this means that a large part of the planning being done heavily impacts the operations under the wings of S&W, e.g. in terms of workload. However in turn the OSP plans are very dependent on the operations of S&W.

4.2.3. Rail department

The tasks planned by OSP are performed by the rail department. Therefore the rail department makes sure empty wagons arrive at warehouses for loading and the unloaded wagons leave the quay. Furthermore the rail department governs the assignment of locomotives, train drivers, train & wagon movements and routing over the rail network. Besides making sure the planned activities take place, the rail department also has the responsibility to govern the safe execution of the plan, plan and conduct maintenance on the rail network and the rail network itself has an important buffer role for the production and storage system of Tata Steel IJmuiden. This buffer is used to ensure production can continue as storage nears its limits. By moving some steel from stores to wagons and placing these on designated yards the buffering functionality is performed.

4.2.4. Information flow

Transport starts with a request from customers, which is translated by On-Site Logistics into tasks that overall form the full transport of products from production to the customer. Customers require a specified delivery moment, resulting in a departure time for either outbound vessel, train or truck. Departing vessels want to minimize their time in port and strive for on-time departure. Export trains depart on their scheduled departure time no matter what, due to the congested hinterland rail network and fixed timetabling, so there are no delays possible here. Whereas vessels and trains require more significant planning, loading of trucks is planned in between other warehouse crane tasks. Via the Sales Department and Outbound department (OTB), transport tasks arrive at the OSL department. OTB determines which products need to be transported from which warehouse to which vessel and at what priority. Transports have a rough plan at this stage, consisting of the steel coil type, amount and total volume and the transports are designated to a route, carrier and modality ('handling unit'). This vessel is planned by the port planner, causing transport tasks (X amount of coils from warehouse Y to quay Z) for the warehouse planner to plan, in turn resulting in a demand for specific wagons and a locomotive to move the wagons to-be-planned by the rail planner.

Besides customers, another large transport task supplier is the internal repositioning of goods between site locations (warehouses, production facilities). Repositioning occurs for two reasons, to manage storage capacity in warehouses or storage areas to keep production going and repositioning is requested for conditioning reasons as some products may not be held for too long in unconditioned warehouses or locations, due to corrosion risk. Internal repositioning tasks are requested by site locations to the OSP department.

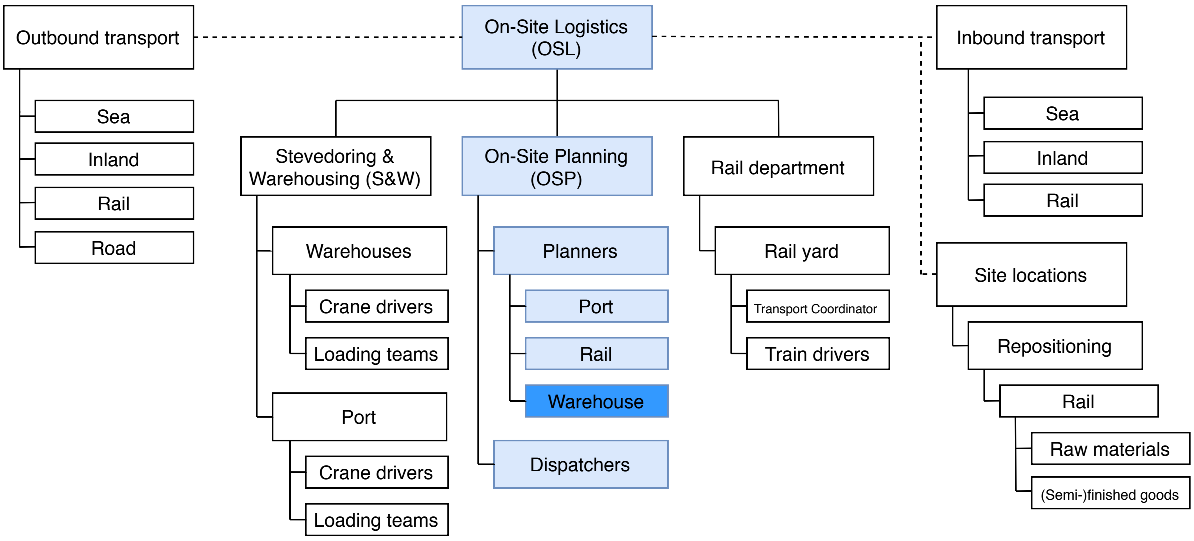


Figure 4.2: Organogram of the on-site transportation process of Tata Steel IJmuiden, focus in this research is on the blue-marked department and actors, especially the darker blue warehouse plan.

Port planning splits the loading of deep sea vessels into grouped clusters of steel coils. This is done to deal with the extensive loading time of deep sea vessels due to the large volume of steel transported per vessel. These clusters are governed in the cluster plan, derived from the stowage plan, which the warehouse plan needs to consider in the case of deep sea vessels.

Finally planners and dispatchers plan *P-klussen*. These are tasks which did not transfer properly from other systems, such as inbound steel trains, inbound and outbound vessels and internal repositioning tasks. These appear separately in the planning system Planwise and need to be manually planned.

4.3. Black box model

In this section, a black box model representation of the planning process is presented. The black box under consideration here results in the warehouse plan as output. The purpose of the black box model is to give a high-level process analysis, showing the inputs, influencing factors and output of the planning process in place at Tata Steel IJmuiden. Later in section 4.5 the black box in this model is specified in more detail using an IDEF0 diagram. In the black box model elements are grouped as input, these elements are considered to be variable in the process, e.g. the amount of outbound transport demand changes over time, whereas the requirements for the process are predetermined and fixed over time.

In the black box model of figure 4.3 the elements are color grouped. In orange, three of the inputs are grouped as these are the inputs that represent the actual to-be-planned movements. *Outbound transport* for instance is in form of loads that need to be fulfilled for a vessel. Here the transports from storage(s) to the port need to be planned. In gray the parameters of the planning process are represented. These include travel time between locations or (un)loading speeds of cranes. The constraints and requirements in green limit the process. In constraints the available resources such as cranes, tracks but also the maximum amount of workload is included. In yellow the disturbances that may hinder the process are represented, e.g. the weather, as some cargo may not be transferred during rain. Finally in purple the KPIs determine the performance of the warehouse plan resulting from the planning process.

The distinction between constraints and requirements is purposefully made in this analysis. In section 4.7 the requirements are specified and in chapter 5 the KPIs are discussed.

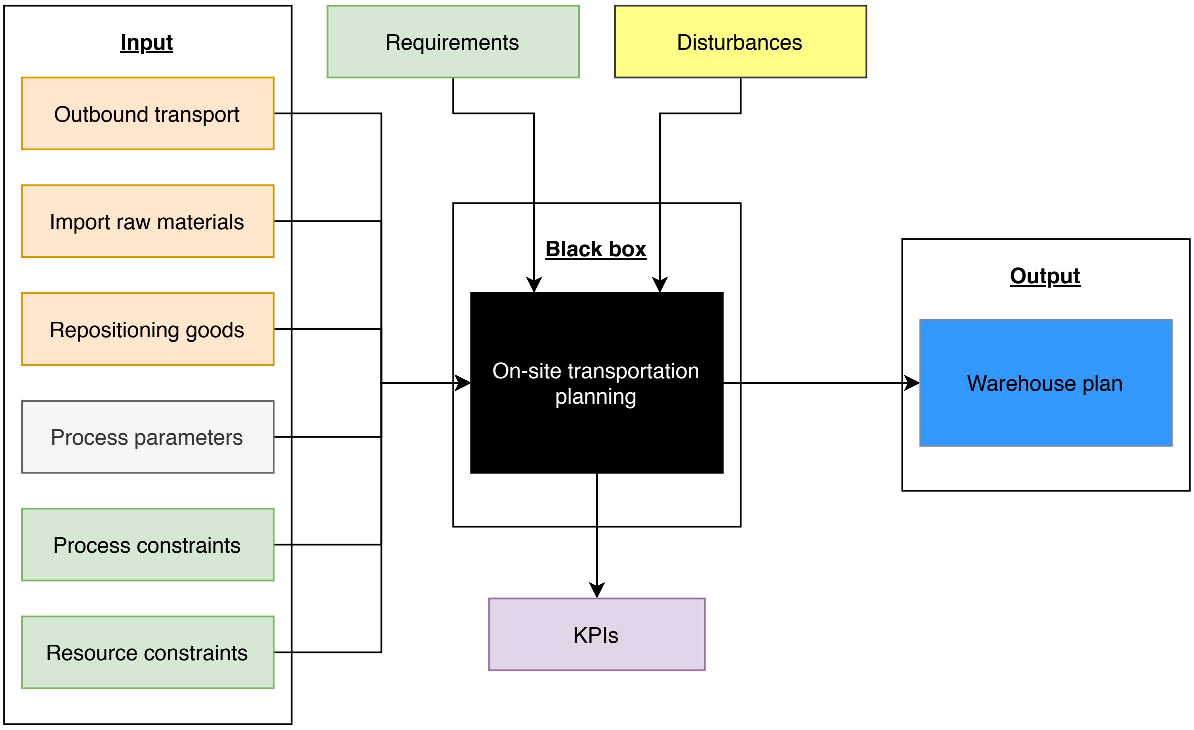


Figure 4.3: Black box representation of the on-site transportation planning of Tata Steel IJmuiden, resulting in the warehouse plan

Each of the elements of the black box model is discussed below.

4.3.1. Input

Outbound transport

- Sea
  - Deep sea, including stowage plan consideration
  - Short sea
- Inland
- Rail

- Road

In the case of deep sea transport, Tata Steel IJmuiden uses a derivative of the stowage plan, the cluster plan. This is the stowage plan broken down into transportable batch sizes and needs to be considered in the warehouse plan.

Import raw materials

- Rail: Lime trains

The only type of import considered in the warehouse plan and OSL department is inbound lime trains. Other imported goods are out of the scope of the OSL department.

Repositioning goods

- Rail: Semi-finished and finished products

Repositioning of goods is only done using the rail network and only the semi-finished and finished product repositioning is within the scope of the warehouse plan. This repositioning is done to balance storage capacity over the facilities, making sure production can keep on going and to store the products in their required conditioning environment.

Process parameters

- Time based: Loading and unloading , travel time between site locations, shunting time.
- Prioritization of tasks
- Locations:
  - Seaport (2 quays)
  - Inland port (1 quay)
  - Rail yard
  - Warehouses types (3):
    - Quay warehouse
    - Production warehouse
    - Storage location (not all storage is covered)
  - Warehouse clusters (9):
    - HAV
    - ZD1 WAW
    - CPR
    - Cluster Zuid
    - TSP
    - Cluster Midden
    - Cluster Noord
    - AOV
    - RVE

The process parameters can be categorized into 3 categories: Time based parameters, prioritization and the various locations. The locations consist of the various outbound and on-site terminals linked to each modality. Road transport is done directly at warehouses. Quay warehouses are used in the port for short term storage, production warehouses are in the process of producing goods and also only facilitate short term storage. Storage locations are broader than only warehouses, there are for instance outdoor shunting areas where loaded wagons are positioned as a storage facility.

Warehouse clusters:
The Tata Steel IJmuiden site is divided into clusters. These clusters are geographically grouped and the workforce used to load and unload wagons at warehouses is also grouped in these clusters. Per cluster the workforce is used for all of the warehouses or site-locations such as open-air track-based storage in that cluster.

Process constraints
The process constraints are categorized into eight main categories. Safety constraints are for example limitations to the number of locomotives or trains that are allowed in one of the warehouse clusters. This is to limit the chance of collisions on track. The resource availability constraints contain for instance the limited number of cranes at a quay or in a warehouse or a warehouse being closed. The resource capacity constraints limit for instance the number of wagons that can be stationed at a quay or warehouse due to the track length. Operating speeds are considered as both parameters and constraints, as their value has a hard constraint due to for instance a crane not being able mechanically to operate faster. Furthermore, warehouses also plan their operations, constraining the warehouse plan and steel production limitations might constrain the planned operations of the warehouse plan.

- Safety constraints
- Resource availability:
  - Warehouse availability
  - Crane availability
  - Workforce availability
  - Wagon availability
  - Locomotive availability
- Resource capacity:
  - Operating capacity (weight limitations) cranes
  - Warehouse (storage) capacity
  - Wagon loading capacity (+ multiple ways of loading a wagon and wagon combinations)
  - Quay track capacity
  - Rail yard capacity
  - Warehouse track capacity
  - Locomotive tractive force
- Operating speed cranes and workforce
- Co-planning of warehouses, i.e. warehouses, organizing their operations, influence the warehouse plan
- Steel Production
- Rail network constraints
- Resource constraints:
  - Warehouse product type constraints
  - Wagon product type constraints

Resource constraints

Finally resource constraints, as part of the overall constraints, provide more detail into the characteristics of the handled products and wagons. The various product and wagon types handled in the on-site transportation plan of Tata Steel IJmuiden are categorized as follows:

Product types:

- Steel:
  - Coils
  - Slabs (Plakken)
  - Packages
  - Tinplate sheet (Blik)
- Bulk: different lime types

Product considerations:

- Orientation (vertical or horizontal)
- Conditioning (transportation and storage)

Broadly speaking products can be split into steel and bulk product types, with four main steel product types. These steel product types can be orientated vertically or horizontally, which needs to be considered in the loading of wagons. Furthermore some steel products are restricted by different conditioning requirements. Conditioning is both in transportation and storage of importance; some products are allowed to become wet and stored outside, others are not allowed to become wet and need to be kept in specific conditions and other products fit somewhere in between.

Wagon types:

- Internal wagons: (not braked)
  - Covered - separate
  - Covered - set
  - Unconvered - separate
  - Uncovered - set
- External wagons (braked and covered)

The loading capacities of wagons vary over the various wagon types, both dependent on the wagon configuration and the product orientation. But wagons are also categorized by internal and external usage, external wagons have braking systems and are always covered whereas wagons for internal usage don't have brakes and may or may not be covered. Internal wagons also come in sets or individually.

4.3.2. Requirements

The requirements of the on-site transportation planning are discussed in section 4.7.

4.3.3. Disturbances

- Weather
- Loading faults
- Unloading faults
- Planned disturbances:

    - Track maintenance
    - Locomotive refueling (1 hour)
    - Crane maintenance
- Ship delayed
- Ship rejected for loading
- Damaged goods
- Equipment malfunction
- Waiting for cargo
- No workforce present or available
- Production disturbances

Disturbances hinder the on-site logistics and warehouse plan after the plan has been made. This ranges from changing weather conditions to ships being rejected for loading while a loaded train is at the quay with the cargo for the vessel and the quay is therefore occupied. It may also happen that goods are damaged during handling or before handling. Apart from disturbances that occur more frequently and have a manageable impact on operations, there can also be disturbances such as accidents. However, accidents cannot be taken into account in the planning process itself beforehand as these are rare and highly variable in terms of their impact on operations.

4.3.4. KPIs

The KPIs of the on-site transportation planning are discussed in section 5.4.

4.3.5. Output

The main output (under consideration) is the warehouse plan. Each workday the warehouse plan is made, defining the operations from at least 14:00h on the day of release till 22:00h the next day. The warehouse plan consists of the following five main elements:

Warehouse plan:

- Cranes and workforce operations at terminals (warehouses, port)
- Wagon sub-type allocation
- Transport task schedule (start time, end time)
- Prioritization of tasks
- Wagon loading configuration

The warehouse plan continuously prescribes the loading and unloading operations of wagons at the warehouses, fulfilling the transport requests as requested by OTB. Furthermore the warehouse plan ensures the manufacturing process can continue by freeing up storage at production facilities. The warehouse plan governs crane and workforce operations and includes wagon allocation to the transportation tasks. The loading configuration of these wagons is also part of the warehouse plan.

4.4. Current planning tool: Planwise

Planwise is a real-time, multi-user system, used to support the decision-making in the planning of tasks within a company. Planwise makes use of order lines, where multiple tasks can be designated to resources. There are several ways to display the input and planning in Planwise: data lists, planning boards, graphical views and reports.

Planwise has been deployed by ORTEC to support Tata Steel IJmuiden in planning, monitoring and administration of the on-site transport of steel and bulk goods on the IJmuiden facilities (ORTEC, n.d.-b). The role of Planwise is primarily to support the On-site planning department's planners with making the stowage plans (order clustering of loads for proper loading into vessels for customers), port plans, warehouse plans and wagon- and locomotive plans. Furthermore it plays a supporting role in the overall rail plan, lime plan (importing raw materials) and maintenance planning of the industrial railway system (Tata Steel, n.d.-b). Planwise is split into the warehouse-port process (Hal-haven process) and the wagon-loco process. The first is used for planning the loading and unloading of cargo at quays, cranes and warehouses, and the second is used to plan the rail operations.

Within the warehouse plan there are three designations for task status: not-started, started and completed. The status can be modified manually or via the progress interface of TRIP or via Collo declaration later on.

Each cargo has a cargo key (lading sleutel), consisting of:

- Transport number
- Import/Export designation
- Destination, tacking number, destination port
- Material type
- Shipment number, LI number
- Warehouse or warehouse group designation
- IVV wagon number

A screen capture of the Planwise system is shown in figure 4.4. In Planwise there are several plan boards, with horizontally the time axis and vertically the various resources (cranes, warehouses, quays). The planning can be made by dragging & dropping tasks into a plan board or by manually making a task. Here several filters are available to have Planwise show only specific tasks or resources. The color scheme in Planwise assists the planners with what tasks are e.g. conflicting with constraints, are yet to be planned or are in the past. SAP and IVV (other software systems) push transport tasks to Planwise, these tasks show in orange (not yet planned) in the lower section of the *hal-haven planbord* (figure 4.4).

The double vertical white lines in Planwise show the planners what is in the bounds of the coming four hours. In general tasks are fixed within this time envelope and based hereon operations run.

The transport tasks in Planwise are categorized as: sea transports or shipments (verschepingen), rail transports (railtransporten) and repositioning transports (omrijzendingen). Furthermore the transports are split into their various sub-tasks: warehouse tasks, crane tasks, quay tasks, etc. Each task in Planwise has a pick-up time window, delivery time window and cargo characteristics (number of wagons, number of coils and weight of the coils), illustrated in equation (4.1), adapted from Van der Linden (2018).

Apart from the *hal-haven planbord*, Planwise also has the *Wagon Loco planbord* and a visual track manager board for planning the rail operations.

$$\text{Transport task} = \begin{cases} \text{On-site origin, e.g. warehouse,} & [t_{o,1}, t_{o,2}] \\ \text{On-site destination, e.g. quay,} & [t_{d,1}, t_{d,2}] \\ \text{Cargo data,} & [\text{\# Wagons, \# Coils, Weight}] \\ \text{Timing data,} & [\text{Start time, loading duration,} \\ & \text{unloading duration, due date}] \end{cases} \tag{4.1}$$

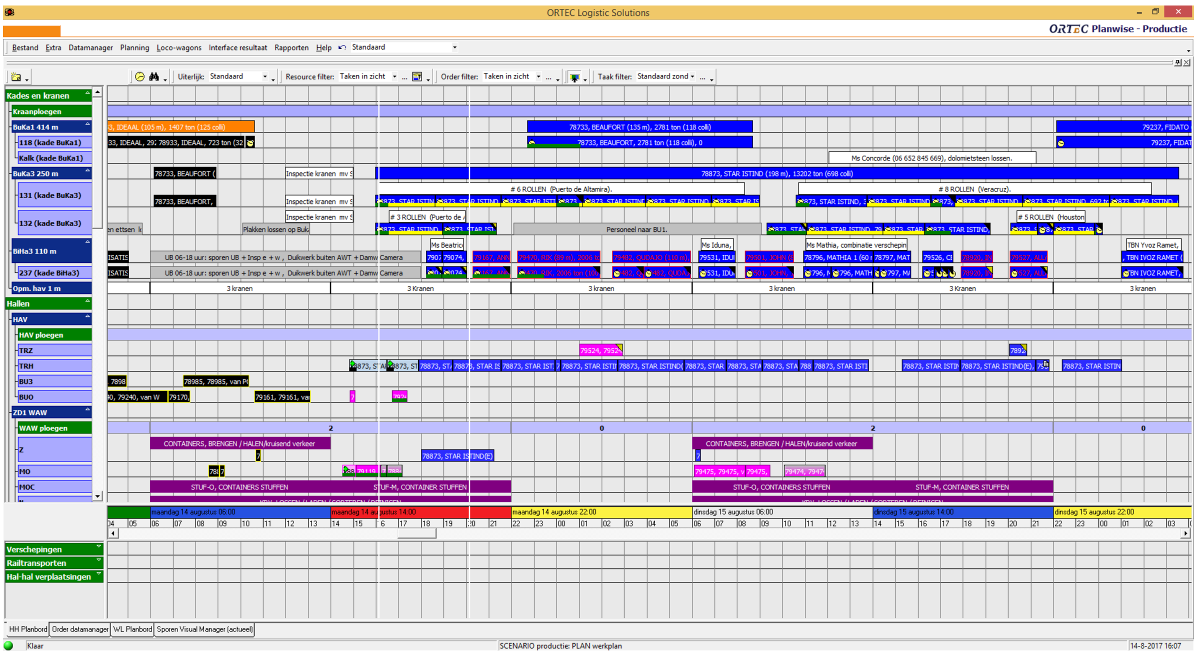


Figure 4.4: Screen capture of the Hal-haven planbord in Planwise (ORTEC, n.d.-c)

4.5. Current planning process - structure

The process leading up to the warehouse plan has three levels. These are illustrated in figure 4.5. Firstly the Supply Chain Planning department (SCP) determines the sales plan for the coming months. Based upon the sales plan, the Outbound department (OTB) drafts the transport plan for the next weeks and months, which is in turn translated by the On-Site Logistics department and its planners to the port plan, rail plan and warehouse plan.

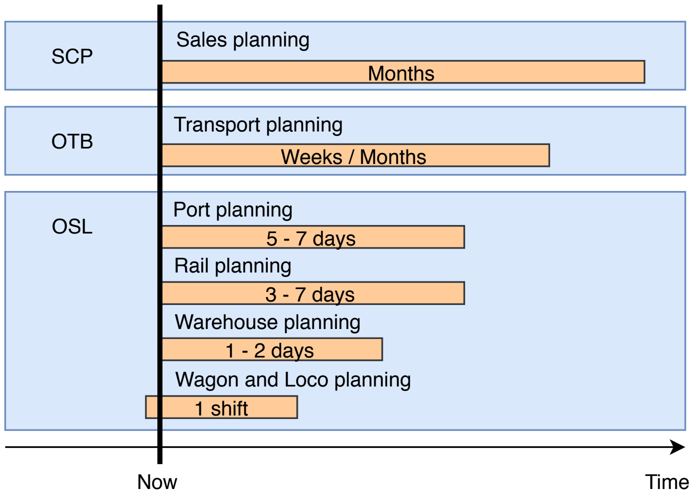


Figure 4.5: Current practice in the various levels of the planning process, SCP: Supply chain planning, OTB: Outbound department, OSL: On-Site Logistics department, adapted from Tata Steel (n.d.-b)

4.5.1. IDEF0 diagrams

The IDEF0 representation of the on-site logistics and warehouse planning process starts at the *plant activities* of Tata Steel IJmuiden, shown in figure 4.6. This is taken as the highest level of the process. Input of the plant activities are the customer orders and raw materials, output is a loaded vessel, train or truck. The plant activities sub-process of consideration for this study are the production process, outbound logistics process and on-site logistics process. The orders and raw materials are transformed by production into products following the production planning from outbound logistics. This production plan is based on the sales plan. Outbound logistics also defines the outbound transportation means or the customer provides this to Outbound logistics. Together with the production data, the outbound transportation means is the input for the on-site logistics process. Should a train, truck or ship be rejected during the on-site logistics process, this is fed back to Outbound logistics.

Within the on-site logistics process, the production data and defined outbound transportation means are sent to the OSP department, Rail department and S&W department, as shown in figure 4.7. The on-site planning process outputs the plan for the on-site transport to the Rail department and S&W department. The on-site planning process receives updates on the loading processes from the Rail department and S&W department. Output from the Rail department and S&W department is either a loaded train, loaded vessel or a rejected train or rejected vessel.

The on-site planning process is split into port planning, rail planning, warehouse planning & dispatching, as shown in figure 4.8. The port planners and rail planners transform the transport means and production data as defined by the OTB department into the port plan and rail plan. These outbound & inbound transport tasks, together with production data are the input of the warehouse plan. Production data in this regard includes storage filling rates of warehouses and internal repositioning tasks. The stowage and cluster plans from S&W need to be considered by the warehouse plan and the port, rail and warehouse plans are updated based on progress updates at the outbound terminals or in case of disturbances.

Warehouse planners follow the daily schedule presented in table C.1 of appendix C (Tata Steel, n.d.-

a). From the daily schedule it becomes clear the warehouse planner work for a large part consists of coordination meetings with other planners and processing of information. Much of this information, such as the storage filling rates need to be requested or adjusted manually. Furthermore nuances in the plan, such as task prioritization are discussed between actors and added as a note to the tasks. Currently (real-time) the following information is not readily available, possibly incorrect or not entered consistently, (Tata Steel, n.d.-b):

- Storage filling rates
- Loading, unloading and transit progress
- Locomotive tracking
- Wagon tracking

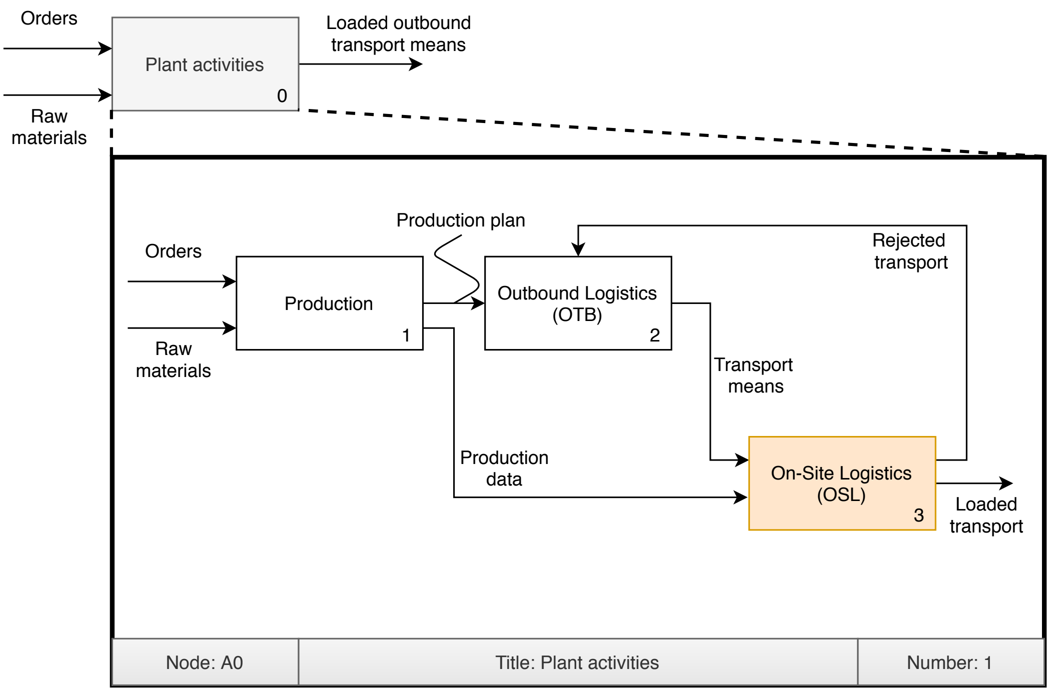


Figure 4.6: Plant activities - IDEF0 diagram, based on Schoenmaker (2016)

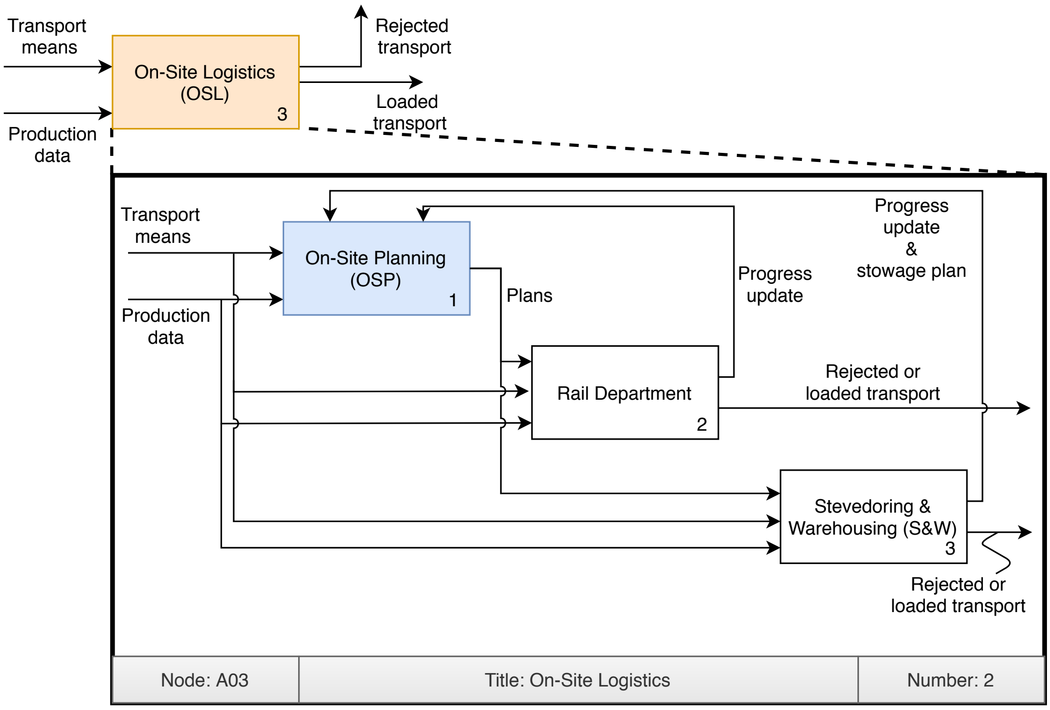


Figure 4.7: On-Site Logistics activities - IDEF0 diagram

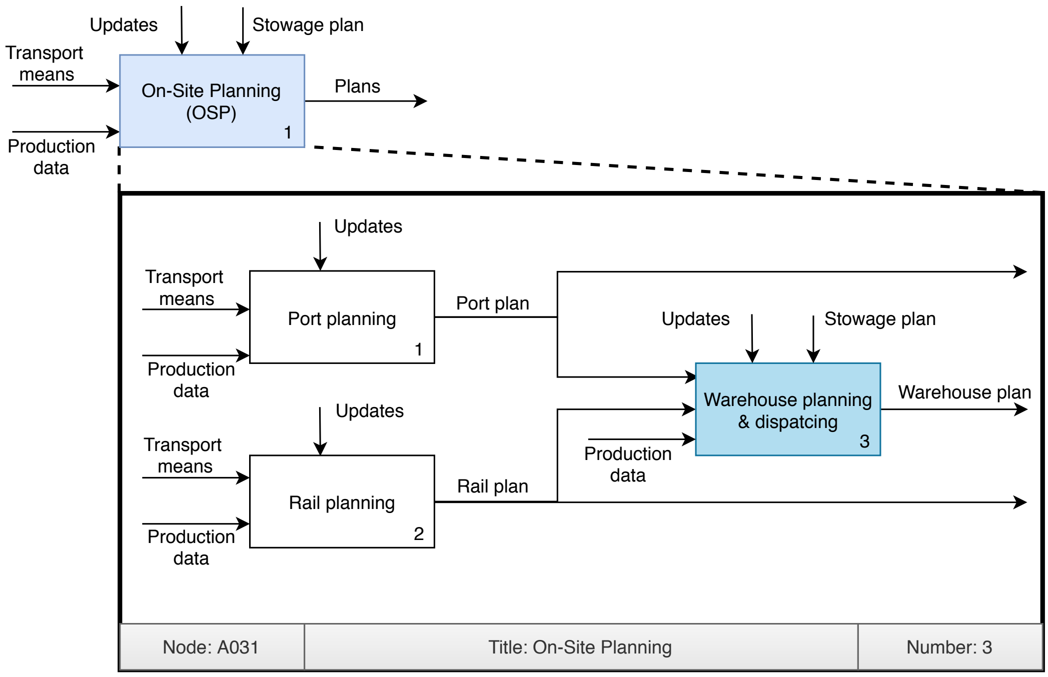


Figure 4.8: On-Site Planning activities - IDEF0 diagram

4.6. Current planning process - timing

The shortest horizon plan is the wagon and loco plan, as these are drafted based upon the warehouse plan. There are three shifts per day: morning (6:00h - 14:00h), afternoon (14:00h - 22:00h) and night (22:00h - 6:00h). Warehouse operations for the next 24 to 48 hours are executed based on the warehouse plan. Weekends are planned 72 hours ahead. The warehouse planner distributes the warehouse plan every day at 14:45h, after the OSL afternoon meeting. As the warehouse plan is operational, it is fixed, apart from exceptions, for the next 4 hours.

In the current planning process planners assume fixed transit times between site-locations, i.e. these times are in the planning phase not dependent on locomotive velocity or exact distance between site-locations. For the transit between warehouses 1 hour duration is assumed and for transit from a warehouse to one of the quays the transit time is set to 2 hours.

4.7. Objective and requirement formulation

As discussed in chapter 2, a key step into determining the relevant KPIs is by firstly identifying the goal or objective of a system. This is also an important step in the analysis of a system and the requirements of a system are defined after this step. In this section, firstly the objectives of the On-Site Logistics department and the warehouse plan are presented. This is followed by the requirements formulation of the warehouse plan in its current practice.

4.7.1. Objective formulation

The following objective has been formulated for the On-Site Logistics (OSL) department (L.A. van Vledder & J.J. Nieuwenhuis, personal communication, 2020):

> *Facilitating safe, on-schedule and as good as possible*[1] *the outbound transports*[2]*, the resources required for transports and production in warehouses by being logistics*[3] *and transport service provider for the IJmuiden site.*

And the following objective has been formulated for the warehouse plan (L.A. van Vledder & J.J. Nieuwenhuis, personal communication, 2020):

> *Planning steel transports from warehouses to the rail yard, ports and internally between warehouses, within existing constraints, in such a way that yields the highest performance in terms of KPIs.*

4.7.2. Requirements of the warehouse plan

The requirements have been determined based on systems archaeology and several meetings with both Laura van Vledder and John Nieuwenhuis and Tata Steel experts. A final brainstorm session on 05/06/2020 was done, in accordance with the method for requirement definition as described briefly in chapter 3 and more extensively in appendix B, to complete the requirements list (L.A. van Vledder & J.J. Nieuwenhuis, personal communication, 2020). The requirements are split into functional and non-functional requirements. Functional requirements prescribe things a system has to do and non-functional requirements prescribe what qualities a system must have.

Functional requirements:

1. The plan must adhere to all safety regulations.

[1] Expressed in terms of KPIs
[2] There are also other transports such as bulk and inbound steel transport that need to be facilitated
[3] Including e.g. loading and unloading operations at warehouses or quays

2. The plan must comply with the predefined constraints, as categorized in section 4.3.
3. The plan must specify which resources are assigned to each task, e.g. what wagon sub-type or which crane.
4. The plan must present every stakeholder with an overview of what is transported from origin to destination.

Non-functional requirements:

1. The plan must be in form of an activity schedule, i.e. assigning tasks to resources over time.
2. The plan must include the possibility of prioritization[4] of tasks.
3. The plan must be adaptable for future changes to the system, providing long-term flexibility.
4. The plan must facilitate both rolling horizon and event-based planning.
5. The plan must be created based on a time frame with a 24 to 48 hours horizon, or 72 hours in case of weekends.

4.8. Characterization of use case based on literature

This section characterizes the use case Tata Steel IJmuiden based on the found distinctions within (on-site) logistics and industrial railway systems from literature. Firstly the on-site logistics and the industrial railway system are discussed in terms of logistic elements, followed by the characterization of the warehouse plan from a planning perspective.

4.8.1. On-site logistics and industrial railway system

Tata Steel IJmuiden being an Integrated Steel Plant can be categorized as a large manufacturing site. An extensive railway network is used for the transportation of the goods on-site. This thesis focuses on the distribution logistics element of that railway network. Specifically, the storage and transport tasks of distribution logistics are under consideration. Order processing, as part of distribution logistics is done by the outbound department of Tata Steel IJmuiden.

The on-site transportation system uses a semi-closed rail network and is therefore classified as guided. The network is semi-closed as it is connected to the national railway infrastructure and not only Tata Steel owned wagons are used on the network. Furthermore a portion of the outbound transportation is done by trucks using the on-site road network, which too is connected to the national infrastructure. Vehicles are dispatched centrally but operated decentralized by drivers on the vehicles (person-guided). The widely branched rail network is mostly single-laned, except for some yard and shunting areas, tracks are used bidirectionally. Therefore network sections can only be operated by one train at a time, constraining operations.

The rail network is a combination of point-to-point and hub-and-spoke network configuration with many-to-many distribution. There are many origin terminals and outbound terminals and some intermediate terminals with consolidation and break-bulk terminal roles, such as the transit hall where sea-going cargo is collected and consolidated. Multiple outbound terminals are identified in form of the rail yard, inland port and seaport.

The cargo is transported in both wagon-load and block train loads and consists of single-commodity goods. Production at Tata Steel IJmuiden is based on a yearly plan drafted by the Sales department,

[4] At the moment this is not yet visible in the current planning visualization but communicated directly between actors

subject to changes over the course of the year. Based hereupon production on a monthly and weekly basis is determined. The production process is operating continuously, creating steel slabs. These steel slabs are the main inventory for the made-to-order steel coils. The production and delivery time of an order of steel coils is typically 12 weeks. Therefore, products, i.e. steel coils, are unique and non-substitutable and these unique coils need to be collected from specific warehouses, i.e. origins. Mainly storage space for steel slabs is used as inventory for steel coil demand and steel coil inventory is subject to variability in the demand and even may be filled due to lack of orders but ongoing production. Thus inventory is in principle on a short-term basis but may in fact be long-term.

As discussed in section 2.2, Crainic and Laporte (1997) discuss characteristics of short distance planning. Based on that, Tata Steel IJmuiden's warehouse plan and on-site transportation system are characterized as follows:

- Delivery characteristics:
  Both indirect and direct deliveries are made to outbound terminals.
- Origin characteristics:
  Multiple depots are considered as origins.
- Vehicle characteristics:
  There is a fixed amount fleet size, with heterogeneous wagons having variable capacities. Transit times between locations are considered as fixed, thus vehicle speed is not a variable.
- Driver characteristics are out of the scope of the warehouse plan.
- Demand characteristics:
  In determining the warehouse plan, demand is known in advance.
- Customer or destination characteristics:
  Customers or in the case of the warehouse plan, outbound terminals, must be visited within specific time windows with the designated cargo.

As discussed in section 2.1 service levels are agreed with customers as a means of performance assessment. In on-site logistics and the Tata Steel IJmuiden case service levels capture only a high level of the performance of the system. As the on-site logistics process and planning only covers a portion of the entire supply chain from manufacturing to the customer and the system boundaries of the on-site logistics lie mostly within the control of Tata Steel IJmuiden, other performance measures need to be defined. This is discussed further in chapter 5.

4.8.2. Warehouse plan

The warehouse plan as is the case at Tata Steel IJmuiden is both on the tactical and operational level of planning decision making. Much of the warehouse plan consists of resource allocation and the optimal use of planned staff and machinery. Besides this the warehouse plan is operated after drafting real-time and is adjusted in real-time, therefore the warehouse plan also contains the operational decision level.

The warehouse planners are responsible for planning and scheduling on-site vehicle operations between terminals and receivers and govern warehouse operations. Therefore they can be classified as dryage operators and in part terminal operators in terms of freight transportation planning decision-makers.

Warehouse planners draft the warehouse plan one to two days ahead in a rolling horizon planning structure, with time segments the size of days. Dispatchers operate and modify the warehouse plan event-driven, with for instance disturbances causing re-planning.

The on-site logistics plans of Tata Steel IJmuiden can be categorized as a form of distribution planning where storage planning, resource (wagons, loading teams, etc.) allocation & scheduling and wagon loading problems are included too. The aim is to fulfill the transport tasks. The type of decision support this research studies is an optimization system, as part of the model component of a DSS. This has the intention of providing decision support for human planners, through analytically solving (a part) of the decision problem.

4.9. Current performance measurement

Currently it is not possible to coherently and clearly express the performance of the on-site transportation planning and in particular the warehouse plan at Tata Steel IJmuiden. The On-Site Logistics department operates in a service role, facilitating the transport and delivery of products to customers. Making sure the requested transports are done and done safely is the main objective of the OSL department. The OSL department uses *Delivery on-time in full (DOTIF)* as the core performance indicator. DOTIF is a high level, Tata Steel IJmuiden wide, parameter focusing on on-time delivery of products at the customer. The on-site operations at the IJmuiden facilities play a key role in the on-time delivery, but DOTIF has a wider scope than merely the on-site environment, as beyond the influence of Tata Steel products may still arrive delayed. Furthermore Tata Steel IJmuiden operates based on a target throughput or volume in tonnes sold, and thus delivered, steel products. This target is yearly and translated to throughput targets on a monthly and weekly basis for the OSL department. Therefore the current key performance indicator of OSL is the achievement of the targeted throughput. Other KPIs of use within the OSL department are derived based on this main objective and play a role in averting the risk of not achieving this objective.

As of yet, there is not a structure in place indicating and providing insight into the performance of the warehouse plan itself and for instance statistics on delayed vessel departures are unknown (L.A. van Vledder & J.J. Nieuwenhuis, personal communication, 2020). Current performance measurement does not fully describe the efficiency and effectiveness of key elements in the on-site transportation operations and warehouse plans, such as equipment usage and delayed operations.

4.10. Conclusions

This chapter describes the on-site transportation planning and warehouse plan of the Tata Steel IJmuiden use case. This is done by using various models, diagrams and characterization based on literature. Furthermore the objective & requirements of both the on-site logistics and warehouse plan are presented and the current planning tool is discussed. Finally the current performance measurement is covered.

The goal of this chapter is to describe the use case and the warehouse planning process and to answer the following research question:

SQ 2: *How are on-site transportation plans created?*

The creation and execution of on-site transportation plans are subject to the inflow characteristics and the outflow characteristics. On-site transportation plans need to facilitate the required transportation service as such that the promised sales plan to the customers is successful. Apart from providing logistics service to the sales and outbound department, on-site logistics also needs to coordinate plans with various departments, manage goods storage and repositioning of goods on the site. The plans need to take many constraints (e.g. vehicle capacities and limited availability of vehicles and on-site infrastructure limitations) and operational parameters (e.g. operating speeds) into account. Furthermore there are many disturbances that can hinder the plan execution. Plans need to be made in such a manner that they are flexible and can handle disturbances without requiring too many resource commitment.

Furthermore this chapter answers the third research question:

SQ 3: *What data is required for the application of data-driven decision support to on-site transportation planning?*

The data required for making on-site transportation plans and adding data-driven decision making to planners is firstly the data currently used to make the plans and secondly the relevant information on which decisions are possible and better or worse. For the Tata Steel IJmuiden warehouse plan this first set of data consists of the transport tasks provided by the Outbound transport department, port plans, rail plans and internal repositioning transport requests, plus the data on the planning constraints such as wagon availability, locomotive availability and workforce availability. The second part of the data which provides the decision support to the planners consists of scores expressing the plans in terms of performance. This performance score is a combination of various Key Performance Indicators which capture the considerations of the plan.

The goal of the warehouse plan and on-site logistics is to make sure delivery of goods is on-time. To do so, some key constraints warehouse planners have to consider are the limited number of locomotives, wagons, cranes and workforce available to be used. Outbound trains will leave at their scheduled departure, so being late is not an option. Outbound vessels that are delayed due to non-successful on-site logistics operations are very expensive and therefore not acceptable. Part of the role of on-site logistics is enabling production to continue, this means efforts need to be made to facilitate storage at the production locations through internal repositioning of goods.

Currently detailed performance measurement of the warehouse plan at Tata Steel IJmuiden is lacking. The only performance measurement in place is high level and focused on achieving long term planned throughput through the system to customers. The warehouse plan is not measured in terms of efficiency and effectiveness and it is unclear what a better or worse plan is in terms of KPIs. These KPIs are not yet determined and their impact on the warehouse plan has not yet been studied. Plans are to be expressed as a balance of KPI scores, upon which informed choices can be presented to planners. In the next chapter these KPIs are determined.

5
Performance Measurement and KPIs

This chapter discusses the performance measurement and KPIs of on-site transportation plans at large manufacturing sites. In particular the KPIs of the use case, the warehouse plan of Tata Steel IJmuiden, are determined.

The chapter starts with an assessment which performance measurement system provides suitable performance indicators for on-site transportation plans at large manufacturing sites. Then this system is used to determine the most suitable KPIs as provided by literature, which are then used as a starting point to formulate the KPIs for the actual use case. These KPIs are finally specified quantitatively through discussions, interviews and use case assessment (objective and requirement formulations). Ultimately, this chapter answers the following research question:

SQ 4: How can the performance of on-site transportation plans be assessed?

Answering the above presented research question is done by covering the following points:

5.1 Determining the Performance Measurement System
5.2 Elaboration on the Performance Measurement System: SCOR
5.3 KPI Determination using SCOR
5.4 KPI Specification for the use case

Finally in section 5.5 this chapter is concluded and the answer to the research question of this chapter is discussed.

5.1. Determining the Performance Measurement System

Performance measurement systems (PMS) provide a good starting point to determine the key performance indicators (KPIs) for a system. Performance measurement systems can provide standardized KPIs, which are quantified and considered as best practices from experience. Estampe et al. (2013) provide a framework for evaluating which performance measurement systems (out of 16 in total), are appropriate for a specific system. The framework proposes eight criteria to narrow down the possible suitable performance measurement systems. Each of the eight criteria is discussed below, discussing them in light of the use case of the warehouse plan of Tata Steel IJmuiden. Thereafter, in figure 5.1, the framework from Estampe et al. (2013) is shown, where shading is included showing the possible PMS based on the determined criteria from the use case.

Decision level
The first criterion is the decision level for which the performance is to be measured. The decision level of the warehouse plan is both tactical and operational, as plans are made on both daily and almost real-time time scales.

Type of flows
Secondly the PMS are distinguished based on the type of flows of the system that need to be measured. Tata Steel IJmuiden's warehouse plan considers the physical flow of goods at the site. Financial and informational flow are out of the performance measuring scope for the warehouse plan.

Level of supply chain maturity
Thirdly the level of supply chain maturity is used as a criterion. Estampe et al. (2013) use the level of maturity distinction as described in Paché and Spalanzani (2007). These levels of maturity refer to a companies ability to govern performance measurement and on which level they govern performance measurement. The maturity level is determined with as reference the whole supply chain or even societal level of maturity. In this perspective the warehouse plan has level 1 maturity: Intra-organizational. On this level performance is managed through the alignment of various corporate functions. The performance measurement of the plans is measured-on and scoped-to the internal, intra-organizational level.

Type of bench-marking
Linked to the supply chain maturity level criterion is the fourth bench-marking criterion. The warehouse plan is subject to internal bench-marking. External benchmarking of the warehouse plan is not possible due to the uniqueness of the use case.

Contextualization
The fifth criterion is the contextualization of the system. The context of the warehouse plan is either *industry* or *all sectors*.

Quality factors
The sixth criterion takes into consideration the focus on quality, linked to continuous improvement, of a company. Quality should be seen in a wide view as companies strive for excellence, more than just satisfying predefined agreements, but in form of total customer and employee satisfaction. Some performance measurement systems include quality and excellence evaluation. Ultimately achieving the highest customer and employee satisfaction may be a goal for any company, also Tata Steel IJmuiden, and therefore this is included as a consideration in the assessment of the suitable performance measurement system for the warehouse plan.

Human capital
Estampe et al. (2013) discuss the increase of importance of human resource management and the value of experience and knowledge in supply chain organization and performance. Therefore human capital is listed as the seventh criterion to filter possible performance measurement systems. The marked supply chain evaluation models are those that also include human factors in supply

chain performance evaluation. This is considered as a favorable but not essential criterion for a performance measurement system for the warehouse plan.

Sustainability
The last criterion, sustainability, is not considered to be in the scope and consideration of the warehouse plan at this moment and is therefore not used for the assessment of suitable performance measurement systems.

5.1.1. Framework application

Based on the eight criteria put forward by Estampe et al. (2013), the SCOR supply chain evaluation and performance measurement system is best suited to further study in light of the warehouse plan. Out of the models that satisfy the criteria of the warehouse plan, the SCOR model is the most complete in these terms. Furthermore the choice for the SCOR model is in line with various sources from literature such as Surie and Wagner (2008) and Akyuz and Erkan (2010) and ORTEC SCOR experts, who advocate the use of the SCOR model for supply chain analysis due to its suitability in terms of various levels of consideration in light of performance measurement, as discussed in chapter 2. SCOR, consisting of widely recognized and applied principles and definitions, is one of the most used performance measurement frameworks. The extensiveness of SCOR and its focus on the planning element of supply chain and logistics are advantageous for using SCOR as a reference model.

	FLR	GSCF	SASC	WCL	ASLOG	EVALOG	AFNOR	SCM/SME	BSC	SPM	ABC	SCOR	SCALE	APICS	ECR	EFQM
Decision level																
	✓	✓	✓	✓			✓	✓	✓	✓			✓	✓	✓	✓
Tactical level	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓
Operational level	✓	✓			✓	✓					✓	✓		✓		
Type of flows																
Physical flow		✓	✓	✓	✓	✓	✓	✓				✓	✓	✓	✓	✓
Informational flow	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓
Financial flow				✓			✓		✓	✓	✓	✓	✓			
Level of supply chain maturity																
Intra-organisational	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Inter-organisational		✓	✓	✓		✓	✓	✓		✓	✓	✓			✓	
Extended inter-organisational										✓		✓	✓		✓	
Multi-chain										✓		✓				
Societal							✓	✓	✓			✓	✓			✓
Type of bench-marking																
Internal	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
External				✓		✓				✓		✓	✓		✓	
Contextualisation																
SME								✓								
Retailer															✓	
Industry						✓								✓	✓	
Service																
All sectors	✓	✓	✓	✓	✓		✓		✓	✓	✓	✓	✓			✓
Quality factors				✓			✓					✓				✓
Human capital				✓					✓			✓				✓
Sustainability							✓	✓	✓			✓		✓		✓

Figure 5.1: Performance evaluation models matrix, with shaded use case distinction. Adapted from Estampe et al. (2013)

5.2. Elaboration on SCOR

In 1996 the Supply Chain Council (SCC) (currently APICS SCC) developed the SCOR (Supply Chain Operations Reference) model (Estampe et al., 2013). Being a reference model, SCOR is aimed at improvement rather than the innovation of logistic activities. SCOR distinguishes four supply chain management levels (Veeke et al., 2008) (Surie & Wagner, 2008):

- **Level 1** - Process types: On this level six main *management processes*: plan, source, make, deliver, return and enable are described. Furthermore the supply chain objectives are determined. This level determines the scope of the SCOR model.

- **Level 2** - Process categories: This level goes more in-depth into the six management processes via three process categories: planning, execution and enable. For all five management processes the three process categories can be formulated. What results is a scheme consisting of 30 process categories with which all supply chains should be configurable.
- **Level 3** - Process elements: The level describing the required information needed and elements to formulate the objectives for improvement.
- **Level 4** - Implementation: Here only best practices and guidelines are presented and no specifics are defined. This is largely out of the scope of the SCOR model.

5.2.1. SCOR - Management processes

The six main management processes are described as being part of control functions. The **Plan** process in SCOR is the management and planning of demand and supply, balancing resources and creating the plan for the complete supply chain. **Source** manages incoming products, inventories, supplier networks, capital assets, supplier agreements and import/export requirements. Furthermore arrival and transfer of products are scheduled in Source. **Make** is production management in the supply chain, scheduling production operation and organizing work-in-progress and non-finished products. **Deliver** governs all steps from order management to carrier selection and shipment of products. This includes shipment routing and warehouse management. **Return** is the management of the return streams of raw materials to its suppliers and products from customers. Finally **Enable** processes are those that support the earlier presented processes of the supply chain. These are for instance financial processes and HR (Veeke et al., 2008) (Surie & Wagner, 2008).

Out of the six main management processes, the *Plan Deliver* sub-process of the Plan process and *Deliver Make-to-Order Product* sub-process of the Deliver process of SCOR are within the scope and consideration of the warehouse plan of the on-site logistics at Tata Steel IJmuiden.

The SCOR model provides best practices for management and standard metrics for performance measurement. The key use of the SCOR model for this study is the standard metrics and framework SCOR provides for performance measurement of sub-processes in a supply chain, including planning. SCOR provides performance measures on each of the three main levels it distinguishes. Performance on the first level is focused on the overview of the supply chain, whereas levels two and three are more specific and relate the metrics to process categories.

5.2.2. SCOR - Performance attributes

Performance metrics in SCOR are categorized in five performance attributes. These performance attributes contain a set of commonly used KPIs and metrics (Surie & Wagner, 2008) (ORTEC, n.d.-a) (SCC, 2010) :

1. **Reliability**: Ability to perform tasks as expected.
   KPI: Perfect Order Fulfillment.
   Metrics: On-time, the right quantity, the right quality.
2. **Responsiveness**: The speed at which tasks are performed.
   KPI: Order Fulfillment Cycle Time.
   Metrics: Cycle time metrics.
3. **Agility**: The ability to respond to external influences.

KPIs: Flexibility and Adaptability.
Metrics: -

4. **Cost**: The cost of operating the process.
KPIs: Cost of Goods Sold and Supply Chain Management Cost.
Metrics: Include labor cost, material cost, transportation cost.
5. **Asset management:** The ability to efficiently utilize assets.
KPIs: Cash-to-Cash Cycle Time and Return on Fixed Assets.
Metrics: Inventory days of supply, capacity utilization.

The first three Performance Attributes; reliability, responsiveness and agility are customer driven and the latter two metric categories; cost and asset management efficiency have an internal perspective. Often there is a balance between efficiency and responsiveness or flexibility in the supply chain and its resulting performance ability. It is encouraged by the Supply Chain Council to use at least one metric from each attribute.

The performance attributes are expressed in one or more KPIs, which are in SCOR often a combination of several metrics. Metrics in SCOR are layered in three levels: level 1 metrics are strategic, level 2 metrics are diagnostics for level 1 and level 3 are diagnostics for level 2. The diagnostic relationship between the levels is to identify the root causes of performance gaps.

5.3. KPI determination

To determine the KPIs, firstly the SCOR model is used to find relevant KPIs literature and practice provide. These are then used to determine the KPIs specifically for the use case.

5.3.1. SCOR KPIs

As discussed in the previous section the *Plan Deliver* sub-process of the Plan process and *Deliver Make-to-Order Product* sub-process of the Deliver process of SCOR are considered to be sources of possible KPIs for on-site transportation plans and thus the warehouse plan. As SCOR is very extensive, the *Plan Deliver* and *Deliver Make-to-Order Product* sub-processes consist of several lower-level processes and metrics. These are also considered in establishing the KPIs from SCOR.

Plan Deliver

The Plan Deliver (sP4) sub-process is described as: "*The development and establishment of courses of action over specified periods that represent a projected appropriation of delivery resources to meet delivery requirements*" (SCC, 2010).

The Plan Deliver sub-process of SCOR lists the following performance metrics:

- Reliability: None
- Responsiveness: Order Fulfillment Cycle Time
  - Establish Delivery Plans Cycle Time
- Agility: None
- Costs: Cost to Plan Deliver, Total Delivery Costs
- Asset Management: Return on Working Capital, Cash-To-Cash Cycle Time

The Establish Delivery Plans Cycle Time metric is part of the Responsiveness performance attribute, specified by the *Establish Delivery Plans (sP4.4)* sub-sub process of Plan Deliver. This sub-process is described as the action of approximating the delivery resource deployment, to achieve the delivery requirements (e.g. service level agreements).

Deliver Make-to-Order Product
The Deliver Make-to-Order Product (sD2) sub-process is described as: "The processes of a delivering product that is sourced, configured, manufactured, and/or assembled from standard raw materials, parts, ingredients or sub-assemblies, in response to a specific firm customer order" (SCC, 2010).

The Deliver Make-to-Order Product of SCOR lists the following performance metrics:

- Reliability: Perfect Order Fulfillment
- Responsiveness: Order Fulfillment Cycle Time, Deliver Cycle Time
- Agility: Downside Deliver Adaptability, Upside Deliver Flexibility, Upside Deliver Adaptability
- Costs: Cost to Deliver, Energy Costs, Finished Goods Inventory Days of Supply
- Asset Management: Cash-To-Cash Cycle Time, Return on Working Capital, Return on Supply Chain Fixed Assets

More specifically the sD2.12 *Ship Product* sub-process of Deliver Make-to-Order provides the following more detailed metrics:

- Reliability: % of Orders Delivered In Full, Delivery Performance to Customer Commit Date
- Responsiveness: Ship Product Cycle Time
- Agility: None
- Costs: Cost to Ship Product
- Asset Management: None

Overview of SCOR performance metrics
The SCOR performance metrics listed above are combined in table 5.1.

5.3.2. Tata Steel KPIs

Based on the performance metrics from SCOR listed in table 5.1, the KPIs that apply to the warehouse plan of the use case of Tata Steel IJmuiden are determined. To do so, interviews have been held with Tata Steel Stakeholders: the on-site logistics manager, on-site transportation planner and business analyst. As discussed in section 2.3 performance measures need to be linked to the main goal of a system and its requirements, in this case, the system is a plan governing on-site transportation and logistics. Therefore a link has been made in the interviews between the SCOR performance metrics and the in chapter 4 formulated objective and requirements of the On-Site Logistics department and warehouse plan.

The following objective has been formulated for the warehouse plan:

Planning steel transports from warehouses to the rail yard, ports and internally between warehouses, within existing constraints, in such a way that yields the highest performance in terms of KPIs.

Furthermore in terms of functional requirements, the warehouse plan needs to be safe and be operable within constraints of the system (e.g. rail network limitations), specify the used resources and be an overview of the transport tasks.

Table 5.1: Overview of SCOR performance metrics

Performance Attribute	Metric	SCOR Process	SCOR Code
Reliability	Perfect Order Fulfillment	Deliver Make-to-Order Product (sD.2)	RL.1.1
	% of Orders Delivered In Full	Ship product (sD.2.12)	RL.2.1
	Delivery Performance to Customer Commit Date	Ship product (sD.2.12)	RL.2.2
Responsiveness	Order Fulfillment Cycle Time	Plan Deliver (sP.4), Deliver Make-to-Order Product (sD.2)	RS.1.1
	Establish Delivery Plans-Cycle Time	Establish delivery plans (sP.4.4)	RS.3.27
	Deliver Cycle Time	Deliver Make-to-Order Product (sD.2)	RS.2.3
	Ship Product Cycle Time	Ship product (sD.2.12)	RS.3.126
Agility	Downside Deliver Adaptability	Deliver Make-to-Order Product (sD.2)	AG.2.13
	Upside Deliver Flexibility	Deliver Make-to-Order Product (sD.2)	AG.2.3
	Upside Deliver Adaptability	Deliver Make-to-Order Product (sD.2)	AG.2.8
Costs	Cost to Plan Deliver	Plan Deliver (sP.4)	CO.3.104
	Total Deliver Costs	Plan Deliver (sP.4)	CO.3.185
	Cost to Deliver	Deliver Make-to-Order Product (sD.2)	CO.2.4
	Cost to Ship Product	Ship product (sD.2.12)	CO.3.130
Asset Management	Cash-To-Cash Cycle Time	Plan Deliver (sP.4), Deliver Make-to-Order Product (sD.2)	AM.1.1
	Return on Supply Chain-Fixed Assets	Plan Deliver (sP.4), Deliver Make-to-Order Product (sD.2)	AM.1.2
	Return on Working Capital	Plan Deliver (sP.4), Deliver Make-to-Order Product (sD.2)	AM.1.3

These notions however do not yet make clear what a better or worse warehouse plan is. Furthermore, reflecting on the performance metrics from SCOR, performance metrics often have a backward-looking focus. The metrics determine the performance after the processes are completed and then intend to providing steering for future instances. In planning the KPIs need to shape the plans that determine future operations (Krauth et al., 2005). Therefore KPIs are needed that influence the plans as they are made, resulting in plans that have a high-performance score in terms of the KPIs and allow for operations to execute the plan as intended.

Evaluation of SCOR performance metrics

The found SCOR Reliability performance metrics describe how well orders are fulfilled, in terms of timing but also if the orders are fulfilled correctly in terms of quantity and quality. In light of on-site transportation planning, the assumption is from the outset that orders are fulfilled correctly in terms of quantity and quality. Therefore including this as a metric as such is not useful. The performance metric for the timing of the orders, making sure orders are planned as such that service levels and deadlines are met, is a useful metric for plans. This metric is then used to measure plans in terms of on-time delivery of orders to destinations.

The Responsiveness metrics both describe the time it takes to make plans and the total duration to complete all the tasks in a plan, i.e. the makespan of the plan. As the warehouse plan is made 24 to 48 hours ahead and only adjusted in real-time on an event basis, the establishing time of plans is not considered to be subject to a performance metric. Furthermore the total makespan of a plan required to complete all the transport tasks is also not considered of high importance, as the plans are made subject to an outbound schedule and predominantly needs to facilitate these outbound transports with the correct load before its deadline.

Including a performance metric similar to those of the Agility performance attribute of SCOR is considered relevant for the warehouse plan. The Agility metrics measure the ability to handle increases in tasks to be planned. Similarly, in terms of the warehouse plan, this is translated to the robustness of the warehouse plan. Robustness describes the ability of a plan to handle possible disturbances or delays in operation and not have tasks miss their deadline as a result. There is a balance to be found in how much time ahead a task needs to be ready for unloading, whilst not being started too early as this results in less flexibility due to there being loaded wagons in the system. This robustness is also linked to the Agility performance metric as a metric dealing with the risk of the plan.

The Cost performance metrics coming from SCOR are, similar to the Responsiveness metrics, aimed at both the costs of making plans and the costs of executing the made plans. Again, the metrics measuring the planning process itself are not considered relevant as the aim is to measure the plans themselves. In measuring the performance of the plans the consideration of resources used does need to be made, limiting the costs of the on-site logistics operations.

Finally Asset Management performance metrics are out of the scope of the warehouse plan as these are monitored on a higher decision level and do not influence the main objective of the warehouse plan directly.

Besides the metrics following the performance attributes of the SCOR model, the warehouse plan needs to consider peak loads in the on-site logistics system. As the warehouse plan is made, it heavily dictates the workload at for instance warehouses and other site locations. It is favorable to spread the workloads if possible, limiting workload peaks. This is relevant both from robustness and a worker perspective. If for instance many of the same wagon types are used at the same time, this yields a high workload for these wagons and comes with a high risk of delays due to disruptions. Furthermore scheduling several tasks closely after another at the same warehouse may lead to a domino effect in delays if one task has a slight delay.

Thus the warehouse plan needs KPIs that measure:

- How many tasks are scheduled on-time,
- How able the plan is to handle possible disturbances,
- How many resources are required to execute the plan, and
- How much workload peaks are experienced in the on-site logistics system.

This all combined results in a performance of a warehouse plan, which: minimizes the number of scheduled tasks past their deadline, has enough time and capacity available to handle disturbances, uses minimal resources and minimizes peak loads too.

As illustrated in figure 5.2 the performance of the warehouse plan can be measured using four main KPIs. These four KPIs are ranked on their expected importance. The most important KPI is making sure steel transports are delivered on-time. This is followed by the consideration of minimizing the costs of planned actions, through minimizing resource/equipment and personnel usage.

Thirdly the plans should consider the peak load and finally plans need to be robust, i.e. being able to reschedule parts of the plan to handle unexpected disturbances.

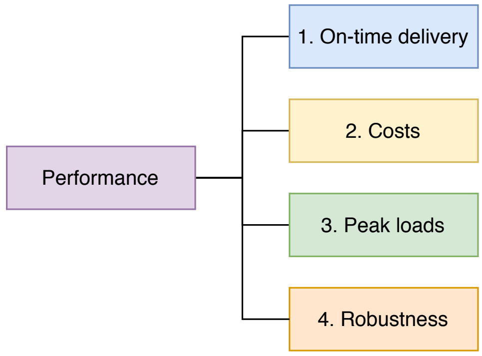


Figure 5.2: Key performance indicators, describing the performance of the warehouse plan.

Considering safety
Safety is noted in the objective of On-Site Logistics at Tata Steel IJmuiden, however not included as a KPI for the warehouse plan. Safety is of utmost importance in operations, and therefore in planning, at large manufacturing sites, and especially Tata Steel IJmuiden. This does not allow for safety to be considered as a trade-off or KPI and therefore safety is included as a constraint. Large manufacturing sites do not accept unsafe behavior, but safety will always be an objective as it is important to keep on considering safety and striving to work ever more safely.

5.4. KPI specification

As described in the previous paragraph, the performance of a warehouse plan can be described using four KPIs: on-time delivery, costs of planned actions, workload and robustness. These KPIs are specified as metrics which in turn are used to measure the performance score of drafted warehouse plans.

These metrics need to adhere to the in section 2.3 discussed performance metric attributes, as provided by Rose (1995) and Akyuz and Erkan (2010). This includes the metrics being direct, portraying information on the proper level without requiring further processing, metrics being linked to the overall objective of an organization and the metrics being developed collaboratively with stakeholders. Furthermore the metrics have no overlap, are also non-financial, easy to use and allow weighted combination. This also means that the defined metrics need to be consistent in their objective sense, i.e. minimizing or maximizing its value. The metrics are all described using cost functions where higher costs are made if the performance decreases, therefore the objective sense of all metrics is minimization of the costs through proper variable values. The warehouse plan is made based on a combination and balance of its KPIs, as shown in equation 5.1. This balance needs to be determined.

The KPI metrics are used in the proposed optimization model of chapter 6 to generate warehouse plans based on optimal performance scores. By analyzing and comparing the results with historical drafted plans, the KPIs and their relative importance to the warehouse plan is evaluated, thus determining the balance between KPIs.

$$\text{Performance} = \text{Weight}_1 \cdot \text{KPI}_1 + \text{Weight}_2 \cdot \text{KPI}_2 \ldots \tag{5.1}$$

5.4.1. KPI 1 - On-time delivery

On-time delivery, i.e. making sure the outbound transport is not delayed, is of high importance. A vessel or train leaving the site late due to its cargo not being loaded timely leads to high costs and is therefore to be avoided at all times. Each transportation task has a deadline or due date at which the cargo needs to be delivered to its on-site destination for loading of the wagons and on to the outbound vessel, or it is combined into one train. The metric of on-time delivery is thus a combination of the planned start time of unloading the wagons at the on-site destination and the due date of that task. Furthermore a cost function is applied, where costs grow exponentially in case of larger delays, as shown in figure 5.3. The exponential growth of costs reflects the real-world situation where too late departure of goods is very bad in terms of performance and results in high costs. However if there is no capacity whatsoever to make sure the goods depart on-time, there is no choice but to schedule them as close to on-time as possible. Thus a large penalty is applied in case of delays. Mathematically the metric is described in equation 5.2. The amount of delay is denoted as δ, tasks are denoted as i, due date of tasks as d_i and start time of tasks as ST_i, in the equation and figure.

$$\text{MIN } Z_{OTD} = C(\delta) \tag{5.2}$$

$$\text{with } \delta = \sum_{i \in I} \max(0,\ ST_i - d_i) \tag{5.3}$$

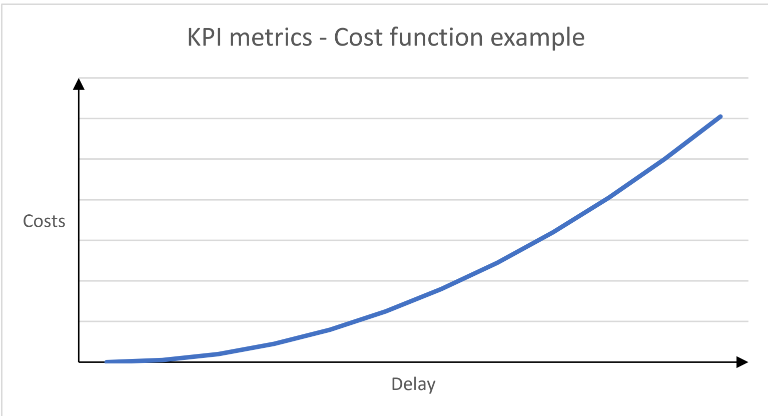


Figure 5.3: Example of the cost functions

5.4.2. KPI 2 - Costs

The second KPI, costs of resource usage needs to be considered in the performance of a warehouse plan. In drafting the warehouse plan costs of the usage of locomotives[1] and workforce are important. For both of these this is twofold: firstly the amount of locomotives and workforce used in a shift needs to be minimized and the shift needs to be used as efficiently as possible, i.e. if a locomotive or workforce group is used in a shift, this needs to be done preferably for the whole shift, maximizing

[1] Locomotives as vehicles and not their operators are used throughout this thesis

their use during this time[2]. By taking the maximum usage of locomotives and workforce over their respective shifts and setting the objective to minimize this value for each shift, both considerations associated with the costs of locomotives and workforce in the warehouse plan are covered. The metric will result in the least possible used amount of locomotives and workforce at a time and lead to high utilization of the used resources over each shift. The metrics for both locomotives and workforce are calculated using equation 5.4. Equation 5.4 describes the minimization of the number of locomotives or workforce used per shift. The cost function of the equation resembles that shown in figure 5.3, with, instead of delay on the x-axis, the usage of resources per shift shall be on the x-axis. In equation 5.4 U_s is the maximum amount of resource used in a shift, U_t is the amount used at time t in shift s. Full shift time buckets are taken as a starting point, but smaller time buckets could be considered.

$$\text{MIN } Z_{usage} = \sum_{s \in S} C(U_s) \tag{5.4}$$

$$\text{with } U_s = \max_{t \in s} U_t \tag{5.5}$$

5.4.3. KPI 3 - Robustness & Peak loads

The robustness and peak load KPIs can be combined, as the intention to minimize peak loads is mainly with risk aversion, i.e. the robustness of the conceptual plans. The combination of the robustness and peak load KPIs is possible in the warehouse plan case because their goal can be achieved similarly and they can be captured in the wagon usage. It must be noted that holds specifically for the warehouse plan use case.

Peak loads are to be minimized in usage of the number of wagons at a time. The fewer wagons are used at a time, the more robustness there is in the conceptual plan to allow for rescheduling using the remaining wagons. It is estimated that having 25% remaining capacity of highly used wagon types is a reasonable target. Therefore, equation 5.6 states that having a margin of less than 25% of a wagon type available at a time will induce costs, where W_t is the fraction of wagons used over wagons available of a type at a time t. By minimizing this the metric results in a plan which yields higher performance if a margin is kept with the number of wagons. The cost function of the wagon usage equation, 5.6, is a function that yields incrementally higher costs per wagon type usage, similarly to which is illustrated in figure 5.3. Thus wagon usage below 75% yields no penalty costs, between 80% and 90% yields a certain amount of costs and above 90% yields even higher costs.

$$\text{MIN } Z_{Wagons} = \sum_{t \in T} C(W_t) \tag{5.6}$$

[2] The rail operations are not modeled in chapter 6 in full detail, this results in some slack in the true KPI value, however the rail operations comply with the warehouse plans thus maximum capacity can be assumed

5.5. Conclusions

This chapter describes the performance measurement of on-site transportation planning and the warehouse plan of the Tata Steel IJmuiden use case. By firstly determining and applying the performance measurement system suitable to assess on-site transportation plans, the fundamental KPIs to evaluate on-site transportation plans have been determined. Thereafter, based on the fundamental KPIs, the use case specific KPIs have been determined and specified. In doing so, the following research question now can be answered:

SQ 4: *How can the performance of on-site transportation plans be assessed?*

The SCOR performance measurement system has been determined as most suitable to be used as a basis for determining KPIs for on-site transportation plans. SCOR is aimed at supply chain analysis and highly regarded as a performance measurement and analysis model. SCOR is based on five performance attributes (reliability, responsiveness, agility, cost and asset management) and uses a four levels layered structure to distinguish between levels of detail of performance measurement in a system. The SCOR metrics have been filtered based on their suitability in light of on-site transportation planning and the warehouse plan use case of Tata Steel IJmuiden.

Subsequently the SCOR KPIs and performance metrics have been used as a foundation to determine the specific KPIs that best suit evaluate the performance of warehouse plans at Tata Steel IJmuiden. It has been determined that the performance of a warehouse plan can be described using four main KPIs:

- On-time delivery of goods
- Costs of planned actions
- Peak loads in resource usage
- Robustness of the formulated plan

These KPIs have been specified into quantifiable metrics. The proposed metrics are formulated in-line with the prescribed best-practices for performance metrics as discussed in section 2.3. Cost functions are used to express the metrics consistently and provide a basis for combining the metrics into a performance score. These cost functions are also of use as there are no direct cost factors available for the warehouse plan as part of the on-site logistics process of Tata Steel IJmuiden.

The combination of the KPIs, expressed in their metrics, results in a function that determines the performance of the on-site transportation plans. Using the determined KPIs the quality of the warehouse plans of Tata Steel IJmuiden can be evaluated quantitatively and compared to plans computed based purely on these KPIs. To evaluate the warehouse plans a planning optimization model for warehouse plans has been made.

In the planning model the four KPIs (on-time delivery, costs, workload and robustness), are translated to three operational and measurable KPIs. On-time delivery is considered fixed, i.e. the planning model must adhere to the set deadlines of tasks and on-time delivery is added as a constraint. Costs are represented by a locomotive usage KPI and a workforce usage KPI and workload peaks and robustness are represented by a wagon usage KPI.

This planning model and the operational KPIs are discussed in the next chapter, chapter 6.

6
Model Development

This chapter discusses the development of the planning model intended to evaluate the in chapter 5 determined KPIs and performance metrics of on-site transportation plans. This model is developed such that original plans drafted by Tata Steel IJmuiden planners can be compared to computer-generated plans in terms of their performance. The planning model is in the form of an optimization model that constructs real-world plans by adhering to a set of constraints and by striving for optimality in terms of its defined objective function.

In this chapter, firstly the model conceptualization is discussed. The predefined set of requirements for the model is discussed and the main elements of the design are presented. Following the model conceptualization, literature is consulted regarding the model classification and background of the type of scheduling problem at hand. Thereafter the mathematical formulation of the planning model is presented and how the model is solved is discussed. Furthermore analysis is done on the problem size of the data sets the model is used with. Finally the model verification is done and conclusions regarding the planning model are presented. Ultimately, this chapter answers the following research questions:

SQ 5: How can on-site transportation planning be modeled?

SQ 6: What is a suitable solution method for on-site transportation models?

Answering the research question presented above is done by covering the following points:

6.1 Model conceptualization
6.2 Scheduling literature background
6.3 Mathematical formulation of the planning model: MILP
6.4 Model setup, including pre-processing, simplifications, assumptions and data set analysis
6.5 Verification
6.6 Sensitivity Analysis

Finally in section 6.7 this chapter is concluded and the answers to the research questions of this chapter are discussed.

6.1. Model conceptualization

This section covers the model conceptualization of the planning model. Firstly the functional and non-functional requirements of the planning model are discussed and secondly the model architecture is presented.

6.1.1. Planning model requirements

The envisaged planning model comes with a set of requirements. These requirements specify what the model needs to do and build upon the in-section-4.7-formulated requirements for the warehouse plan. The planning model aims to provide results in terms of the formulated performance measurement metrics such that evaluation of the KPIs can be done and the performance of warehouse plans can be expressed quantitatively. Based on this objective, the functional (what the model has to do) and non-functional (what qualities the model has to have) requirements for the planning model are as follows (L.A. van Vledder & J.J. Nieuwenhuis, personal communication, 2020):

Functional requirements:

1. The planning model must comply with the warehouse plan functional requirements as formulated in section 4.7.
2. The planning model must create plans based on quantitative KPIs.
3. The planning model must create plans based with data from original, real-world, data sets.
4. The planning model must be able to plan representative data sets in terms of size and complexity; planning outbound shipments, export trains and hall transfer tasks ('omrijzendingen').
5. The planning model must have a time scale resolution which is compliant with the level of detail at which currently warehouse plans are made.
6. The planning model must be able to generate warehouse plans from different days, i.e. handle different data sets.
7. The planning model must maintain the structure of transportation tasks as these currently are, i.e. consisting of four main steps (jobs): wagon-supply, loading, transit, unloading.

Non-functional requirements:

1. The planning model must plan a full day's[1] data set in a fixed horizon planning manner[2].
2. The output of the planning model must be as such that it is importable into the current planning tool Planwise, for expert validation.
3. Solving of the planning model must be finished within a reasonable time (0 - 1 hour)[3] and at a reasonably high level of optimality (80+% optimal).

6.1.2. Planning model architecture

Based on the formulated requirements, a model architecture containing the main elements of the planning model has been made. The high-level representation of this model architecture is shown in figure 6.1. In this figure the steps from retrieving a current warehouse plan to importing the,

[1] Consistent with the current planning horizon.

[2] This results in clearly defined in scope and comprehensive plans for analysis and links to the current planning process of 24h to 48h planning ahead.

[3] Real world plans are made in a continuously operating environment which makes long solve times impractical. Furthermore rescheduling should be quick if new tasks are added.

by the model remade, warehouse plan into Planwise are shown. At the center of the figure are the computations of the (optimization) model, these are discussed in more detail in section 6.3.

Firstly real-world data and resource data are extracted from the current planning tool. The data sets include all the relevant information needed from the to-be-planned transportation tasks. In the pre-processing step this information is filtered and translated into a proper format for the computations. This includes constructing four main steps for each task (wagon-supply, loading, transit, unloading) and conversion of timestamps to the time base of the model. Resource data is also pre-processed to input for the model. An overview of the resources used in the model is presented in appendix D. Model parameters include the cost functions of the KPI metrics and optimization parameters. After the optimization model has successfully computed the new warehouse plan, the output is processed again. This post-processing step reformulates the model output into importable data for the current planning tool. The imported plans, together with the quantitative output of the computations are used for validation of the warehouse plans and evaluation of the model results.

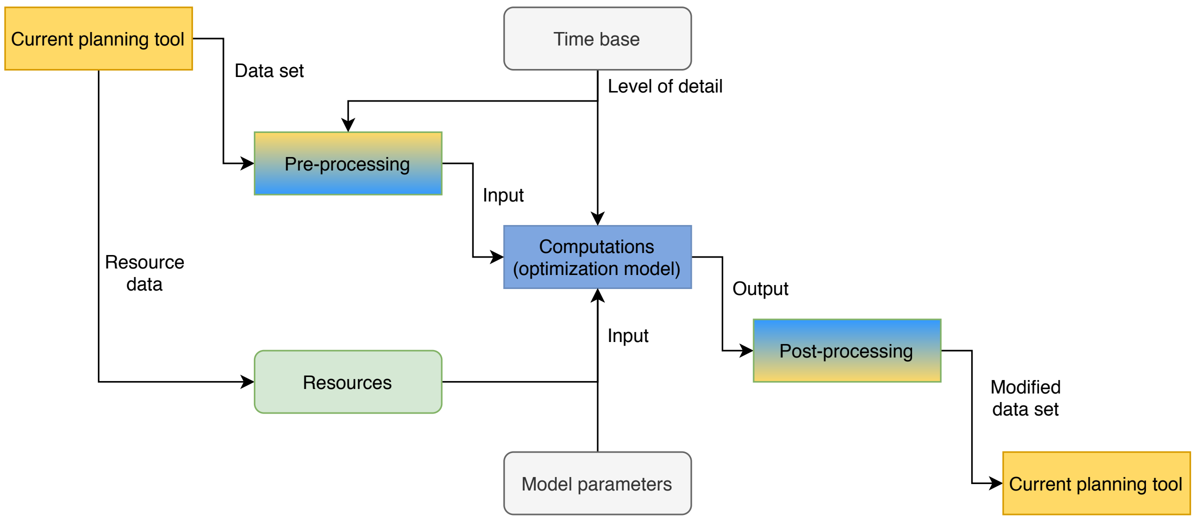


Figure 6.1: High level model architecture. Yellow = Planwise, Yellow/Blue = Excel & Python, Blue = Python

6.2. Scheduling literature background

This section provides a literature background into scheduling problems, project scheduling and classifies the planning problem of this research as a Resource Constrained Multi-Project Scheduling Problem. Furthermore time base and event representation analysis is done in light of the scheduling problem at hand.

6.2.1. Scheduling problems

In literature, scheduling is described as assigning processors, or machines, and resources to tasks. This has the intention the complete the tasks subject to constraints. Classical scheduling theory has two general constraints: tasks can only be processed by one processor at a time and processors can only process one task at a time. Scheduling problems are characterized by three sets: $T = T_1, T_2, ..., T_n$ of n tasks, $P = P_1, P_2, ..., P_m$ of m processors and $R = R_1, R_2, ..., R_s$ of s resources (Błażewicz et al., 2007a).

In scheduling problems, tasks are characterized by:

1. Processing time (vector), $p_{i,j}$, describing the processing times of each sub-process of the complete task (possibly depending on the processor).
2. Arrival time, l_j, i.e. the earliest time at which the processing of the task can start.
3. Due date, d_j, specifying the latest time for completion of the task and possibly penalties for exceeding this time, i.e. delays.
4. Deadline, D_j, i.e. the hard constraint of the due date.
5. Weight, w_j, or priority of the task.
6. Resource requests, r_j, which resources and how many the task processing consumes.

Tasks may also be subject to precedence constraints, making the start time of tasks dependent on the preceding tasks. Precedence constraints define the order in which tasks must be completed before a subsequent task may start. For instance $T_i \prec T_j$ means task T_i must be processed before the processing of task T_j can start.

Schedules, being the assignment of processors to tasks over time, subject to resources and other constraints need to satisfy the following conditions:

- Each processor can only be assigned to at most one task at every moment and each task can only be assigned to one processor at every moment.
- Tasks are processed on the time interval between the arrival time and deadline (in case of hard constrained deadlines).
- All tasks are to be completed within the schedule time horizon.
- Precedence constraints of tasks are satisfied.
- Resource constraints are satisfied.

In the case of this study, the processors are specialized. Each task requires a specific set of processors or origin and destination. In the case of dedicated processors, one of three models fits the problem: flow shop, open shop or job shop processing (Błażewicz et al., 2007a).

In job shop processing, jobs are composed of ordered lists of tasks where each task has a required processor and processing time. The main goal of job shop problems is to find the minimal makespan for the whole schedule, based on the job sequences on machines.

A more complex variant of the general scheduling problem is that which, besides considering tasks and processors, also needs to consider resource constraints. Resources can either be renewable or non-renewable. Renewable resources have a constrained total usage at a given moment, non-renewable resources have a constrained total consumption. Doubly constrained resources are both limited in total usage and total consumption. Furthermore resources can be discretely-divisible or continuously-divisible. Discrete resources can only be assigned to tasks in discrete amounts, based on a set of finite possible resource allocations, whereas continuous resources can be assigned arbitrarily (Błażewicz et al., 2007b).

6.2.2. Project scheduling

Project scheduling is a classification of scheduling problems, where tasks are referred to as activities that are part of one or more projects, i.e. projects are a set of tasks. Within projects, different tasks may require different resources and completion times (Herroelen et al., 1999). Within a project, tasks are performed following precedence constraints. In between tasks, dummy activities may be used. These dummy activities lack duration and require no resources (Hillier, 2002b).

The characteristic of project scheduling is useful in the case of the warehouse plan due to the nature of having several sub-tasks, or activities, in a project or main task. Even more so as these activities are linked through precedence constraints. As discussed earlier, the tasks that govern the on-site transportation operations can be split into four subsequent parts: wagon-supply, loading, transit and unloading. Each of these parts makes use of different resources and processors, e.g. locomotives are only used during wagon-supply and transit, but wagons are used for all four parts & the loading and unloading parts take place at different site-locations.

6.2.3. Resource Constrained Project Scheduling

The scheduling optimization problem as encountered in the use-case of Tata Steel IJmuiden's warehouse plan is identified as a type of Resource Constrained Project Scheduling Problem (RCPSP). RCPSPs are scheduling problems where several activities, which are contained in a set, part of a project and subject to precedence constraints, need to be scheduled subject to resource constraints. Oftentimes the objective function of RCPSPs concern minimizing the makespan of the project (Hillier, 2002c) (Habibi et al., 2018) (Van Eynde & Vanhoucke, 2020). Furthermore, RCPSPs are considered to be NP-hard problems (Blazewicz et al., 1983).

In Resource Constrained Project Scheduling Problems projects have J activities: $j = 1, ..., J$. An activity's processing time is denoted as d_j and these activities cannot be interrupted during processing. Resources k are contained in the set $k = 1, ..., K$, each having R_k amount available. Activity j uses r_{jk} units of resource k during its processing. Dummy activities $j = 0$ and $j = J + 1$ are added to projects to represent its start and end, these activities have zero processing time and resource usage. The model aim is to determine starting times S_j for all activities of all projects, as such that an optimal objective function value is achieved (Van Eynde & Vanhoucke, 2020).

In the case of the warehouse plan, multiple projects which consume the same resources are considered, extending the standard RCPSP to a multi-project RCPSP: Resource Constrained Multi-Project Scheduling Problem (RCMPSP) (Van Eynde & Vanhoucke, 2020). These multiple projects are all the transport tasks that need to be scheduled. Now the problem is extended with the notion that a schedule must be constructed that allows the execution of activities of various projects in parallel whilst not violating the resource constraints.

The standard RCPSP problem focuses on the objective to schedule activities as such that the total makespan is minimized within resource constraints. However in the warehouse plan case the focus is on minimizing overall resource usage (and therefore costs) and limit peak resource usage, within hard deadlines of projects. The overall makespan of the schedule is less important. Positive slack, delaying non-critical activities, by properly deciding starting times of projects can be used to achieve the objectives. This results in a resource leveling problem that generates a feasible schedule based on deadlines of projects and yields desired resource usage profiles (Hillier, 2002b).

6.2.4. Classification as Resource Constrained Multi-Project Scheduling Problem

The warehouse plan is classified as a project scheduling problem based on the in Hillier (2002a) presented classification scheme of project scheduling problems. Using this scheme the following key characteristics are identified for the warehouse plan:

- Activities are processed in a *job shop* with m machines. Jobs have their own 'routes' from one machine or warehouse, to the next (e.g. inland port) and the number of machines m is constant.
- There are multiple types of machines, each with their own resources.
- There are multiple types of resources.
- Jobs make use of renewable, limited, resources, which are both linked to machines and non-machine related. An example of this is the wagons, which are not linked to warehouses, but for instance workforce are resources that are warehouse specific.
- The resources are available and vary in amount over time. Workforce availability as a resource is for instance not constant over time but subject to work shifts.
- Activities have precedence constraints within a job and there is zero time-lag between activities.
- Dummy activities may be used to extend the time between activities with precedence constraints and to add slack into the schedule.
- Ready times are zero or are deterministic.
- All activities have their own, integer and deterministic duration p_j.
- Projects consisting of activities have deterministic deadlines δ_n.

6.2.5. Time base and Event representation

Both the time base and event representation of the problem at hand need to be determined. These notions, being strongly related, have a large impact on the way of modeling the problem and literature, e.g. (Grossmann & Furman, 2009) provides advantages and disadvantages for various options.

To begin, the time base is categorized as either discrete or continuous. This describes whether events can take place only at predefined moments and with prescribed duration (discrete) or at any point in time with arbitrary duration (continuous). Continuous-time decisions consist of sets of continuous variables, this has an advantage that it allows for more flexible solutions in terms of timing. The disadvantage of using a continuous-time base is the increased complexity of modeling resource and inventory constraints which may hurt the method's capabilities to accurately model the problem. Discretization of time, on the other hand, results in a finite number of intervals and events can only be scheduled to start or end at the beginning and end of an interval. This has as an advantage that the problem's constraints only need to be checked at the boundary points of these intervals, reducing model complexity and increasing ease of solving the problem, especially in case of resource and inventory constraints. What needs to be considered with discrete-time is the resolution or granularity of the modeling, i.e. how small or how many time intervals are considered. Having insufficiently small time intervals may lead to sub-optimal solutions or even in-feasibility in solving the problem (Grossmann & Furman, 2009).

Based on the decision of the time base, the event representation choice can be made. Figure 6.2 illustrates the various options in event representation, including the categorization of discrete or continuous-time basis.

In modeling the warehouse plan, a discrete-time base with global time intervals of 30 minutes as event representation is used in this thesis. Global time intervals are used due to the nature of the problem which allows for a time base that is time segmented and the problem size which benefits from a segmented time horizon. Using time intervals leads to the problem becoming an allocation

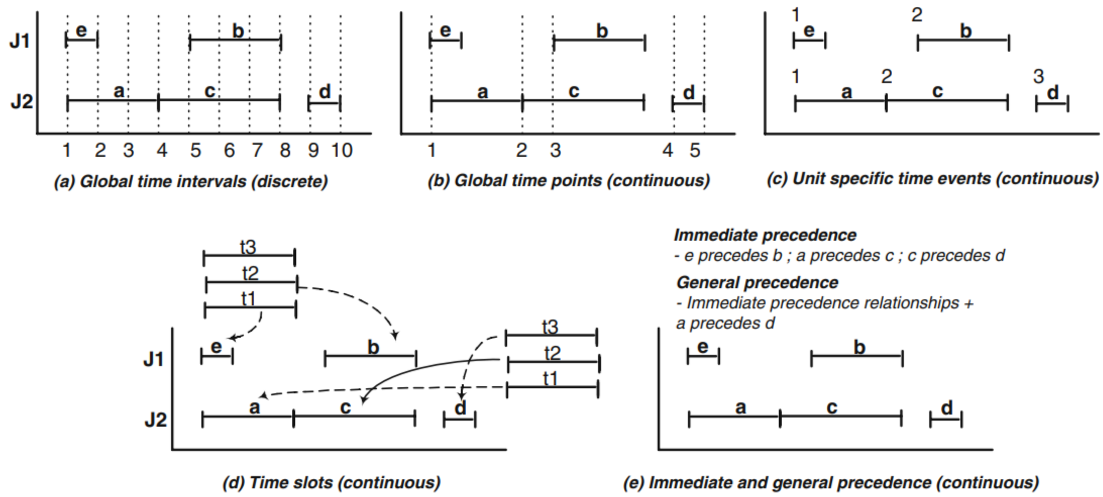


Figure 6.2: Different options of event representations in scheduling, from (Grossmann & Furman, 2009)

problem of start times of tasks to an interval x_{ijt}.

6.3. Mathematical formulation of the planning model: MILP

As described in the previous section, the warehouse plan of Tata Steel IJmuiden can be classified as a Resource Constrained Multi-Project Scheduling Problem (RCMPSP). By classifying the warehouse plan as a RCMPSP, the following core attributes of the warehouse plan problem have been identified:

Given a set of I tasks (in literature *projects*), i.e. transportation tasks, consisting of jobs J, each activity requiring resources R_{ij}, having due dates d_{ij} and processing times p_{ij}, the *starting time* x_{ijt} of each job in terms of the time base T needs to be determined such that the optimal objective function value, consisting of the in-chapter-5-determined KPIs, is achieved.

Therefore the problem consists of four main elements: tasks I with jobs J, resources R and time T. Furthermore the objective function Z and decision variables X complete the basis of the model.

Transportation tasks (I), referred to as *tasks* consist of four **jobs** j: wagon-supply, loading, transit and unloading. These jobs each require a specific amount of resources (site location cranes, site location track space, wagons, workforce and locomotives) and have a specific process duration and job due date. Furthermore precedence constraints, meaning the jobs are subsequent and can only start after the predecessor is completed, characterize the scheduling problem.

Resources (R) consist of the cranes at site locations (i.e. origin and destination on transport tasks), track space at site locations, the workforce needed to load the wagons at site locations (grouped in the clusters along with the site locations), the various possible wagon types and their availability and the available tractive force of the locomotives used for moving the wagons on-site. The cranes are to be modeled as such that each of them can only process one job at a time. Site location track space allows for multiple tasks to be stationary at one site location simultaneously, as long as there is enough space available for the wagons at the location. The resources are classified as renewable, i.e. after a wagon set or locomotive has been used in a job, it will become available again for use in another job. Wagons will be in use for the entirety of a task, i.e. all jobs, whereas locomotives are only in use during the wagon-supply and transit job. The cranes and the workforce are used during the respective loading and unloading jobs of a task.

Time (*T*) is modeled discretely as a vector with the length of the planning horizon and segmented into 30 minute sized time steps. The planning horizon runs from 00:00h till 06:00h the following day. This captures a full 24 hours of a day including three full shifts and as shipment tasks and train tasks are often due the next day or even later in the week, these deadlines are better captured with the extended time horizon.

Objective function (*Z*) of the model is a combination of the KPIs as discussed in chapter 5. The first KPI of chapter 5, On-time delivery, is included as a hard constraint (i.e. plans must be as such that all deadlines are met) in the model and is therefore not explicitly modeled in the objective function. Furthermore the Cost-KPI is considered for both locomotive usage and workforce usage, modeled explicitly in separate objectives and the Robustness & Peakload KPI returns as the wagon usage objective.

Finally the **decision variables** X of the problem are the starting times of all the jobs of all the tasks. All variables and parameters are non-negative and integers.

The warehouse plan RCMPSP is modeled in form of a Mixed Integer Linear Problem (MILP). The rest of this section discusses the MILP mathematical formulation, covering the decision variables, auxiliary variables, parameters, objective function, functional constraints and non-negativity constraints. The MILP formulation is based on the foundations of the in Pritsker et al. (1969) presented MILP formulation for multi-project scheduling problems with resource limitations. Firstly in table 6.1 an overview is given of the elements of the MILP.

Table 6.1: Overview of MILP elements of the Resource-Constrained Multi-Project Scheduling Problem

Indices & sets	**Description**
T: $t = \{1,...,T_{end}\}$	Time horizon, with index t, divided into discrete time segments
I: $i = \{1,...,I_{end}\}$	Tasks, with index i, i.e. transport tasks
J: $j = \{0,...,3\}$	Jobs, with index j, part of each task i
Y: $y = \{0,1,2\}$	Dummy jobs: y_0, y_1 and y_2
K: $k = \{1,...,k_{end}\}$	Resource types
S: $s = \{1,...,s_{end}\}$	Shifts: 00:00 - 06:00h, 06:00 - 14:00h, 14:00 - 22:00h, 22:00 - 06:00h
HS: $hs = \{1,...,hs_{end}\}$	Half-shifts: regular shifts split in half
Parameters	
r_{ijk}	Resource requirement of resource type k of job j of task i
d_{ij}	Due date of job j of task i
p_{ij}	Processing duration of job j of task i
l_{ij}	Release date of job j of task i
R_{kt}	Resource availability of resource k at time t
Time step size	Size of each time step
Cost function values	Resulting cost for each KPI as a function of the resource usage
Decision Variables	
x_{ijt}	Starting time of job j of task i at time t
Auxiliary Variables	
y_{0it}	Tracker dummy job 0: time between wagon-supply and loading
y_{1it}	Tracker dummy job 1: time between loading and transit
y_{2it}	Tracker dummy job 2: time between transit and unloading
U_{loc_t} & U_{loc_s}	Locomotive auxiliary variables
$U_{workforce_t}$ & $U_{workforce_{hs}}$	Workforce auxiliary variables
U_{wagon_t} & $U_{frac-wagon_t}$	Wagon auxiliary variables
Objective Function	
Locomotive usage	Equation: 6.6
Workforce usage	Equation: 6.8
Wagon usage	Equation: 6.10
Functional Constraints	
Tasks are scheduled precisely once	Equation: 6.12
Resource usage	Equation: 6.13
Precedence constraints	Equation: 6.14
Earliest start time	Equation: 6.15
Latest start time	Equation: 6.16
Dummy tracker lower bound	Equation: 6.17 - 6.19
Dummy tracker upper bound	Equation: 6.20 - 6.22
Dummy tracker summation	Equation: 6.23 - 6.25
Non-functional Constraints	
Decision variable values	Equation: 6.26
Auxiliary variables values	Equation: 6.26

6.3.1. Time horizon

Firstly the time horizon is determined. As discussed earlier a discrete-time base with fixed intervals is applied. This results in a time vector where the time horizon is cut into intervals of a predetermined length. As discussed earlier the time step size is set to 30 minutes. Setting the time step to 30 minutes is a combination of computation time, result accuracy and current planning detail practice. More on this is discussed in section 6.6. As the time horizon of the schedule is 30 hours, the time vector contains $(30 * 2 =)$ 60 entries. Thus $T = \{0, 1, ..., 59\}$.

6.3.2. Decision variable

The decision variables have a binary characteristic, being either zero or one. The decision variables describe the start time of job j of task i.

$$x_{ijt} = \begin{cases} 1, & \text{if job } j \text{ of task } i \text{ starts at time } t \\ 0, & \text{otherwise} \end{cases} \qquad \forall\, i \in I,\ \forall\, j \in J,\ \forall\, t \in T \tag{6.1}$$

6.3.3. Auxiliary variables

Several auxiliary variables are introduced to model the warehouse plan. As opposed to the decision variables which are explicit decisions for the model, the auxiliary variables are defined implicitly based on the decision variable values. These auxiliary variables are grouped into the dummy trackers y and in objective function auxiliary variables. The objective function auxiliary variables are used to compute the KPI metrics of the warehouse plan, based on the decision variable x of each job.

The **dummy trackers** are, similarly to the decision variables, binary. These trackers represent the time between the regular jobs, where for example after loading a wagon that wagon is stalled at a site-location for a certain amount of time before the transit job will commence. During this certain amount of time, the model needs to take the wagon usage and site-location track space into account. The dummy trackers make sure this is done. Dummy trackers have value 1 at each time instance where that dummy activity is ongoing and 0 if not, as described in equations 6.2 to 6.4.

$$y_{0it} = \begin{cases} 1, & \text{at time } t \text{ if } y_0 \text{ is in between job } j = 0 \text{ and } j = 1 \\ 0, & \text{otherwise} \end{cases} \qquad \forall i \in I, \forall t \in T \tag{6.2}$$

$$y_{1it} = \begin{cases} 1, & \text{at time } t \text{ if } y_1 \text{ is in between job } j = 1 \text{ and } j = 2 \\ 0, & \text{otherwise} \end{cases} \qquad \forall i \in I, \forall t \in T \tag{6.3}$$

$$y_{2it} = \begin{cases} 1, & \text{at time } t \text{ if } y_2 \text{ is in between job } j = 2 \text{ and } j = 3 \\ 0, & \text{otherwise} \end{cases} \qquad \forall i \in I, \forall t \in T \tag{6.4}$$

The **objective function auxiliary variables** consist of resource usage counters at each time step t and peak values over shifts and half-shifts, in case of the locomotive usage and workforce usage respectively. The computation of the variables is based on that of the resource constraint shown in equation 6.13.

The locomotive auxiliary variable has a computation step where the total tractive force used at time t is translated to a minimal value of the number of locomotives required at that time step to transport those wagons. Following this, the maximum amount of locomotives required at all time steps of a shift is computed and in turn, used for the KPI metric of the number of locomotives required per shift.

The workforce auxiliary variable is similar to the locomotive auxiliary variables, however it does not require the computation step from tractive force to amount of locomotives and the workforce shifts are half-shifts of that of the locomotives. Furthermore the workforces are grouped in warehouse clusters, therefore workforce calculations are per cluster as these are interchangeable between site-locations within the same warehouse cluster.

In the case of the wagon usage auxiliary variable, the number of wagons used per wagon type is firstly divided by the capacity of that wagon type at that time instance. This fraction is thereafter used in the computation of the KPI cost function of that wagon type.

6.3.4. Objective function

Based on the performance metrics presented in chapter 5, the objective function for the MILP has been constructed. The objective function of the planning model consists of multiple KPIs which are optimized at the same time, resulting in a multi-objective problem. The objective function consists of the weighted sum of multiple objectives, as presented in equation 6.5. For the MILP planning model the On-time delivery KPI as discussed in chapter 5 is considered as a hard constraint, i.e. it is represented in constraint 6.16. Therefore the objective function is threefold: the KPI metric for the locomotive usage objective (equation 6.6), the workforce objective (equation 6.8) and the wagon objective (equation 6.10). Each of these metrics makes use of piece-wise linear functions to approximate the in-chapter-5-described cost functions. Section 6.4 discusses the exact cost function values.

Note that the objective function values are calculated for all workforce groups (each site cluster) and wagon types separately. In case of the wagon usage KPI, for example, this yields four equations, one for each wagon type (PLWG, VWWG, GHUIF, SETJE). Below these computations are generalized in their formulation.

$$\text{MIN } Z_{tot} \tag{6.5}$$

$$Z_{tot} = W_1 \cdot Z_{loc} + W_2 \cdot Z_{workforce} + W_3 \cdot Z_{wagons}$$

$$Z_{loc} = \sum_{s \in S} C_s(U_{loc\,s}) \tag{6.6}$$

$$\text{with} \quad U_{loc\,s} = \max_{t \in s}(U_{loc\,t}) \tag{6.7}$$

$$Z_{workforce} = \sum_{hs \in HS} C_{hs}(U_{workforce_{hs}}) \tag{6.8}$$

$$\text{with} \quad U_{workforce_{hs}} = \max_{t \in hs}(U_{workforce_t}) \tag{6.9}$$

$$Z_{wagons} = \sum_{t \in T} C(U_{frac-wagon_t}) \tag{6.10}$$

$$\text{with} \quad U_{frac-wagon_t} = \frac{U_{wagon_t}}{R_t} \tag{6.11}$$

6.3.5. Functional constraints

One start time for each job

Constraint 6.12 prescribes that all jobs must be started, and therefore scheduled, exactly once.

$$\sum_{t \in T} x_{ijt} \quad = \quad 1 \qquad \forall i \in I, \forall j \in J \tag{6.12}$$

Resources

There are five main resource categories under consideration: locomotives, wagons, site location cranes, site location track space, and site cluster workforce. A full overview of each resource type, sub-type and capacity is discussed in appendix D. The cranes, track positions at a site location where wagons can be placed and work shifts available determine the number of jobs that can be scheduled at a time at one site location. Each loading and unloading job has a predetermined site location at which the action needs to take place.

Constraint 6.13 defines the resource usage. This prescribes that the sum of all resources of type k required at time t for all activities scheduled at that time subject to x_{iju} must be less than or equal to the total available resources of that type at that time. The u period defines the period that a job is processed. At each time step, the u range evaluates the running jobs from the current time back to their starting time based on the job duration. This ensures that resource usage of ongoing jobs is considered in the resource constraint. Furthermore the dummy tracker variables are included in the constraint, with their respective resource usage.

$$\sum_{i \in I} \sum_{j \in J} \sum_{u=\max(0,t+1-p_{ij})}^{t} r_{ijk} \cdot x_{iju} + \sum_{i \in I} r_{0ik} \cdot y_{0it} + \sum_{i \in I} r_{1ik} \cdot y_{1it} + \sum_{i \in I} r_{2ik} \cdot y_{2it} \quad \leq \quad R_{kt} \tag{6.13}$$

$$\forall k \in K, \quad \forall t \in T$$

Precedence relations

Constraint 6.14 defines that the start times of all following activities must be later than their predecessor. This constraint only needs to consider regular jobs as the dummy activities are optional for the model, dependent on the optimal allocation of start times of the regular jobs in terms of the objective function values.

$$\sum_{l_{ij}}^{d_{ij}} t \cdot x_{ijt} + p_{ij} \quad \leq \quad \sum_{l_{ij+1}}^{d_{ij+1}} t \cdot x_{ij+1t} \quad \forall i \in I,\ j = (0,1,2) \tag{6.14}$$

Earliest start time

Constraint 6.15 prescribes that the chosen starting time of the decision variable may not be earlier than the release date of a job.

$$l_{ij} \quad \leq \quad \sum_{t \in T} t \cdot x_{ijt} \quad \forall i \in I, \forall j \in J \tag{6.15}$$

Latest start time

Constraint 6.16 prescribes that the chosen starting time of the decision variable plus the duration of that job must be before the deadline of that job.

$$\sum_{t \in T} t \cdot x_{ijt} + p_{ij} \quad \leq \quad d_{ij} \quad \forall i \in I, \forall j \in J \tag{6.16}$$

Dummy trackers

To model the usage of resources in between regular jobs, i.e. wagon-supply, loading, transit and unloading, three tracker variables are added to the model: y_0, y_1 and y_2. These trackers are binary variables which take the value 1 if they are in between regular jobs at time t and zero otherwise, as shown in equations 6.2, 6.3 and 6.4. Furthermore for y_0, y_1 and y_2 three sets of constraints are added. Firstly constraints 6.17, 6.18 and 6.19 define the lower bound of the interval of t, based on the start time and processing time of the prior job of each task, for which the values of the dummy trackers are allowed to be 1. Secondly constraints 6.20, 6.21 and 6.22 define the upper bound of the interval of t, based on the start time of the subsequent job of each task, for which the values of the dummy trackers are allowed to be 1. Finally constraints 6.23, 6.24 and 6.25 prescribe the exact amount of times y_0, y_1 and y_2 have to be the value 1. This makes sure that the entire gap between regular jobs is filled with value 1 for the tracker variables.

$$\sum_{t \in T} t \cdot x_{i0t} + p_{i0} \quad \leq \quad t \cdot y_{0_{it}} + M \cdot (1 - y_{0_{it}}) \quad \forall i \in I, \forall t \in T \tag{6.17}$$

$$\sum_{t \in T} t \cdot x_{i1t} + p_{i1} \quad \leq \quad t \cdot y_{1_{it}} + M \cdot (1 - y_{1_{it}}) \quad \forall i \in I, \forall t \in T \tag{6.18}$$

$$\sum_{t \in T} t \cdot x_{i2t} + p_{i2} \quad \leq \quad t \cdot y_{2_{it}} + M \cdot (1 - y_{2_{it}}) \quad \forall i \in I, \forall t \in T \tag{6.19}$$

$$t \cdot y_{0_{it}} + 1 \quad \leq \quad \sum_{t \in T} t \cdot x_{i1t} \quad \forall i \in I, \forall t \in T \tag{6.20}$$

$$t \cdot y_{1_{it}} + 1 \quad \leq \quad \sum_{t \in T} t \cdot x_{i2t} \quad \forall i \in I, \forall t \in T \tag{6.21}$$

$$t \cdot y_{2_{it}} + 1 \quad \leq \quad \sum_{t \in T} t \cdot x_{i3t} \quad \forall i \in I, \forall t \in T \tag{6.22}$$

$$\sum_{t \in T} t \cdot x_{i0t} + p_{i0} + \sum_{t \in T} y_{0_{it}} - \sum_{t \in T} t \cdot x_{i1t} = 0 \quad \forall i \in I \tag{6.23}$$

$$\sum_{t \in T} t \cdot x_{i1t} + p_{i1} + \sum_{t \in T} y_{1_{it}} - \sum_{t \in T} t \cdot x_{i2t} = 0 \quad \forall i \in I \tag{6.24}$$

$$\sum_{t \in T} t \cdot x_{i2t} + p_{i2} + \sum_{t \in T} y_{2_{it}} - \sum_{t \in T} t \cdot x_{i3t} = 0 \quad \forall i \in I \tag{6.25}$$

6.3.6. Non-functional constraints

The non-functional constraints below prescribe the nature of the decision and auxiliary variables. These variables are either binary, integer or continuous.

$$\begin{array}{lllll}
x_{ijt} & = 0,1 & & & \forall i \in I, \forall j \in J, \forall t \in T \\
y_{0:2_{it}} & = 0,1 & & & \forall i \in I, \forall t \in T \\
U_{loc_t} & \geq 0 & \& & U_{loc_t} \in \mathbb{Z} & \forall t \in T \\
U_{loc_s} & \geq 0 & \& & U_{loc_s} \in \mathbb{Z} & \forall s \in S \\
U_{workforce_t} & \geq 0 & \& & U_{workforce_t} \in \mathbb{Z} & \forall t \in T \\
U_{workforce_{hs}} & \geq 0 & \& & U_{workforce_{hs}} \in \mathbb{Z} & \forall hs \in HS \\
U_{wagon_t} & \geq 0 & \& & U_{wagon_t} \in \mathbb{R} & \forall t \in T
\end{array} \tag{6.26}$$

Note: Previous method for dummy trackers

In earlier versions of the MILP of this thesis the dummy trackers were modeled as dummy jobs. These were similar to the regular jobs, but represented the dummy activities the dummy trackers now handle. Whereas the dummy trackers are binaries which take a value of 1 when needed and 0 if not, the dummy jobs would have a decision variable as start time based on the end time of the previous regular job. Furthermore these dummy jobs would have a duration, or processing time, dependent on the previous and subsequent regular job start times. However, this made it not possible to compute the resource usage of all ongoing jobs (including the dummy jobs) at all time steps t in constraint 6.13. This was not possible due to the nature of the range u over which the sum of time has to be taken. In the case of the dummy jobs this range had a variable length, which was not computable properly in the model. Therefore the dummy tracker method has been incorporated into the model to handle the resource usage of the dummy activities.

Note: Rail process

The rail process of the on-site transportation planning at Tata Steel IJmuiden has been simplified in the model. In real-life operations planners consider the spatial vicinity of site-locations when assigning tasks to time slots at certain site-locations. The planners strive to maximize the tractive force usage of the locomotives. This is done by planning tasks subsequently at the same site-location (or within the same cluster) to combine the locomotive trips of both tasks. As spatial attributes and the rail network itself are not modeled as such, these rail operations and decisions have been approximated by modeling locomotive capacity at each time step as the estimated available tractive force of the five operating locomotives. This allows the model to maximize the efficiency of used locomotive tractive force and results in the actual number of locomotives used over a shift. Furthermore workforces are grouped in the site clusters and these also represent site-location vicinity.

6.3.7. Model illustration

In figure 6.3 an illustration of the MILP model formulation in form of a schedule is given. Included in the illustration are several of the variables and parameters, sets and indices of the MILP model. The illustration shows a schedule with horizontally the time and vertically the tasks i. In each task row, the various jobs j are scheduled, with dummy jobs and as an example for the first jobs a resource requirement of a resource $k = 0$ is included.

Note: Figure 6.3 is not an actual model result.

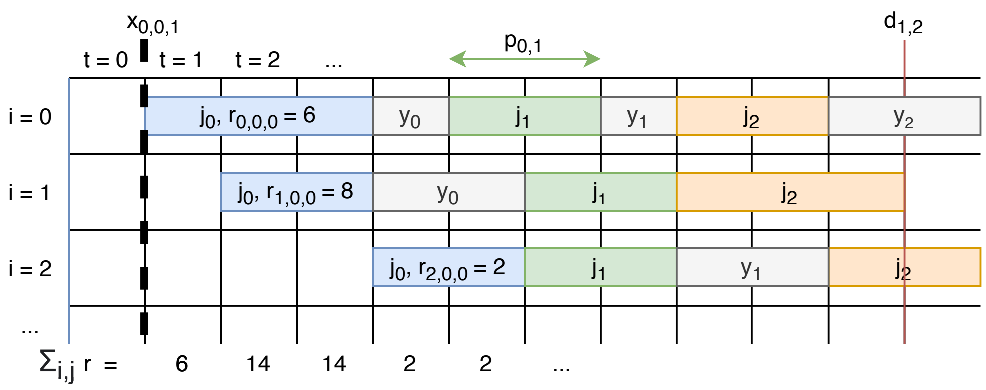


Figure 6.3: Example representation of a schedule including many of the variables, indexes and other parameters of the MILP model.

6.4. Model setup

In this section the model simplifications and assumptions are discussed first. These are split into data simplifications (as part of the data pre-processing step) and modeling simplifications. Thereafter the model parameters are discussed, followed by data analysis on the problem size of the data sets used to run the model. Finally the modeling tool is discussed.

6.4.1. Data Pre-processing

The planning model plans three types of transport tasks: outbound shipments, trains and hall-transfers. The road transport tasks and hall-transfers between port warehouses have been removed. This results in most of the transport tasks, but in reality, more tasks are part of the warehouse plan, such as inbound shipments. Furthermore there are some redundant items in the data sets when exported from the current planning tool, such as unavailabilities which are included as mock-up tasks in the data sets. These also need to be removed. These filter steps in the pre-processing are as follows:

1. Filter on date: Only transport tasks with a loading or unloading job on the respective date are considered.
2. Filter on type of transport task: shipments, trains and hall-transfers.
3. Remove inbound transports.
4. Filter tasks that are transits within the port cluster (HAV cluster).

After the filtering of the data sets, the transport tasks are structured in the four jobs and the resource usage of the transport tasks is structured. As discussed in paragraph 4.5, transit times between warehouses (i.e. for hall-transfer tasks) are set to 1 hour and transit times from a warehouse to the port site-locations is set to 2 hours. Transit from a warehouse to the rail yard is set to 1 hour as this is geographically centralized on the site. Wagon-supply job duration is set to 1 hour, unless in case of an exception as discussed in the next paragraph. Therefore, transit times for the respective task types are set as follows:

- For wagon-supply jobs the transit time is set to 30 minutes.
- For transit jobs between warehouses or to the rail yard the transit time is set to 60 minutes.
- For transit jobs from warehouses to the port locations the transit time is set to 120 minutes.

Furthermore 30 minutes of wagon usage is added after the unloading jobs of shipment tasks. This is done to account for the transition period after unloading wagons in the port and these wagons thus not instantaneously being available for use in other transport tasks. Note that this extra transition period is not considered for train and hall-transit tasks as these wagons become available much closer to the other site-locations and the transition period can thus be disregarded. In the case of export trains the unloading jobs are considered as a sink as the wagon capacity of these tasks is not constraining the plans and the wagons leave the site.

Modifications and simplifications

In case of tasks that have one or more jobs planned originally outside of the model planning horizon, these jobs have been modified to be included in the model. This is done due to the nature of the model being as such that each task it plans needs to have the structure of all four jobs. Besides modifications and simplifications to the hall-transfer tasks, the following modifications and simplifications hold for the model:

- Duration and time stamps are rounded up to the nearest time step size matching the time base of the model. In doing so, the minimal duration of a job is assumed in the model to be 1 time step.
- Unloading jobs of wagons, i.e. the crane job at the port or the departure time of an outbound train, are set to the end of the scheduling time horizon if these originally fell outside of the planning horizon.
- In case of hall-transfer tasks where the loading job was scheduled originally the previous day, the wagon-supply and loading jobs of these tasks are manually fixed to the start of the time horizon. In this case the wagon-supply job does not consume locomotive tractive force or wagons. The loading job does not consume wagons, workforce and is set to 30 minutes, i.e. minimal duration.
- Deadlines for unloading of hall-transfers are set to at the latest 24 hours after the loading job.
- Wagon type allocation to transport tasks is fixed.
- Wagon loading arrangement is out of the scope of the model.
- Start times of the unloading jobs of shipments and train tasks are fixed, either to the end of the schedule as discussed above or to the original times. This is done due to these tasks being considered as input for the warehouse plan.
- At the start of the time horizon, the model considers all wagons to be available.
- The shunting process of wagons by locomotives is not explicitly included as a job within the transportation tasks. The shunting is implicitly included in the wagon-supply and transit job duration.
- The data sets include a few tasks which had more wagons than there is rail track capacity at the site locations the tasks visit. In practice the workers would handle this by placing one wagon outside the warehouse and through shunting arrangements they would load the extra wagon. For this thesis these exceptions have been manually adjusted to fit the site location track capacity or the task is split into two separate tasks.

The hall-transfer modifications in case of a part of the task falling on the previous day, result in the model having a few time steps of 'warm-up' time.

6.4.2. Modeling tool

The MILP planning model is solved using the Gurobi mathematical optimization solver. Gurobi is a commercial solver which is available with an academic license. Gurobi is used via the Anaconda-Spyder graphical development environment with Python as the programming language. Gurobi translates the Python code to C in which the solver operates. The Gurobi setup is shown in figure 6.4. Using Gurobi+Python to model and solve the MILP allows for the usage of many of the Application Programming Interface (API) features of Gurobi. This ranges from the way constraints are modeled to more advanced functionalities such as piece-wise linear functions used for the cost functions of the objectives of the MILP and multi-objective functionalities. Furthermore Gurobi uses several heuristics to reduce the solving time of large models, plus the modeler can tune the solution process.

The full Python code of the MILP model is added in appendix E.

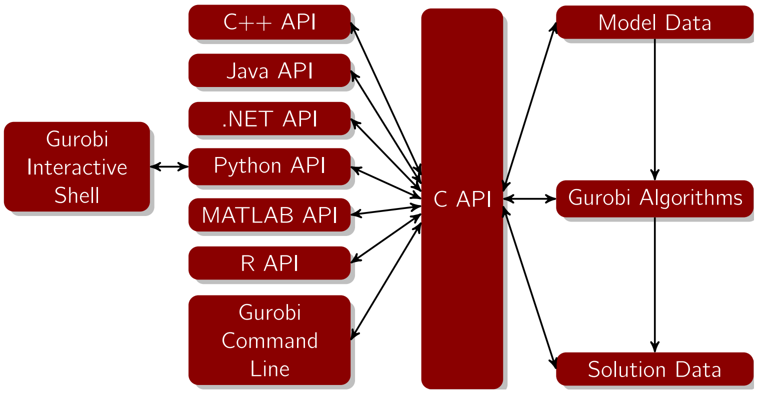


Figure 6.4: Gurobi application overview, source: Gurobi Optimizer Reference Manual

6.4.3. Data sets: Problem size

As described in the planning model requirements, the planning model must schedule real-world data sets. These data sets are exported from the current planning tool, Planwise. In general warehouse plans are made 24 hours in advance and days are structured into three shifts: 06:00 - 14:00, 14:00 - 22:00 and 22:00 - 06:00. In practice warehouse plans are continuously updated and do not start or end at a specific time. The planning model does considers a finite planning horizon in this thesis. To accommodate this, the current warehouse plans are set to a specific date but have a time horizon of 30 hours. Thus exported plans as data sets consist of all the warehouse operation parts of transport tasks from 00:00h up to 06:00h the next day. This means that for instance in the case of hall transfer tasks the wagon-supply and loading steps of the task may have been planned originally on the day before and in the case of a shipment task, the full loading of the vessel may be executed the next day or later in the week.

For the analysis of the performance metrics proposed in chapter 5, three data sets, i.e. three planned days, have been chosen: August 21st 2020, August 23rd 2020 and August 25th 2020. For each of the data sets an overview of the number of tasks, per task type and totals, is shown in table 6.2. From this overview it is clear that the data set of 21st of August 2020 is the smallest data set of the three, and 23rd and 25th of August have very comparable size. The train tasks consist of the fewest tasks per category. Most tasks are the Hall-transfer tasks, which only slightly outnumber the shipment tasks. Translating the tasks to the number of jobs per data set shows the (estimated [4]) amount of starting time decision variables the model needs to consider. This needs to be extended with the time horizon step size, the auxiliary dummy job tracker variables, the KPI auxiliary variables and constraints for the full problem size.

Data sets & COVID-19 pandemic

Note that these data sets are smaller in size, i.e. number of tasks per day, compared to 'normal' operations. This is due to the data sets being during the COVID-19 pandemic. The economic impact of the pandemic causes the data sets to be smaller than average operational plans.

Following the table presenting the amount of tasks per data set, tables[5] 6.3, 6.4 and 6.5 present the grouping of tasks per site cluster. This shows in which site cluster the most tasks are scheduled and

[4] Estimation as each data set includes for instance hall-transfer tasks with fixed wagon-supply and loading jobs due to these originally falling outside of the planning horizon

[5] ZD1 WAW cluster has zero capacity during the night shifts

Table 6.2: Overview of the number of tasks, per type and totals, for each data set.

	21-8-2020	23-8-2020	25-8-2020
Shipment tasks	26	31	30
Train tasks	11	20	20
Hall-transfers	33	38	36
Total number of tasks	70	89	86
Total number of jobs	280	356	344

thus which workforce groups are most busy, for each data set. Right away it is clear that there are no tasks in the data sets which require the AOV cluster and only a few tasks which are in part in the HAV cluster [6]. Furthermore the *Cluster Midden* is most used for all data sets, which is mainly due to the hall-transfer tasks. Note that the figures in this table include, in case of the hall-transfer tasks, both the loading and unloading jobs at the site-locations.

Table 6.3: The grouping of tasks per site cluster for 21st of August data set, capacity per time step

21-8-2020	HAV	ZD1 WAW	CPR	Cluster Zuid	TSP	Cluster Midden	Cluster Noord	AOV
Capacity	100	2	4	2	2	7	3	1
Shipment tasks	0	0	1	7	0	9	9	0
Train tasks	0	0	1	2	1	3	4	0
Hall-transfers	3	0	13	0	8	35	7	0
Total	3	0	15	9	9	47	20	0

Table 6.4: The grouping of tasks per site cluster for 23rd of August data set, capacity per time step

23-8-2020	HAV	ZD1 WAW	CPR	Cluster Zuid	TSP	Cluster Midden	Cluster Noord	AOV
Capacity	100	2	4	2	2	7	3	1
Shipment tasks	0	2	1	4	6	15	3	0
Train tasks	0	0	4	2	0	6	8	0
Hall-transfers	1	0	8	4	6	51	6	0
Total	1	2	13	10	12	72	17	0

Table 6.5: The grouping of tasks per site cluster for 25th of August data set, capacity per time step

25-8-2020	HAV	ZD1 WAW	CPR	Cluster Zuid	TSP	Cluster Midden	Cluster Noord	AOV
Capacity	100	2	4	2	2	7	3	1
Shipment tasks	2	4	0	4	3	11	6	0
Train tasks	0	0	7	2	0	4	7	0
Hall-transfers	3	1	6	4	9	44	5	0
Total	5	5	13	10	12	59	18	0

Similarly to the overview presented on the number of tasks per site cluster, tables 6.6, 6.7 and 6.8

[6]This is mainly due to the HAV (port) cluster hall-transfer tasks being filtered in pre-processing

show the amount of wagons used in each data set per wagon type and per task type. Note that in these tables only the wagon types[7] which are used in the three data sets are shown, these are 6 types out of 21 in total. Furthermore note that the *Setje* wagon type is a collection of five wagons, i.e. one Setje represents a grouped set of five wagons, thus uses five capacity of tractive force for a locomotive and five track spaces at a warehouse. The *DA* wagons are not considered to be constrained, or relevant from a KPI perspective, and as the *RILNS* wagon is only used once this is also left out of the wagon KPI scope.

A clear structure is determined in the wagon types over the different transport task types:

- Shipment tasks mainly use *PLWG* and *VWWG* wagons,
- Outbound train tasks use *DA* wagons,
- Hall-transfer tasks use *GHUIF* wagons and the *Setjes*.

Note that this wagon type usage differentiation holds for these data sets in particular. *DA* wagons are owned by Deutsche Bahn and are reserved for train tasks only. Generally *Setjes* are the wagons used for Hall-transfer tasks, but the *PLWG*, *VWWG* and *GHUIF* wagons could be used too. Apart from the *PLWG* and *VWWG* wagons the *GHUIF* wagons are also used for shipment tasks, in particular these are reserved for inbound shipment tasks.

Furthermore note that the amount of wagon movements is the number of times the wagons are moved, i.e. twice (wagon-supply and transit), times the total amount of wagons used in the data set. This value indicates the amount of work for the locomotives.

Table 6.6: The amount of wagons used in the 21st of August data set, per wagon type, per task type and totals, capacity per time step

21-8-2020	DA	GHUIF	PLWG	RILNS	SETJE	VWWG	Wagon movements
Wagon capacity	134	63	55	1	12	74	
Shipment tasks	0	4	22	0	0	53	
Train tasks	27	0	0	1	0	0	
Hall-transfers	0	34	10	0	16	7	
Total	27	38	32	1	16	60	238

Table 6.7: The amount of wagons used in the 23rd of August data set, per wagon type, per task type and totals, capacity per time step

23-8-2020	DA	GHUIF	PLWG	RILNS	SETJE	VWWG	Wagon movements
Wagon capacity	134	63	55	1	12	74	
Shipment tasks	0	5	31	0	0	58	
Train tasks	36	0	0	0	0	0	
Hall-transfers	0	44	0	0	24	0	
Total	36	49	31	0	24	58	294

[7] Abbreviations/Wagon type codes: GHUIF = Gele Huif (covered wagon), PWLG = Platte (flat) Wagon, VWWG = Vaste Wiege (Fixed cradle) Wagon

Table 6.8: The amount of wagons used in the 25th of August data set, per wagon type, per task type and totals, capacity per time step

25-8-2020	DA	GHUIF	PLWG	RILNS	SETJE	VWWG	Wagon movements
Wagon capacity	134	63	55	1	12	74	
Shipment tasks	0	8	38	0	0	44	
Train tasks	58	0	0	0	0	0	
Hall-transfers	0	25	1	0	24	0	
Total	58	33	39	0	24	44	294

6.5. Verification

Important in model development is the verification of the model. Verification is checking if the model is right, i.e. whether it properly does the computations it is intended to do. The verification of the model is done through verification tests. In these tests the model constraints are tested if they work properly and if the computations in the model result in the expected values. The verification test checks the following elements:

- No capacities of resources are violated,
- Precedence relation of jobs is maintained,
- Earliest and latest start times are maintained,
- Deadlines are satisfied,
- Dummy trackers are consistent with their constraints,
- Shift ranges include all time steps,
- Each task is planned in full,
- Proper rounding and cost function allocation is done in the KPIs,
- The resulting KPI values correspond to the planned schedule.

Throughout conceptual modeling the model constraints have been tested manually for their correctness and desired results. Furthermore *modular design tests* have been done during the programming of the model. This entails verifying each constraint, as it is added to the model, separately. These modular tests are done on a small instance of the model, which has mock-up data as input and output generated to verify the code. It is important to test each constraint in a modular, separate, manner as the full model, with a full real-world data set is much more complex and more difficult to verify. During each modular design test also extreme value tests are done to check if the model handles these properly. An example of this is adding a task with a very large amount of wagons, larger than the capacity of those wagons. In this case the MILP needs to be infeasible as the resource constraint is violated.

The full model, with all constraints, has also been verified, firstly with mock-up data as input and secondly with all real data sets. In the case of infeasibility, Gurobi provides functionality to return the Irreducible Inconsistent Subsystem (IIS) of the MILP. The IIS provides the modeler with insights as to which constraint makes the model infeasible and allows for easier debugging of the model. Finally the verification is completed using the current planning tool Planwise, as this visualizes the model output and has a built-in warning system in case of a constraint violation, e.g. planning more tasks in a cluster at the same time than there is workforce available.

6.6. Sensitivity analysis

Besides verification, sensitivity analysis of the model parameters is done. The sensitivity analysis provides insights into the model's workings and how it and its results respond to different model parameter settings. Out of the model parameters as presented in table 6.1 the *Time step size* and *Cost function values* are parameters worth analyzing the model responds to. The other listed parameters are data set specific and therefore not in the scope of the analysis of the model response.

Time step size
The time step size of the model greatly influences the model size (amount of possible starting times of each job) and thus the run time of the model to achieve solutions. Furthermore smaller or larger time step sizes may greatly influence the resulting quality of the solutions, larger step size for the worse and smaller for the better. As worse solutions are not considered, the smaller step size which balances model result quality and model run time is preferred.

Setting the model step size to 15 minutes instead of 30 minutes was found in intermediate model tests to result in rapidly growing model run times as the model developed to its full size. Therefore the impact of smaller step size on the model results was tested on the performance evaluation runs of the old plans. In these runs no optimization algorithm influenced the plan but the plan was purely evaluated in terms of the formulated KPIs. These runs have been performed with 15 minutes and 1-minute step sizes, but did not show significant changes in the results and resulted in the same conclusions and insights. Additionally comparison of the model results with the old plans is fairer if the computations, and thus settings, are as similar as possible. Therefore the time step size of 30 minutes is maintained as suitable for the planning model.

The resulting run times for each data set are discussed more in section 7.6.

Cost function values
The cost function values are set based on expert insights and preliminary model runs. These preliminary model runs are done to study suitable lower bounds for the cost functions to start from. The suitability is based on which resource usage level is achievable by the model and keeps the objective function values low. This latter element helps with solving the model as lower variable values generally speed up the solving computations and thus reduce solving times. The resulting cost function values and their setup are discussed in section 7.1.

6.7. Conclusions

This chapter describes the development of the planning model intended to model the warehouse plans of Tata Steel IJmuiden and which can be used to quantitatively evaluate the determined KPIs of the warehouse plans and on-site transportation planning. This chapter aims to answer two research questions, firstly the fifth research question is answered:

SQ 5: *How can on-site transportation planning be modeled?*

To answer this research question, firstly the model conceptualization is done. This includes the description of the modules of the full model, from data gathering to model output processing. Furthermore the model requirements are formulated. Based on the system description of chapter 4 and the model conceptualization, literature is consulted on scheduling problems. This provides the answer to the first research question this chapter covers: On-site transportation planning can be modeled as a Resource Constrained (Multi-)Project Scheduling Problem (RCPSP). Resource Constrained Project Scheduling Problems are a subclass of scheduling problems that fits the problem as found at Tata Steel IJmuiden's warehouse plan. The warehouse plan is mainly focused on creating plans which properly service the on-site logistics process within the constraints set by the available resources.

Furthermore the sixth research question is answered:

SQ 6: *What is a suitable solution method for on-site transportation models?*

After determining the warehouse plan of Tata Steel IJmuiden is a variant of the Resource Constrained Project Scheduling Problem, having multiple projects and multiple objectives, the solution method for the problem had to be determined. Formulating the warehouse plan mathematically as a Mixed-Integer Linear Problem (MILP) is a suitable method to solve the planning problem. Mixed-Integer Linear Problems can be solved exact and quantitatively using optimization solvers such as Gurobi, as has been done in this thesis. The mathematical formulation has been programmed in the Python API of Gurobi and three real-world data sets have been solved successfully.

With the model development complete, the model generated plans can be analyzed quantitatively and the performance metrics evaluated. This model result evaluation is discussed in the next chapter, chapter 7.

7

Results and Evaluation

This chapter discusses and evaluates the results of the planning model. The planning model generates warehouse plans of Tata Steel IJmuiden and present quantitative results based on the determined KPIs and performance metrics of on-site transportation plans. The plans and their results are analyzed and compared in this chapter, to answer the following research question:

SQ 7: To what extent can increased decision support improve on-site transportation planning?

To answer this research question, firstly the cost functions of the KPIs as used in the planning model are discussed. This is followed by the validation of the generated plans, using expert consultation and visual representation of the generated plans in the current planning tool: Planwise. Thereafter the original and new plans are compared quantitatively, resulting in clear insights into the effect of the KPIs and the possibilities of the planning model as designed. Based on the quantitative insights, several scenarios have been formulated which are executed using the model to gain more insights into the relationship between the KPIs and the model results. Finally the planning performance improvement is evaluated and conclusions are drawn answering the research question of this chapter.

Comprehensively, this chapter covers the following points:

7.1 KPI parameters: cost functions and weights
7.2 Validation of generated plans
7.3 Quantitative analysis of the KPIs
7.4 Quantitative analysis of the original plans compared to the new plans
7.5 Experimentation with the planning model
7.6 Evaluation of the planning performance improvement
7.7 Evaluation of the planning model

Finally in section 7.8 the answer to the research question of this chapter is discussed.

7.1. KPI parameters: cost functions and weights

Computation of the model results requires, apart from the in chapter 6 discussed parameters and settings, the exact definition of the cost functions and weights of the KPIs. These set the boundaries and balance of the resources that the KPIs measure and steer the model results. As discussed in chapters 5 and 6 three KPIs are studied: locomotive usage, workforce usage and wagon usage. The locomotive usage and workforce usage are measured per shift and half-shift, respectively. Wagon usage is measured for each time step. The used values in the cost functions for all KPIs are fictional. These cost values are only used for the model computations and provide quantitative insights. The cost values are not realistic and therefore do not represent real-life value of the resources used. The complex on-site logistics operations make real-life cost values difficult to determine and as of yet the exact cost definition of each resource is unavailable. The cost functions for each KPI are setup[1] as presented in table 7.1. In figure 7.1 the cost functions are illustrated graphically. The threshold value is the starting value of the cost function, i.e. from this value onward costs are computed. The set threshold values are chosen based on early model results and prove to result in well balanced plans.

Table 7.1: Overview of the cost function specification for each KPI

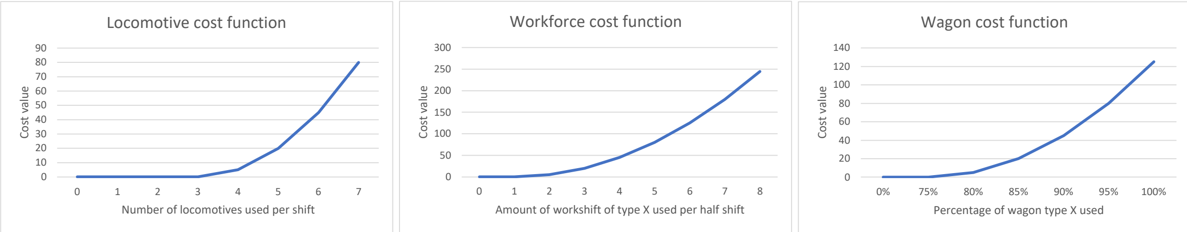
KPI	Cost function shape	Unit	Threshold	Time Scale	KPI value
Locomotive usage	Quadratic	Per locomotive	3	Per shift	Summation over all shifts
Workforce usage	Quadratic	Per workforce group, per cluster	1	Per half-shift	Summation over all half-shifts, per cluster
Wagon usage	Quadratic	Per 5% wagon capacity, per wagon type	75%	Per time step	Summation over all time steps, per wagon type

With the defined cost functions, having lower boundaries where no costs are made which balance the KPIs, there is no need to assign specific weights to any of the KPIs. The KPIs are balanced with their cost functions based on starting values, where if the model can have little to no resulting costs the resulting plans are considered as high quality in terms of KPI performance. Thus the weight of each KPI is set equal to one.

7.2. Validation of generated plans

After verification of the model, setting the model parameters and achieving model results, the model results require validation. Validating the planning model, as described in chapter 6, is done by writing the model output as such that it can be imported back into the current planning tool Planwise and inspected by the expert planners. This expert validation is done for each of the three data sets with the base KPI parameter settings as presented in section 7.1. In the expert validation the data modifications and model simplifications & assumptions have been considered.

[1]Cost function shape is piece-wise linear within step size in case of the wagon usage, and the cost functions continue after the capacity of five locomotives as in the original plans these limiting values may have been violated



(a) Locomotive cost function (b) Workforce cost function (c) Wagon cost function

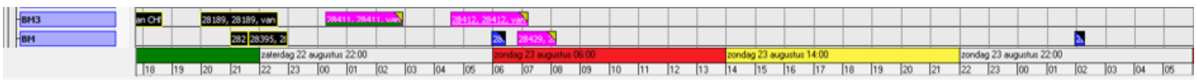
Figure 7.1: Cost functions for each of the KPIs

Planwise, apart from visualizing the new plans, also provides insights into the usage of workforce and wagons and has incorporated warnings if jobs are scheduled too early or too late for the subsequent jobs. Important to note is: Planwise screen captures as reported in this thesis do not show the locomotive jobs, only the loading and unloading jobs are shown at their site-locations. Furthermore, the planning model considers time as steps of 30 minutes. Job duration is therefore in the model considered having a minimum of 30 minutes duration or multiples of 30 minutes. However, the Planwise plans as visualized show the original duration of jobs.

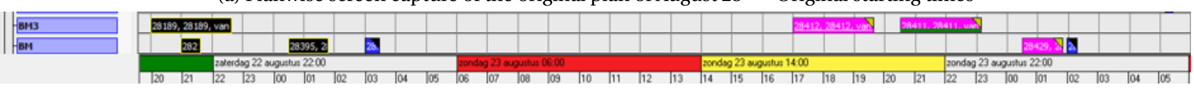
The model outputs for all three of the data sets are considered valid, however three main differences are noted. Firstly the planning model picks different starting times for various jobs, secondly there is more time slack between jobs and spreading of jobs over time and thirdly the planning model assigns jobs less consecutively at the same site-location. For the data set of August 23rd these are highlighted below in paragraphs 7.2.1 till 7.2.3.

7.2.1. Visual model output comparison: Starting time choices

The first main difference noted in the model output, i.e. new plans, compared to the original plans, is the distinct differences in starting time the model makes. There are many examples found where the model, considering all the constraints and aiming for the best performance in terms of the defined KPIs, assigns different starting times to jobs. The resulting differences visually and quantitatively (discussed in section 7.3) are clear. Figures 7.2a and 7.2b are examples where very different starting times are assigned to the same jobs (colored pink in the figures).



(a) Planwise screen capture of the original plan of August 23rd - Original starting times

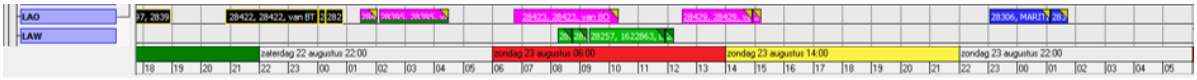


(b) Planwise screen capture of the new plan of August 23rd - Starting times by the model

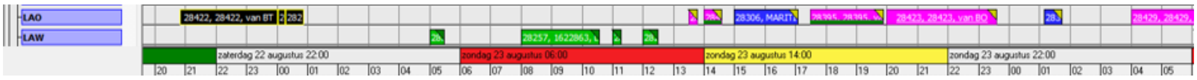
Figure 7.2: Set of screen captures of Planwise with both the original and new plans of August 23rd; showing the original and new starting times of the jobs.

7.2.2. Visual model output comparison: Job spreading over time

Secondly in the new plans differences are noted on the spreading of jobs over time. Partly this is spreading or slack due to the model assuming jobs have a duration of 30 minutes or multiples of 30 minutes and when these are rescheduled in Planwise the original duration is re-assigned by Planwise, but this is also a 'choice' of the model. The planning model may decide it is better to spread the jobs more in time at the same site-location and in doing so achieve better plan performance in terms of KPIs. Furthermore, the added slack in between jobs at the same site-location, compared to the original plans, does not necessarily result in a worse plan performance as this provides a more robust plan, which is more capable of handling slight delays in execution without this delay stacking over time. Figures 7.3a and 7.3b illustrate the differences, as described in this paragraph, in the green-colored jobs of the *LAW* warehouse.



(a) Planwise screen capture of the original plan of August 23rd - Jobs scheduled tightly

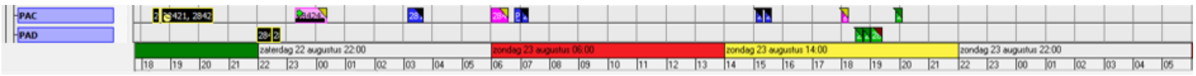


(b) Planwise screen capture of the new plan of August 23rd - Jobs more spread out

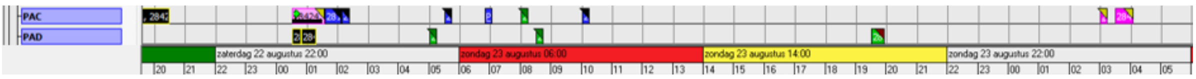
Figure 7.3: Set of screen captures of Planwise with both the original and new plans of August 23rd; showing job spreading at the LAO and LAW warehouses.

7.2.3. Visual model output comparison: Job assignment within warehouse clusters

Thirdly the new plans schedule jobs such that they are grouped in time at the same site cluster but not at the same time, thus minimizing the amount of workforce needed to load and unload the wagons. But the new plans do not yet sequentially plan the jobs optimally at the same site-location. Figures 7.4a and 7.4b show some examples where the jobs in the new plan are scheduled alternating between the PAC and PAD warehouses instead of sequentially first at the one warehouse and thereafter at the other warehouse. Scheduling jobs closely after another minimizes the time the workforce spends traveling between site-locations and allows for a more easy combination of transit jobs on one locomotive, maximizing its tractive force usage. A KPI which stimulates this kind of grouping of jobs is not part of the current planning model.



(a) Planwise screen capture of the original plan of August 23rd - Not alternating between warehouses



(b) Planwise screen capture of the new plan of August 23rd - Alternating between warehouses

Figure 7.4: Set of screen captures of Planwise with both the original and new plans of August 23rd; showing jobs being scheduled between the PAC and PAD warehouses.

7.3. Quantitative analysis of the KPIs

With the model and its results validated, the original plans can be compared to the optimized (new) plans quantitatively. For both the original plans and new plans the KPI scores per data set have been computed. As discussed in section 6.4.3 the data sets are very similar. This similarity is also noted in the results for both the original and newly optimized plans. Because the plans of August 23rd are the largest data set, these are shown in this section explicitly. The tables and charts with the results for all the data sets are found in appendices F and G.

Note that for the data sets of August 23rd and August 25th near-optimal plans have been constructed by the planning model. August 23rd is estimated 90% near optimality and August 25th is estimated 80% near optimality[2]. The resulting plans score very well in terms of the KPIs, with little better solution space left, and in light of the objective of this study these levels of optimality are sufficient.

7.3.1. KPI 1: Locomotive usage

Tables 7.2 and 7.3 and figure 7.5 show the clearly different results for the original plan and new plan of August 23rd. Contrary to the original plan, the planning model succeeds in spreading the locomotive usage and optimizing the usage within shifts. Returning in all data sets is the large peak of locomotive usage at the start of the time horizon, in the 01:00 - 01:30h time shift, in the original plans. This peak usage is due to the modeling of Hall-transfer tasks which are in reality planned partly on the previous day. As discussed in chapter 6, these tasks, where the loading of the wagons is done outside of the planning scope, do need to be included in the plan evaluation. These plans are manually set to have the wagon-supply, loading and transit jobs at the first three time steps of the plan. Therefore there is a very large amount of wagons that are in transit at the same time. The noted peak is thus not realistic, but the load on the resource does needs to be handled by the planning model. In the second shift of the time horizon the original plan has several peaks that exceed the estimated locomotive capacity. These peaks will be handled in real life by the rail department, smoothing out their operations and combining jobs as much as possible. The nature of the planning model however, explicitly considering the locomotive KPI in plan generation, potentially better considers the rail process limitations. Overall the locomotive usage load is handled well and the model succeeds in achieving a good KPI score.

Table 7.2: Locomotives per shift - August 23rd - original

Shift	Locomotives used	Costs
0	18	1125
1	9	180
2	7	80
3	3	0
Total	37	1385

Table 7.3: Locomotives per shift - August 23rd - new

Shift	Locomotives used	Costs
0	3	0
1	4	5
2	4	5
3	4	5
Total	15	15

[2]Based on Gurobi which estimates the best possible objective value.

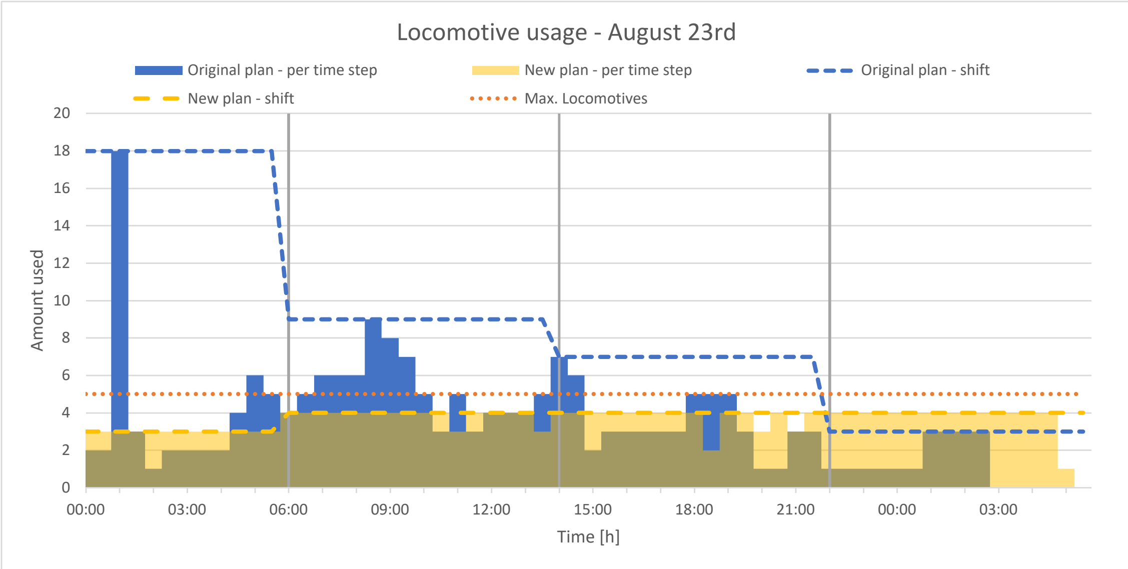


Figure 7.5: Locomotive usage - August 23rd

7.3.2. KPI 2: Workforce usage

As seen with the locomotive usage, the planning model also succeeds in achieving low and spread out workforce usage over time and per half shift, as is shown in the graphs of figure 7.6 and tables 7.4 & 7.5. The less busy clusters of site-locations result in similar usage of workforce for both the original and new plans, but with the busy clusters the new plans very much show less and more spread workforce usage, e.g. at the *Cluster Midden*. In terms of the KPI score, most of the costs in the original plan are due to many tasks being located at *Cluster Midden*. Here the new plan too does not achieve zero costs, however in the optimized plan there are only 2 workforce units needed and these are used throughout the day consistently.

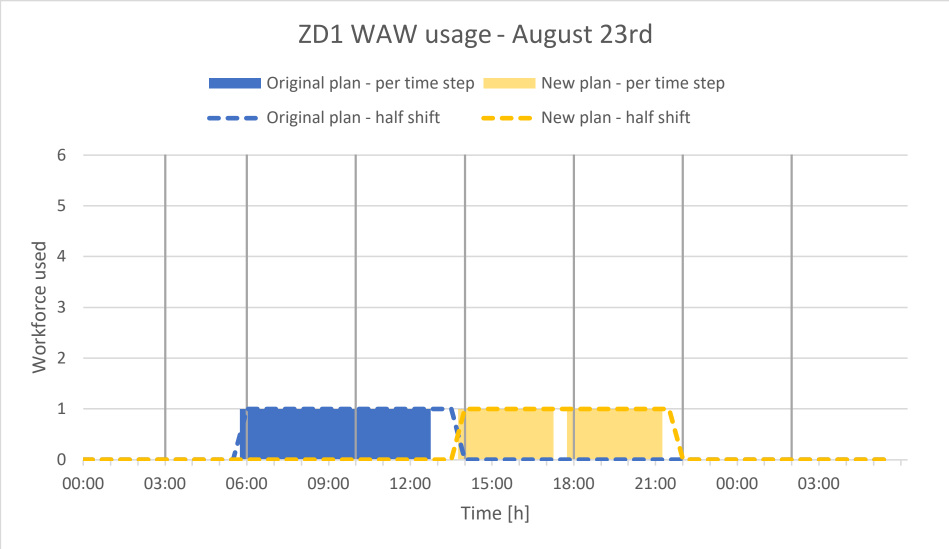
Note that in the graphs of figure 7.6 it shows that at the end of the full regular shift marks (06:00h, 14:00h and 22:00h) the workforces are less used. This is due to the current planners taking the transition of shifts into consideration. In these transitions generally less loading and unloading work is done and the workers are for example doing administrative tasks or are leaving the cranes.

Table 7.4: Workforce per half shift - August 23rd - original

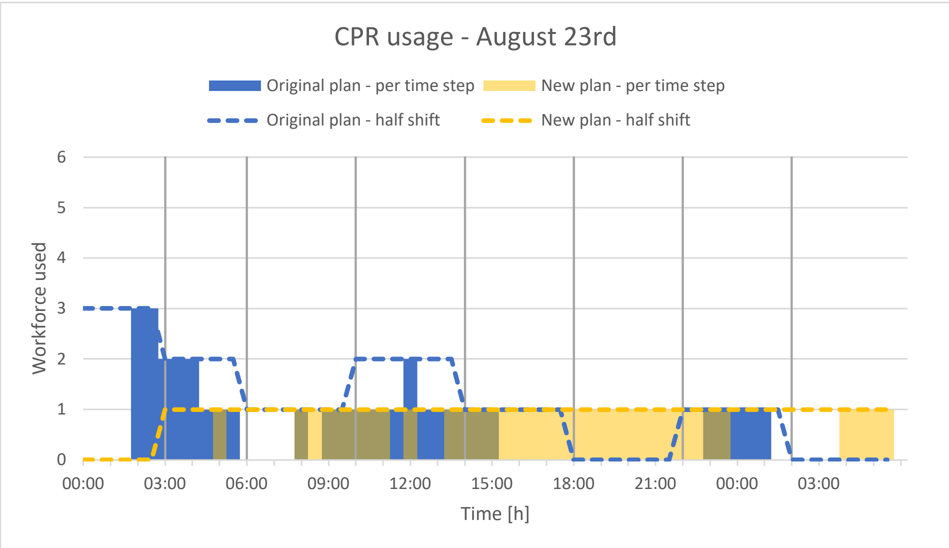
Half shift	ZD1 WAW Amount used	ZD1 WAW Costs	CPR Amount used	CPR Costs	Cluster Zuid Amount used	Cluster Zuid Costs	TSP Amount used	TSP Costs	Cluster Midden Amount used	Cluster Midden Costs	Cluster Noord Amount used	Cluster Noord Costs
0	0	0	3	20	4	45	5	80	9	320	3	20
1	0	0	2	5	2	5	5	80	2	5	3	20
2	1	0	1	0	1	0	0	0	4	45	2	5
3	1	0	2	5	1	0	2	5	5	80	1	0
4	0	0	1	0	1	0	1	0	5	80	1	0
5	0	0	0	0	1	0	1	0	4	45	2	5
6	0	0	1	0	0	0	2	5	2	5	0	0
7	0	0	0	0	0	0	1	0	0	0	0	0
Total	2	0	10	30	10	50	17	170	31	580	12	50

Table 7.5: Workforce per half shift - August 23rd - new

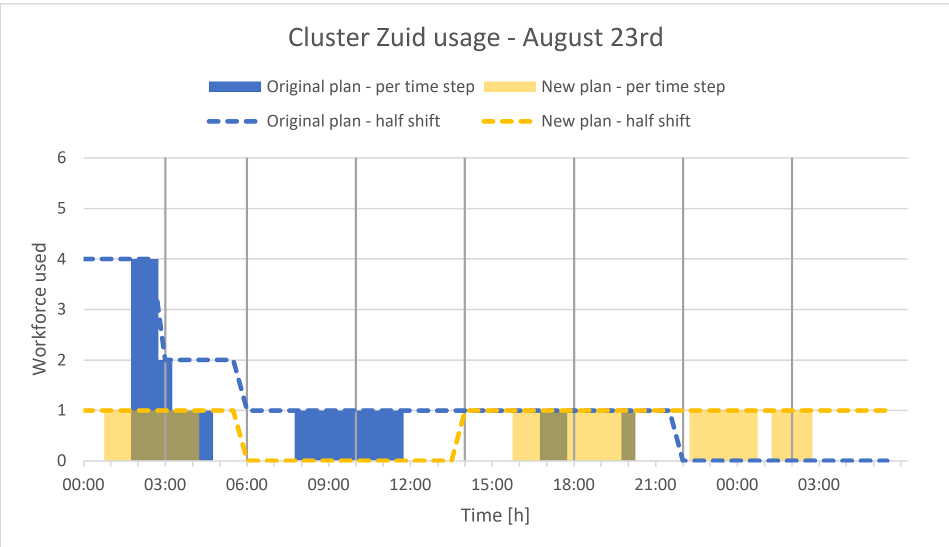
Half shift	ZD1 WAW Amount used	ZD1 WAW Costs	CPR Amount used	CPR Costs	Cluster Zuid Amount used	Cluster Zuid Costs	TSP Amount used	TSP Costs	Cluster Midden Amount used	Cluster Midden Costs	Cluster Noord Amount used	Cluster Noord Costs
0	0	0	0	0	1	0	1	0	2	5	1	0
1	0	0	1	0	1	0	1	0	2	5	1	0
2	0	0	1	0	0	0	1	0	2	5	1	0
3	0	0	1	0	0	0	2	5	2	5	0	0
4	1	0	1	0	1	0	1	0	2	5	1	0
5	1	0	1	0	1	0	1	0	2	5	1	0
6	0	0	1	0	1	0	1	0	2	5	1	0
7	0	0	1	0	1	0	1	0	2	5	1	0
Total	2	0	7	0	6	0	9	5	16	40	7	0



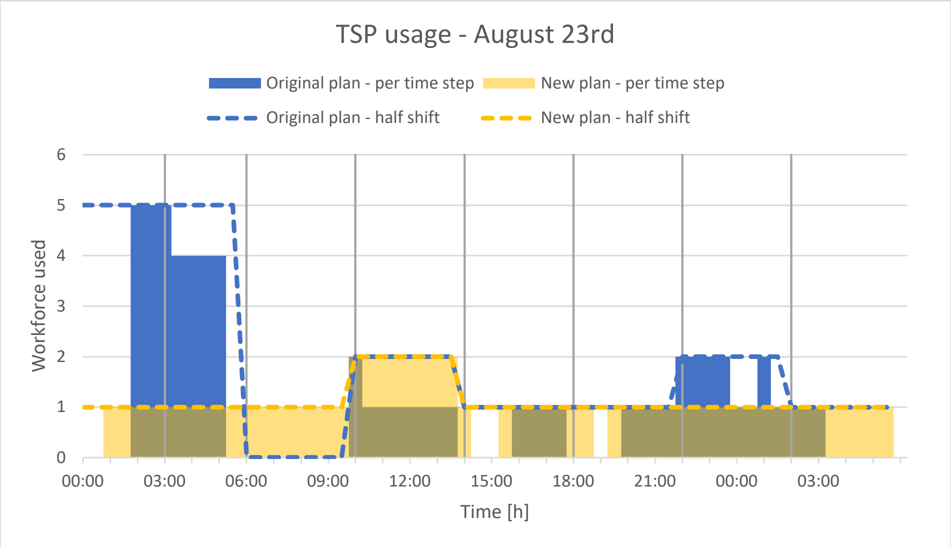
(a) Workforce WAW cluster usage - August 23rd



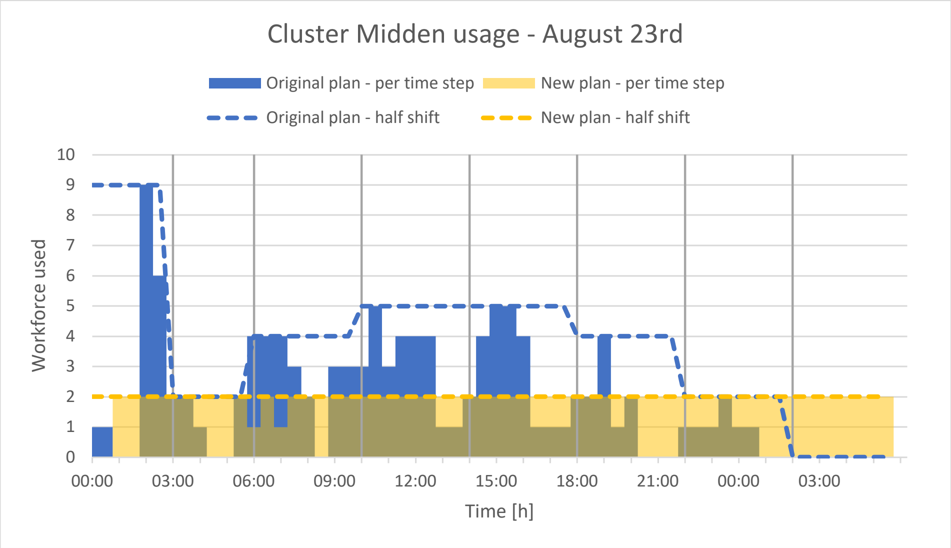
(b) Workforce CPR cluster usage - August 23rd



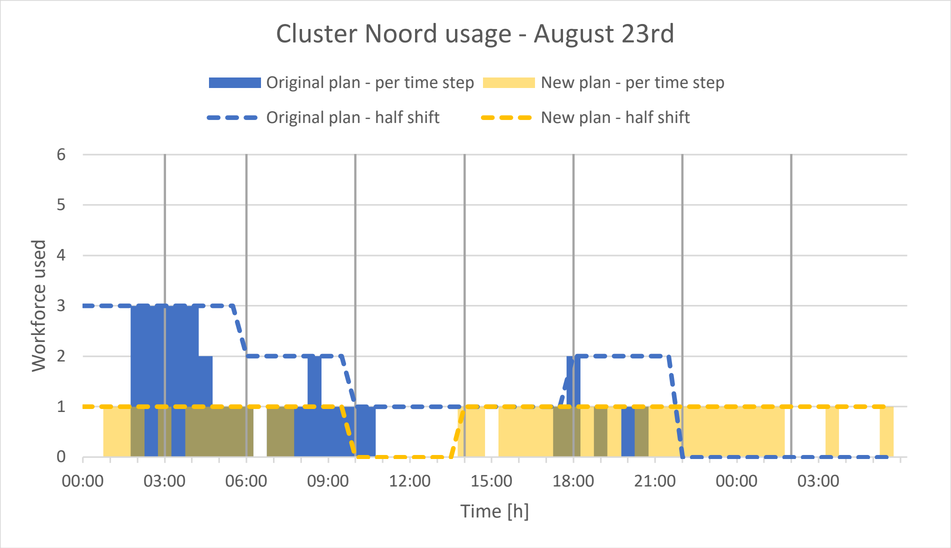
(c) Workforce Cluster Zuid usage - August 23rd



(d) Workforce TSP cluster usage - August 23rd



(e) Workforce Cluster Midden usage - August 23rd

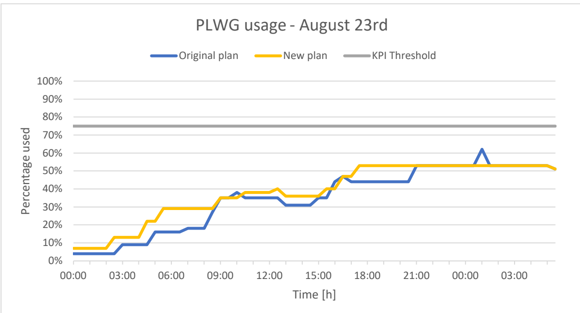


(f) Workforce Cluster Noord usage - August 23rd

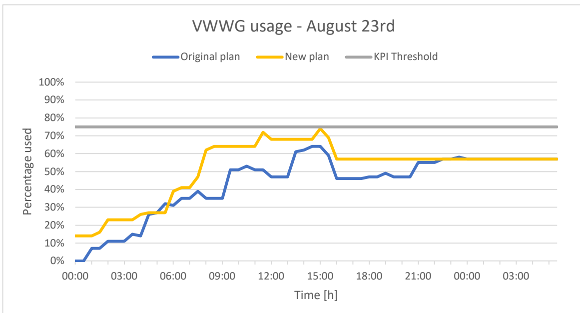
Figure 7.6: Workforce usage per cluster - August 23rd

7.3.3. KPI 3: Wagon usage

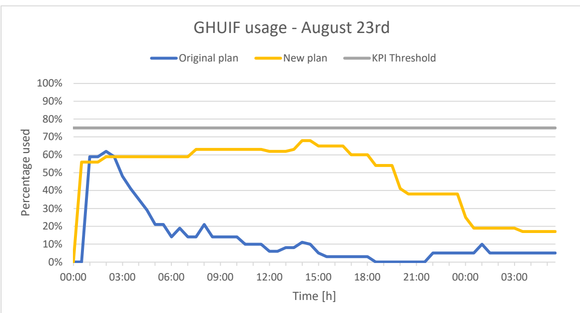
In terms of the wagon usage KPI, there are both similarities and differences in the results comparing the original and new plans of August 23rd, illustrated in the graphs of figure 7.7 and in the tables 7.6 & 7.7. Firstly the wagon usage starts from zero or near zero. In reality this would be rare as there will be tasks busy with loaded wagons crossing the midnight mark. In the model however the plans start without started tasks. Furthermore the PLWG and VWWG wagons usage have very similar results for both the original and new plans. The usage for both these wagon types gradually increases over the planning horizon. This is due to these wagons being used in the data set of August 23rd for the shipment tasks. These tasks in the data set have mostly their unloading jobs due at the end of the planning horizon. As these wagons are plentiful and the usage does not exceed the KPI threshold, the planning model will allow these wagons to be used for much of the day and balance the other resources more. This is also clearly seen in the GHUIF usage graph, where the planning model keeps these wagons in use for much longer and in doing so better balances the other resource loads. Only the SETJE wagon type yields for both the original and the new plans KPI costs. The original plan has the high peak at the start of the planning horizon, as explained in the locomotive usage KPI paragraph 7.3.1, due to the Hall-transfer tasks mainly using SETJE wagon types. This large resource load is handled better by the planning model, but it is clear the model has more difficulties with this wagon type and it often comes close to resulting costs.



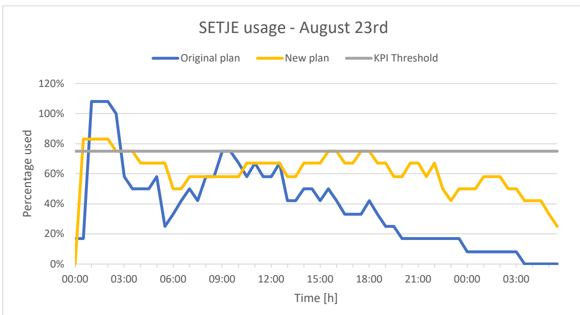
(a) PLWG usage - August 23rd



(b) VWWG usage - August 23rd



(c) GHUIF usage - August 23rd



(d) SETJE usage - August 23rd

Figure 7.7: Wagon usage per type - August 23rd

Table 7.6: Wagons costs - August 23rd - original

Wagon type	Costs
PLWG	0
VWWG	0
GHUIF	0
SETJE	500
Total	500

Table 7.7: Wagons costs - August 23rd - new

Wagon type	Costs
PLWG	0
VWWG	0
GHUIF	0
SETJE	60
Total	60

7.4. Quantitative analysis of the original plans compared to the new plans

This section discusses the quantitative results of the full plans in terms of the KPI metrics and resource usage. The original plans are compared to the base model results based on the KPI cost values and total amount of resources used per plan. Firstly the plans are compared in terms of KPI cost values, secondly the plans are compared based on the resource usage. For each plan, the number of locomotives per shift are added up, the total workforce per half-shift for all clusters are added up and finally the average percentage wagon capacity used per wagon type is computed. Note that in all the computations, KPI cost value and resource usage, the first shift (00:00h - 06:00h) is excluded. This is done to more fairly compare the original plans, of which in the first shift locomotive and workforce usage has high peaks. These peaks are caused by the modified scheduling of loading jobs of hall-transfer tasks which partly took place before the start of the planning horizon. The new plans balance this load over the day. Thus the comparison of original and new plans here is based on the regular three planning shifts at Tata Steel IJmuiden, i.e. 06:00h - 14:00h, 14:00h - 22:00h and 22:00h - 06:00h.

The results in terms of the KPI cost values are presented graphically in figure 7.8. In this graph the 'cost' values per KPI and per data set are plotted on a logarithmic scale for better comparison as the cost-functions have an exponential shape. Not considering the first shift (00:00h - 06:00h) removes nearly all the moments where wagon 'costs' are made in the original plans. The short, high peaks in locomotive usage during the second shifts (06:00h - 14:00h) results in high cost values for the locomotive KPIs of the original plans and as the KPI value for the workforces are summed over all the workforces this combines into a large KPI value. Overall it is clear that the planning model is able to out-perform the original plans based on the formulated KPIs. The KPI cost functions work as intended, with reduced peaks and resource usage and this is also seen in the KPI values.

However, only examining the KPI cost values may give a distorted picture in the comparison. This is due to the combined thresholds and exponential cost function shapes which heavily penalize high resource usage in the original plans. Therefore the comparison of the original plans versus the new plans is also done based on the resource usage overall, shown graphically in figure 7.9. Note that in figure 7.9 the wagon usage value is the average percentage and not the true number of wagons used.

For each data set it is clearly visible that the combined locomotive and workforce totals of the new plans are much less. In terms of the wagon average the new plans have a higher average, however this is not a problem as the wagon usage percentage per type generally remains well below their KPI threshold of 75% for each plan. Table 7.8 shows the overview of the data of figure 7.9 with additionally the difference per original and new plan. Not considering the wagon usage increase, as

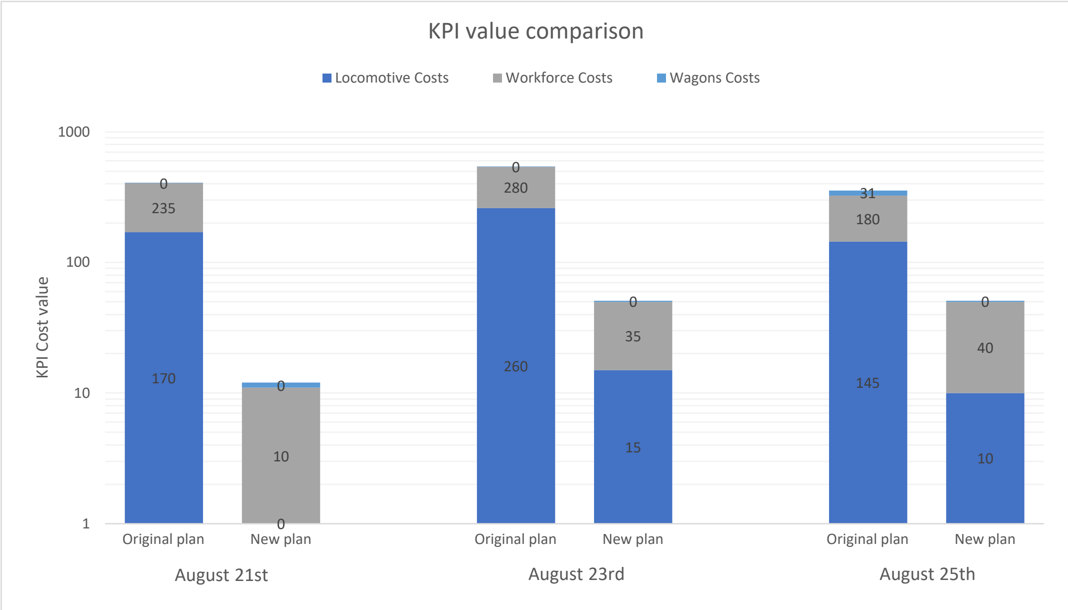


Figure 7.8: Graphical representation of the KPI values per data set, comparing original plans to optimized plans by the planning model

this is proven not to be bad for the plan performance, the results of table 7.8 show that the planning model is able to reduce combined locomotive and workforce usage up to 25% on average. Furthermore note that this is with 90% and 80% optimal plans for August 23rd and August 25th respectively. Additionally, although the exclusion of the first shift in the comparison of this section yields a realistic estimate, it must be noted that the planning model does include the resource load that is seen in the first shift but balances this over the rest of the planning horizon. The exclusion of the first shift therefore somewhat favors the original plans in the comparison. Therefore the shown 20+% resource usage reduction can be seen as a safe estimate.

Data sets size & COVID-19 pandemic

Do note that these data sets are smaller in size, i.e. number of tasks per day, compared to 'normal' operations, due to the COVID-19 pandemic, as discussed in chapter 6 and the data sets not including each task type of the on-site logistics at Tata Steel IJmuiden.

Table 7.8: Resource usage results & percentage change per data set, comparing original plans to optimized plans

	August 21st			August 23rd			August 25th		
	Orig. plan	New plan	Delta	Orig. plan	New plan	Delta	Orig. plan	New plan	Delta
Locomotive shifts	17	9	-47%	19	12	-37%	26	11	-58%
Workforce half-shifts	38	30	-21%	44	38	-14%	38	38	0%
Wagon average [%]	26	40	+54%	33	52	+58%	38	42	+11%
Total	81	79	-2%	96	102	+6%	102	91	-11%
Total without wagons	55	39	-29%	63	50	-21%	64	49	-23%

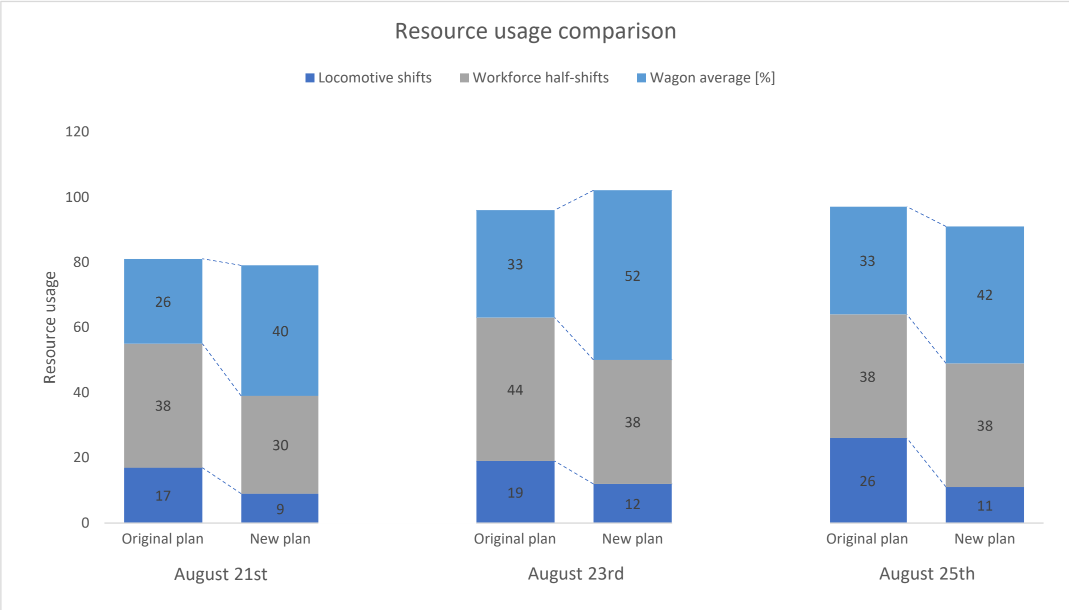


Figure 7.9: Graphical representation of the resource usage results per data set, comparing original plans to optimized plans by the planning model

7.5. Experimentation with the planning model

The results discussed in the previous section show the viability of using a planning model to create on-site transportation plans. To gain extra insights into the planning model's potential and the formulated KPIs experimentation with the planning model is done. The experimentation consists of a set of three scenarios and is done using an experimental plan.

7.5.1. Experimental plan

To structure the experimentation and scenario execution with the planning model, a basic experimental plan is drafted. The experimental plan consists of the three formulated scenarios, the set of model parameter changes and the hypothesis of the results of the scenarios. The following three scenarios are studied:

Scenario 1: Zero locomotive and workforce usage during the final 30 minutes of a regular shift.
Scenario 2: Reduced GHUIF usage by setting the KPI threshold lower.
Scenario 3: Reduced locomotive usage by KPI parameter tuning.

These scenarios are based on real-world operations or relevant insights provided by the experts at Tata Steel IJmuiden. The results of the scenarios are compared to the base model results as presented earlier in this chapter. For each scenario the model setup, hypothesis and results are discussed.

All of the scenarios are done with the August 23rd data set.

7.5.2. Scenario 1: Zero locomotive and workforce usage - end of shift

In the first scenario the goal is to analyze if the planning model can create plans which are also performing well if the plans have a similar consideration of the end-of-shifts work efficiency as the planners currently apply. The reason as explained in chapter 7.3.2 is that during this period in a shift, less to no actual loading occurs in the real world use-case. This consideration is implemented into the model by setting the capacity of the locomotive tractive force and each workforce cluster to zero for the last time step of each regular shift. In doing so the planners' intention to not plan jobs during these time steps is recreated.

The hypothesis of this scenario is that the results of the planning model will still out-perform the original plans in terms of the KPI scores. Furthermore it is expected that the scenario results in comparison to the base model results will only show a slight increase in the number of locomotives used and possibly one extra unit workforce for the *Cluster Midden* workforce group. The other workforces will not increase as there is still some capacity left in the shifts as can be seen in figure 7.6.

Results scenario 1:
The results of scenario 1 show that not using locomotives during the last half-hour of a shift results in one extra locomotive used in the second shift of the day. For the rest of the shifts, no change in locomotive requirement was found. This result is shown in figure 7.10, where the scenario 1 result is compared to the base model result of August 23rd.

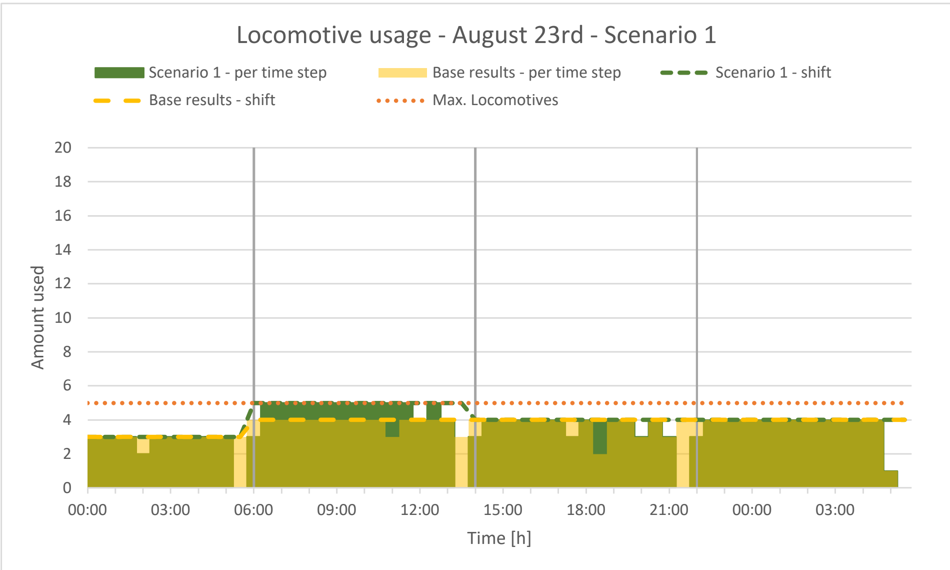


Figure 7.10: Locomotive usage - Scenario 1 - August 23rd

The workforce results of scenario 1 generally only show minor changes. In most clusters there is no significant change in the usage of workforce. Most notably are the *TSP* and *Cluster Midden* workforce clusters. At TSP one half-shift requires two, as opposed to one, workforce groups and at Cluster Midden one half-shift requires three, as opposed to two, workforce groups. These results are shown graphically in figure 7.11 and 7.12.

Similarly to the workforce results of scenario 1, the wagon usage results do not significantly change apart from the SETJE wagon types. The SETJE wagons are higher in use but also stayed within the set KPI threshold. This result is shown in figure 7.13.

The full scenario 1 results are shown in appendix F and G.

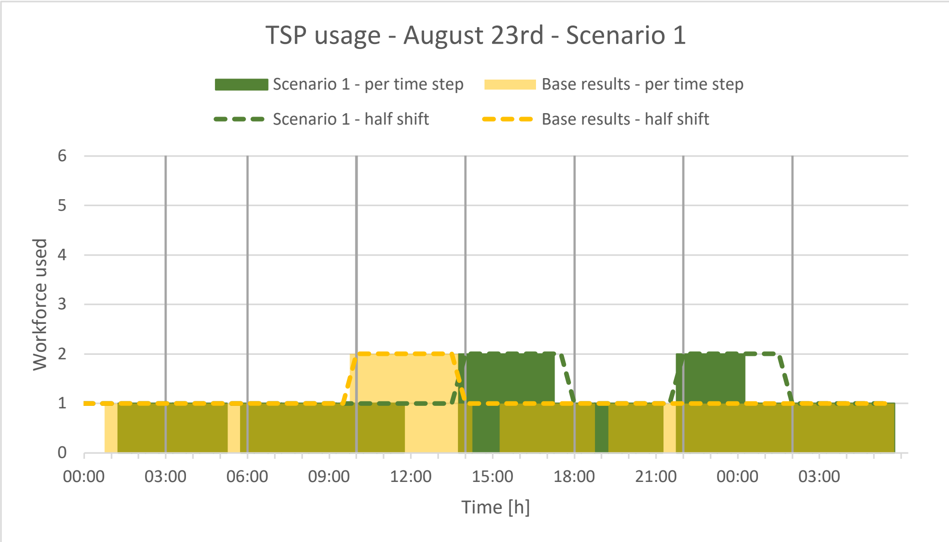


Figure 7.11: Workforce TSP cluster usage - Scenario 1 - August 23rd

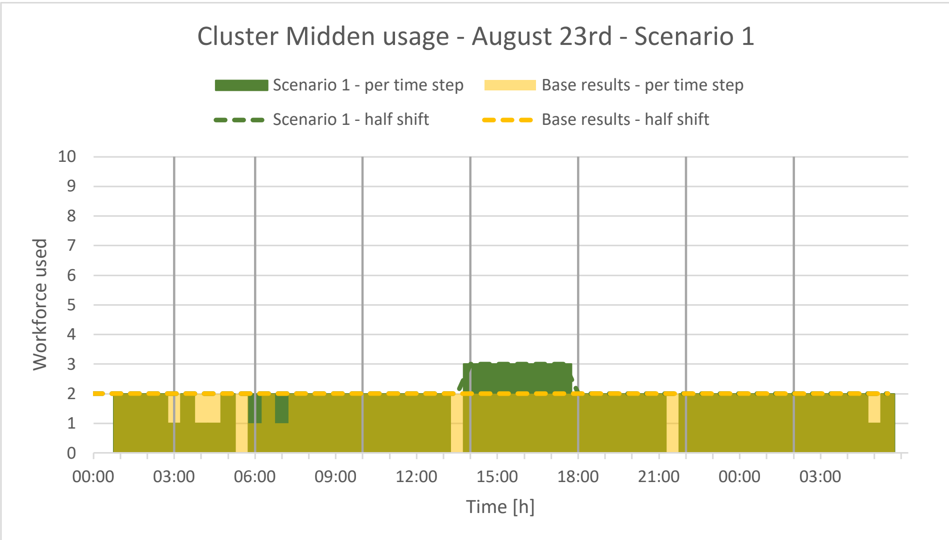


Figure 7.12: Workforce Cluster Midden usage - Scenario 1 - August 23rd

The planning model output with the settings of scenario 1 still clearly out-perform the original plans, therefore the hypothesis of scenario 1 is confirmed. Compared to the base results there was as expected a slight increase in the locomotive and workforce usage but still, a very well-performing plan resulted.

7.5.3. Scenario 2: Reduced GHUIF usage

The GHUIF wagons are mostly used for inbound shipment tasks. Therefore it is preferable to use minimal GHUIF wagons at certain times to allow for a large inbound shipment. This scenario studies the ability of the model to handle such requests and what the impact of this is on the other KPI scores and resource usage. The goal of this scenario is to assess what the impact of lowering the GHUIF KPI cost threshold is on the GHUIF usage and the other KPIs. Thus the threshold of the GHUIF wagon KPI is set to 50% instead of 75%. Therefore the model optimizes to keep the GHUIF wagon type usage below 50% or as close to 50% as possible.

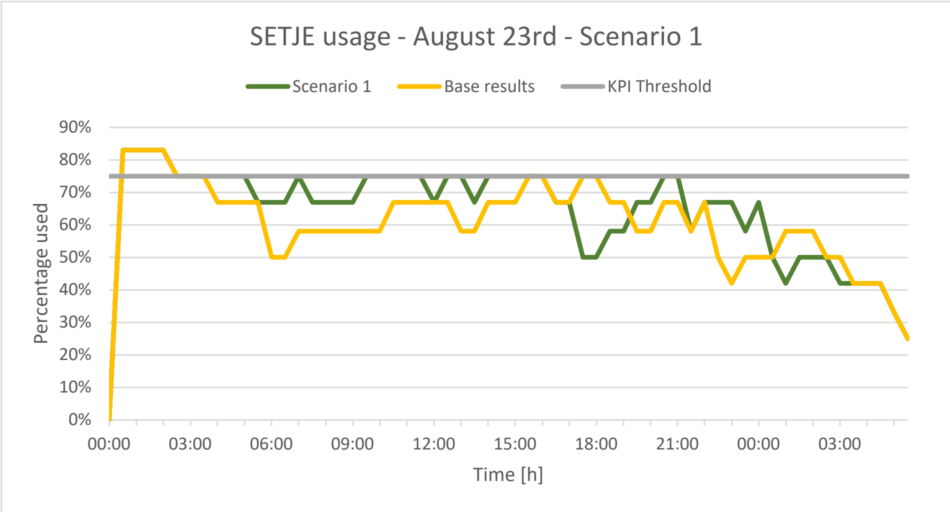


Figure 7.13: SETJE usage - Scenario 1 - August 23rd

In the base model results, the GHUIF wagon type is a large portion of the day above 50% capacity. It is thus expected that the GHUIF usage will be at 50% for nearly the full day until there is more room in the locomotive capacity to further reduce the GHUIF usage. This will result firstly in more locomotive usage at the start of the plan to keep the GHUIF usage low. The workforce usage is not expected to change significantly as the planning model will balance this load evenly.

Results scenario 2:
The results of scenario 2 show a slight increase in the locomotive usage in the first shift, compared to the base model results. This locomotive usage goes up from three to four. The locomotives are not fully used during the third shift in the scenario results, however this does not result in a reduced amount needed for the whole shift.

The workforce usage of scenario 2 is similar to the base results, only increasing very little at *Cluster Zuid* and shifting usage in *CPR* and *Cluster Noord*.

Most importantly in terms of the wagon usage very clear differences are visible. Where the PLWG and VWWG usage stays very similar to the base model results, the Setje usage increases similarly to scenario 1 and moreover the GHUIF usage drastically changes. GHUIF wagons are used much less over the whole day as is shown in figure 7.14. The GHUIF wagon usage takes a similar shape to the GHUIF usage of the original plans by the warehouse planners. At the start of the day, the GHUIF usage is high, but this steadily decreases towards 20% usage at around 12:00h and remains low for the rest of the plan.

The full scenario 2 results are shown in appendix F and G.

The results from scenario 2 clearly show the capability of the planning model to formulate plans with very good KPI performance and at the same time allow for tactical decision-making support. Here the scenario was examined where a large number of GHUIF wagons were expected to be needed for other tasks. The planning model has adjusted accordingly, stimulating reduced GHUIF usage, and subsequently proved this was possible while maintaining a high plan performance level. The hypothesis of scenario 2 is confirmed, as at first the GHUIF usage was still higher than 50% but

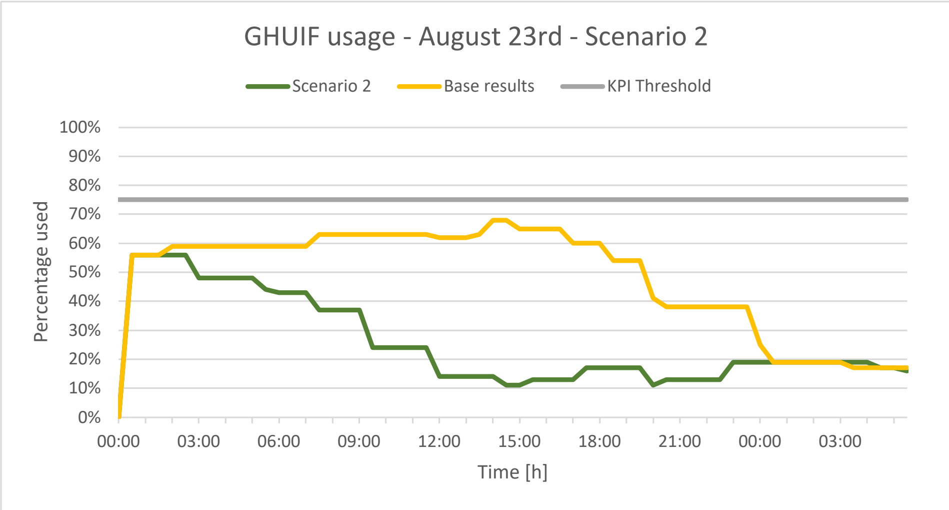


Figure 7.14: GHUIF usage - Scenario 2 - August 23rd

this reduced steadily over the course of the plan, with an impact on the locomotive and workforce usage as expected.

7.5.4. Scenario 3: Reduced locomotive usage

One of the main objectives of the planning model is reducing the locomotive usage. It is interesting to investigate if the locomotive usage can be reduced more than the results of the base model. This is done in four ways:

- Firstly the locomotive cost function threshold is lowered,
- Secondly the locomotive KPI-weight is increased,
- Thirdly the locomotive metric is changed to half-shifts,
- Fourthly a cost function with different thresholds per shift is studied.

The listed four analyses are discussed one-by-one in the rest of this section. Overall it is expected that the most promising results are found by adjusting the shift size of locomotives to half shifts, as this presents the most added flexibility for the model in its decision making.

Analysis 1: Cost function adjustment

The cost function adjustment is two-fold; first the cost function threshold of up-to three locomotives per shift yield zero costs is lowered to three locomotives yielding 'five' costs, four yielding 20 costs, etc. In the second stage of the analysis this is lowered further to two locomotives yielding 'five' costs, three locomotives yielding 20 costs, etc. The adjustments of the KPI cost function are expected to result in less locomotive usage, at the cost of more workforce and wagon usage.

The model results with adjusted cost functions showed for both cases no significant differences. The locomotive usage per shift did not change. The workforce usage and wagon usage did not change significantly. The KPI value of the locomotive KPI did change accordingly, i.e. consistently with the cost function threshold change. It is therefore concluded that the adjustments of the first analysis of this scenario did not change the locomotive usage compared to the base model results.

Analysis 2: Locomotive KPI weight increase
In the second analysis the KPI weight of the locomotive KPI is increased to two in the planning model objective function. This is done with the cost function setting of analysis 1, where the threshold of the locomotive KPI cost function is lowered to two locomotives yielding 5 costs, three locomotives yielding 20 costs, etc. The goal of this analysis is to evaluate the effect on the locomotive usage of both increasing the locomotive KPI, while keeping the other KPI weights set to one, and lowering the KPI threshold of the locomotive cost function. It is expected that the combination of both the analysis 1 setting and the relative KPI weight increase does effect the locomotive usage significantly.

Contrary to the expectation, the model results of analysis 2 did not show significant changes in the locomotive usage, nor in the workforce or wagon usage. The only notable changes are that the first locomotive shift now required four (previously three) locomotives and the last shift required three (previously four). Due to the first shift being two hours shorter than regular shifts, the total resulting locomotive usage would be only for two hours of locomotive use, which is not considered a significant change. Overall the results are very similar to those of analysis 1 and thus the base model results. As expected the total objective value did change according to the weight change and the KPI cost function adjustments, however this did not yield changes in the resource usage within the generated plan. Therefore it is concluded that the combined adjustment of analysis 1 and the addition of analysis two did not change the locomotive usage compared to the base model results.

Analysis 3: Locomotive usage per half-shift
In analysis 3 the locomotive usage is measured per half-shift, similarly to the workforce usage. Besides computing locomotives per half-shift the cost function threshold is adjusted systemically as is done in analysis 1 of this scenario. Firstly a run is done with the regular cost function of the locomotive KPI. Secondly the cost function threshold is lowered to three locomotives yielding '5' costs and thirdly the threshold is lowered further to two locomotives yielding '5' costs. It is expected that the added choice flexibility of the amount of locomotives used through the half-shifts, in combination with the cost function adjustments, will result in less locomotives used per half-shift than the base model results, while keeping similar workforce and wagon usage.

As expected the model results of this analysis showed reduction in locomotive usage compared to the base model results due to the added flexibility of half-shifts. However, this reduction is only small, even in the last analysis run with the lowest cost function threshold setting (from one locomotive onward yielding costs). The locomotive usage of this last run is shown in figure 7.15. The figure shows that the difference is only one full shift with one less required locomotive. Besides this a small cost increase in Setje wagon type was noted; compared to the base model results the short peak in high Setje usage at the start of the plan (as can be seen for example in figure 7.13) was extended briefly in the analysis 3 results.

Analysis 4: Locomotive cost function per shift
In the final analysis of the scenario 3 experiment, the locomotive usage resulting from cost functions with different values per shift is examined. In this analysis a planning model run is done with lowered cost function thresholds for the first and last shifts, i.e. the shifts during nighttime. The thresholds are lowered for the night shifts with one step, which yields '5' costs for three locomotives used at night. The goal of this analysis is to evaluate if the planning model with the current KPIs can be used to for example mimic higher costs of operations at night and adjusting resource usage

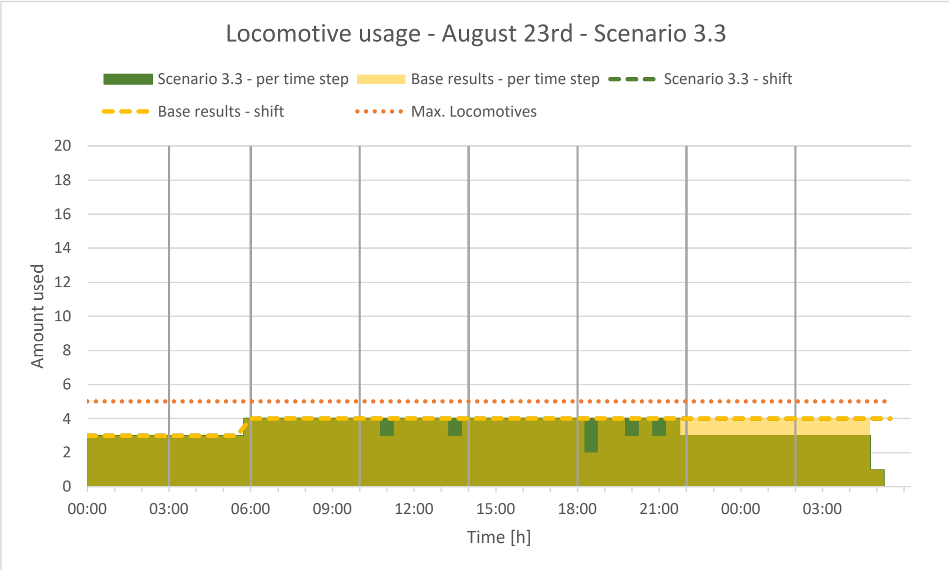


Figure 7.15: Locomotive usage per half-shift - Scenario 3, Analysis 3 - August 23rd

accordingly. These costs may be monetary due to higher labor costs, but could also be due to more environmental nuisance for the people living near the manufacturing site. The cost function adjustments of this analysis are expected to result in reduced locomotive usage during the first and last shift compared to the base model results at the expense of more locomotive usage during the day shifts.

The model results show as expected less locomotive usage in the night shifts compared to the day shifts, with three locomotives required during the night shifts and five and four during the two day shifts. These results are illustrated in figure 7.16. These results show that applying different cost functions for different situations, such as nighttime higher cost levels, will steer the model results in the desired direction and thus enable the user of the planning model to get desired results for the situation.

Results scenario 3:
Overall the results of the analyses of the scenario 3 model runs show that the locomotive usage is not easily lowered further. Adjustments to the cost functions did not greatly impact the locomotive usage per shift but the found change also did not come at the expense of the other resources. Therefore some steering of the model results through the cost function is possible. However the cost functions and the KPIs as formulated did yield robust results, which continued to generate well performing plans even with bigger cost function and KPI-weight modifications. Measuring the locomotive usage in half-shifts added flexibility for the planning model to yield slightly better performing plans. This resource usage reduction does need to be evaluated in terms of the available operational flexibility. Finally, through adjustments such as higher cost levels associated with nighttime operations, which are easily interpreted by users, the planning model results can be steered towards even more favorable plans. This proves the planning model is capable of KPI-based planning combined with situational steering.

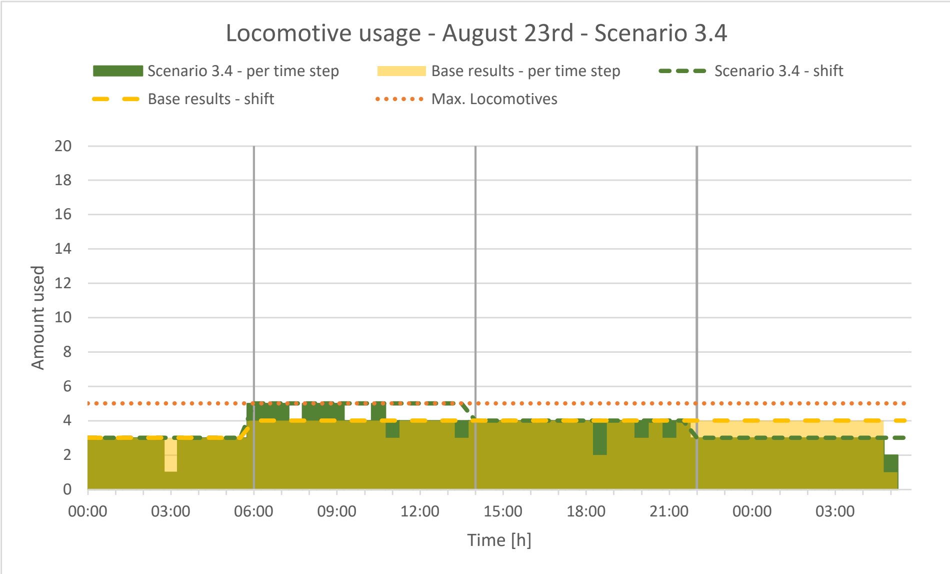


Figure 7.16: Locomotive usage - Scenario 3, Analysis 4 - August 23rd

7.6. Evaluation of the planning performance improvement

Based on the base model results and the results from the performed scenarios the planning performance is. This evaluation is split into two parts: planning performance in light of the KPIs and planning process & operations evaluation.

7.6.1. Planning performance - KPI findings

The final base model results and scenario results show clear differences in planning performance compared to the benchmark of the old original plans. This performance comparison leads to several clear findings in terms of the overall performance, the formulated KPIs and the planning process. These findings regarding the KPIs are discussed below:

Finding 1:
Creating optimal plans based on the formulated KPIs results in valid, realistic and well-constructed plans. Additionally the addition of some extra slack in between jobs, whilst maintaining planning performance, was not considered as faulty. This adds robustness and provides a transition time between jobs for the workers.

Finding 2:
It is possible to make warehouse plans while considering three KPIs simultaneously and have the resulting plans performing well.

Finding 3:
The results from the planning model out-perform the original plans in terms of the formulated KPIs. This is especially the case in load balancing of resource usage and furthermore peaks in the locomotive and workforce usage are greatly reduced.

Finding 4:
To achieve even better warehouse plans, an extra KPI needs to be added which stimulates sequential planning of jobs at the same site-location, above the currently stimulated sequential planning

within a site cluster.

Finding 5:
The analyses of scenario 3 show that the formulated KPIs yield robust results even when tuning of the cost functions or the KPI-weights is done. Some steering of the model results is possible through adjusting the cost function thresholds and the KPI-weights, but this does not instantly impact the ability of the model to also consider the other KPIs and provide well performing plans.

7.6.2. Planning performance - Planning process & operations findings

The findings regarding the planning process and operations are discussed below:

Finding 1:
The results show that the complex warehouse plan can be modeled and solved by a planning model. This presents opportunities to apply this model in real-life to make warehouse plans from scratch. These generated plans can be used as feasible starting points for the planners to further adjust, complete and add tasks to the plans over the day.

Finding 2:
The planning model results enable planning based on adjustable decision rules depending on the expected business of the day and initial plans. The planning model can be used multiple times to evaluate different plans based on different optimization goals. For example, the decision can be made by planners to accept long wagon usage, i.e. wagons can be loaded for a long time, in case of a relatively calm day in terms of the number of tasks that require scheduling. In doing so the more costly resources can be used less and more efficiently.

Finding 3:
The planning model allows planners to better consider the resources at hand. Current plans are more focused on using the current resources within their constraints, but planners are less able to consider many resources at the same time. Individual preferences and experiences come into play here. Decision support in form of the planning model has thus high potential in practice to form an unbiased base plan.

Finding 4:
Usage of the planning model in operations will give the port-planners many additional insights in the KPIs and in early stages presents a feasibility check during the formulation of the port plan. This reduces workload and saves time for both the port-planners and the warehouse-planners and possibly the rail-planners too.

Finding 5:
The results of scenario 1 and 2 show that the planning model is capable of generating well performing plans even with business considerations such as workforce efficiency at the end of shifts or the need to free up space in a wagon type.

Finding 6:
The results of scenario 3 show that measuring locomotive usage also in half-shifts enables some further reduction in that resource usage through the added flexibility in the planning. Furthermore scenario 3 shows the capability of the planning model to apply KPI-based planning in combination with situational steering of KPI parameters. These KPI parameters could for instance be higher cost

levels at night for locomotives, lowering the cost function threshold during these shifts and resulting in lower locomotive usage at night at the cost of more usage during the day.

Finding 7:
If the planning model is developed further it has high potential to incorporate and consider the surrounding logistics processes such as the rail operations. This enhanced consideration of for example the rail operations is of much-added value to the overall on-site logistics operations.

Finding 8:
Finally the planning model, in potential, allows plans to be made further ahead if the data on tasks is available, for quick rescheduling and other applications such as maintenance planning and tactical decision making. The tactical decisions can be made using planning model results based on the outlook of shipments and outbound trains. This can for example adjust the prospective locomotive usage per shift for the coming days and service level agreements with other departments can be made.

7.7. Evaluation of the planning model

Apart from the findings on the model results' performance compared to the original plans and how the planning model can impact the planning process and operations, the planning model itself is evaluated too. This evaluation is done based on the model requirements as formulated in chapter 6.

Functional requirement evaluation:

1. The planning model must comply with the warehouse plan functional requirements as formulated in section 4.7.
   Compliance: Yes

2. The planning model must create plans based on quantitative KPIs.
   Compliance: Yes

3. The planning model must create plans based on data from original, real-world, data sets.
   Compliance: Yes

4. The planning model must be able to plan representative data sets in terms of size and complexity; planning outbound shipments, export trains and hall transfer tasks ('omrijzendingen').
   Compliance: Yes

5. The planning model must have a time scale resolution which is compliant with the level of detail at which currently warehouse plans are made.
   Compliance: Yes

6. The planning model must be able to generate warehouse plans from different days, i.e. handle different data sets.
   Compliance: Yes

7. The planning model must maintain the structure of transportation tasks as these currently are, i.e. consisting of four main steps (jobs): wagon-supply, loading, transit, unloading.
   Compliance: Yes

Non-functional requirement evaluation:

1. The planning model must plan a full day's[3] data set in a fixed horizon planning manner[4].
   Compliance: Yes

2. The output of the planning model must be as such that it is importable into the current planning tool Planwise, for expert validation.
   Compliance: Yes

3. Solving of the planning model must be finished within a reasonable time (0 - 1 hour)[5] and at a reasonably high level of optimality (80+% optimal).
   Compliance: Yes and no. The planning model run times vary over the different model run settings and data set sizes. This ranges from within reasonable time to much longer and optimality of results is not guaranteed. Section 7.7.1 discusses this more in-depth.

7.7.1. Run time

This section goes more in-depth in the model run times with different run parameter settings and the three data sets (having different sizes).

Per data set the following parameters of the model run settings are varied systematically:

- MIP Focus: Determines the high-level solution strategy of the Gurobi solver. The default value is 0 which balances the search for new feasible solutions and optimality of the current solution. Value 1 results in a faster search for more feasible solutions, value 2 focuses on the optimality of solutions and value 3 can be used if the quality of the solution improves very slowly, focusing on the bound.
- Presolve: This determines the time the presolve may take. The Gurobi solver takes some time to presolve the formulated model, setting this to value 2 allows more time to be allocated to the presolve process. This may result in tighter models and speed up the further solution search.
- Cuts: This parameter affects the MIP cutting plane generation of the Gurobi solver. Setting this value to 2 allows the solver to be more aggressive in the cut generation. MIP cutting planes are used to remove parts of the solution space which are not desirable (i.e. do not lead to better feasible solutions) [6]

The MIP Gap, which sets the cutoff value for the accepted level of optimality for the computations, is set to 10% near-optimal (thus 90% optimal solutions are accepted as model run output). Further-

[3] This is consistent with the current planning horizon

[4] This results in clearly defined in scope and comprehensive plans for analysis and links to the current planning process of 24h to 48h planning ahead.

[5] Real world plans are made in a continuously operating environment which makes long solve times impractical. Furthermore rescheduling should be quick if new tasks are added.

[6] For more information on the Gurobi solver processes refer to: gurobi.com/resource/mip-basics

more the time limit of the model runs is set to 5 hours, thus if at that time there is no solution or the solution has not passed the MIP Gap threshold, the model run is terminated.

This results in 12 runs, shown in table 7.9, where the time to the first feasible solution and the time to the first optimal, or that which is below the MIP Gap value, solution are measured. The results of these 12 runs for each data set are presented in table 7.10.

Table 7.10 shows that the run time is very dependent on the size of the data set, i.e. the number of tasks that need to be scheduled. Also the run time of the August 25th data set is very large compared to the other two data sets, with no found optimal or near-optimal solutions after 5 hours for any run setting. Using a warm start, loading a found feasible solution at the start of the optimization run, does enable August 25th runs to reach more optimal solutions. The in table 7.10 noted percentages in case of no optimal or near-optimal solution found are the reached optimality estimates after 5 hours.

Overall the model run times for the August 23rd data set show that run times of 40 minutes are to be expected to reach optimal solutions with the current planning model.

The model runs are done using Gurobi optimizer version 9.0.2, build v9.0.2.rc0 (win64), in Python version 3.7.6 using Spyder Anaconda. The used computer has an Intel Core i7-8650U processor.

Table 7.9: Overview of the twelve model run time settings tested for each data set

Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
MIP Focus	0	0	0	1	1	1	2	2	2	3	3	3
Presolve	Base	2	2	Base	2	2	Base	2	2	Base	2	2
Cuts	Base	Base	2	Base	Base	2	Base	Base	2	Base	Base	2
MIP Gap [%]	10	10	10	10	10	10	10	10	10	10	10	10
Timelimit [h]	5	5	5	5	5	5	5	5	5	5	5	5

Table 7.10: Model run time results, as tested with the twelve model run settings of table 7.9

	Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Aug 21st	Time to feasible solution [min]	15	1	1	1	1	1	20	1	1	20	1	1
	Time to optimal or MIPGap [min]	19	3	4	4	3	7	22	3	4	75	45	29
Aug 23rd	Time to feasible solution [min]	24	11	21	10	11	11	24	30	29	34	37	36
	Time to optimal or MIPGap [min]	56	46	46	38	39	42	51	64	60	-, 75%	-, 75%	-, 75%
Aug 25th	Time to feasible solution [min]	55	26	19	76	77	79	21	20	20	138	-	39
	Time to optimal or MIPGap [min]	-, 75%	-, 82%	-, 80%	-, 80%	-, 80%	-, 80%	-, 80%	-, 80%	-, 80%	-, 40%	-	-, 70%

7.8. Conclusions

In this chapter the quantitative planning model results are analyzed and evaluated. The results are compared to the original plans as made by the Tata Steel IJmuiden warehouse planners. Based on the results, the formulated operational KPIs expressed as the locomotive, workforce & wagon usage, are evaluated. Furthermore experimentation is done with the planning model and finally the planning model itself is evaluated based on its requirements. This chapter has the aim of answering the following research question:

SQ 7: *To what extent can increased decision support improve on-site transportation planning?*

To answer this research question the planning model results are quantitatively and qualitatively analyzed and compared to the original plans. Thereafter several scenarios are used for experimentation with the model to further analyze the model's workings, potential and how the KPIs relate. Based on the full set of results, key findings have been formulated covering the planning performance, formulated KPIs, planning process and on-site logistics operations at Tata Steel IJmuiden in light of the warehouse plan. This combined enables answering the research question.

The clear differences in the original plans and the resulting plans formulated by the planning model based on the KPIs and the absence of a calculation of real-world costs for each resource-use make it hard to state how much real-world improvement increased decision support in form of a KPI-based planning model has on on-site transportation planning. However, based on the KPIs in form of locomotive, workforce and wagon usage, it is concluded that the planning model, through application of the quantitative KPI objectives, is able to potentially[7] reduce combined locomotive and workforce usage per shift and half-shift, respectively, by up to 25%, while maintaining robustness through keeping wagon usage below 75% of capacity.

Thus using the planning model will result in reduced and more efficient resource usage. There will be fewer peak loads for the workforce and the planning model will be able to create schedules considering three or more KPIs, which govern usage over many resources, at the same time. At the least, the planning model enables planners to start from a feasible plan early on, with quantitative insights on the performance of the plan. This reduces planner workload and has the potential to decrease overall time planners need to spend on the warehouse plans. This potential echoes through to the port plan and rail plan and those planners as the warehouse planning model simultaneously considers for instance rail operation constraints such as locomotive tractive force. Further development of the planning model potentially allows planning further ahead, including maintenance planning and tactical decisions on the on-site logistics resources based on medium-term forecasts. The decision support model allows moving from constraint-based planning to KPI-based planning.

[7] Considering data set size (COVID-19 operations and not all task types)

8
Conclusions, Discussion & Recommendations

This thesis has the goal of gaining insights into the on-site transportation planning of large manufacturing plants and their performance measurements. With these insights, it is determined to what extent on-site transportation planning can improve by applying data driven decision support. Through studying and analyzing the performance and quantitative key performance indicators (KPIs) of on-site transportation plans of a large manufacturing site and by adding to the scientific body of knowledge of this topic, the goal of this thesis has been completed. The first step was studying the literature background on on-site transportation plans and creating a scientific foundation for this research. Thereafter the use case of Tata Steel IJmuiden's warehouse plan was analyzed and a set of KPIs which determine the performance of the warehouse plan have been formulated. Through the development of a planning model that generates warehouse plans based on the KPIs, the quantitative performance of the warehouse plans has been evaluated. These steps provide the answers to the sub-research questions and culminate in the answer to the main research question, which was formulated as follows:

Main research question:

How can the on-site transportation planning at a large manufacturing plant be improved, by 1.) adding company KPIs and 2.) data-driven decision support based on the parameters of the locality and its constraints?

This chapter covers the final conclusions, discussion and recommendations. Firstly the answers to the first six sub-research questions are discussed, followed by answering the seventh and last sub-research question and the main research question. Thereafter the scientific and societal contribution of this thesis is discussed. Discussion on the overall thesis results is done and finally this chapter concludes with recommendations for further research and recommendations for the commissioner of this thesis.

8.1. Conclusions

Before answering the main research question, firstly the sub-research questions are answered briefly based on the answers formulated at the end of each chapter of this thesis. This section closes off with the answer to both the seventh sub-question and the main research question.

Sub-Question 1: Characteristics of on-site logistics and industrial railway systems
The literature study into on-site logistics and industrial railway systems was used as background for this thesis and to answer the first research question:

What are the characteristics of on-site logistics and industrial railway systems?

On-site logistics is characterized by its categorization as either procurement logistics, production logistics, or distribution logistics, along with agreed service levels with customers. The on-site logistics system consists of site infrastructure, arranged in one of the various network arrangements and distribution structures. Furthermore characterization of on-site logistics depends on the type of goods in the system, type of terminals in the network and the network usage. The core tasks of on-site transportation systems is the collection and delivery of goods and having the role of buffer for previous and subsequent systems. The transportation is done based on a push or pull flow. Rail-based on-site transportation is a subclass of on-site logistics and this includes industrial railway systems. Industrial railway systems are characterized by the transport configuration of the trains and the concurring yard type. Industrial railway systems make use of a guide-path network structure which limits the freedom of movement of its vehicles to the rail network in place.

Sub-Question 2: On-site transportation planning at large manufacturing plants
Analysis of the on-site logistics system and current warehouse planning at Tata Steel IJmuiden was done to answer the second research question of this thesis:

How are on-site transportation plans created at large manufacturing plants?

The process of formulating on-site transportation plans at large manufacturing plants is dictated by the inflow, i.e. production, and outflow, i.e. customer orders and pick-up of goods, characteristics. Key is the role of on-site transportation as the service provider of goods on-site, ranging from production or storage areas to outbound terminals. Furthermore on-site transportation planning has a role in the coordination of operations between various departments, storage of goods and distribution of goods on-site. On-site transportation plans are subject to many complex constraints related to the site resources, operational parameters such as vehicle speeds and the (rail) network. At the same time, a variety of disturbances, predictable and unpredictable, may hinder the execution of the plans. Safe, on-time and undamaged delivery of goods is key to the service role of on-site transportation and its planning.

Sub-Question 3: Data requirement for on-site transportation planning
An important step on the way to developing the planning model and gaining quantitative insights into the performance of on-site transportation plans was the determination of what data is required to apply data-driven decision support to on-site transportation planning. This resulted in the third research question:

What data is required for the application of data-driven decision support to on-site transportation *planning?*

The data required for the application of data-driven decision support consists of two elements: firstly the data which is currently used in planning and secondly the data which determines what better or worse decisions are in on-site transportation plans. In the case of the Tata Steel IJmuiden warehouse plan, the first element consists of the transport tasks which are to be scheduled, the port plan, the rail plan and the requested internal repositioning tasks. Additionally the information on the constraints (e.g. resource capacities) needs to be known. The second data element which governs the decision making in the plans consists of quantitative values which express the plans in terms of their performance. This performance is a combination of several metrics that translate specific and measurable key elements of the transportation plans.

Sub-Question 4: Performance measurement of on-site transportation plans
Based on the SCOR performance measurement framework and analysis of the use case of Tata Steel IJmuiden, the KPIs which combined quantitatively express the performance of on-site transportation plans have been formulated. This answered the fourth research question:

How can the performance of on-site transportation plans be assessed?

Based on the SCOR performance measurement system a set of performance metrics is determined which combined express the performance of on-site transportation plans. These have been used as the foundation for the performance metric determination of the warehouse plan of Tata Steel IJmuiden. This resulted in the following four KPIs which combined express the performance of the warehouse plan:

- On-time delivery of goods
- Costs of planned actions
- Peak loads in resource usage
- Robustness of the formulated plan

Furthermore these KPIs have been specified as quantifiable metrics and evaluated based on the in literature found guidelines and best-practices of performance measurement and KPI formulation. On-site transportation plans can thus be assessed in terms of their performance by using the combined value of the formulated and quantified KPIs.

Sub-Question 5: Modeling on-site transportation planning
With the literature background, system analysis and performance measurement complete, the planning model which creates on-site transportation plans based on KPIs has been developed. This answers the fifth research question:

How can on-site transportation planning be modeled?

Literature study into planning problems and system analysis of the Tata Steel IJmuiden use case determined that the scheduling problem at hand could be formulated as a Resource Constrained Multi-Project Scheduling Problem (RCMPSP). The RCMPSP is a subclass of the Resource Constrained Project Scheduling Problems and fits the problem as found at Tata Steel IJmuiden's warehouse plan. The warehouse plan is mainly focused on creating plans which properly service the on-site logistics process within the constraints set by the available resources and surrounding processes. The tasks of the warehouse plan can be modeled similarly to the projects of project scheduling problems, where projects consist of several steps with precedence relationships. The warehouse plan has many tasks and thus is considered as 'multi-project'.

Sub-Question 6: Solving on-site transportation models
After determining that the warehouse plan can be modeled as an RCMPSP type of scheduling problem, the sixth research question had to be answered:

What is a suitable solution method for on-site transportation models?

The mathematical formulation of RCMPSP scheduling problems and thus the warehouse plan on-site transportation model, as a Mixed-Integer Linear Problem (MILP) is a suitable method to solve the planning problem. This mathematical formulation, after translation to computer code, can be solved using optimization solvers. In this thesis, the mathematical formulation has been programmed in the Python API of the Gurobi solver. Using Gurobi resulted in successful solutions to three real-world data sets of the warehouse plan.

Sub-Question 7 & Main Research Question: Improving on-site transportation planning
With the model complete, verified and validated, the model results have been analyzed and evaluated. This was done with the intent to answer the seventh research question:

To what extent can increased decision support improve on-site transportation planning?

Answering the seventh research question, combined with the answers to the other research questions, results in the answer to the main research question:

How can the on-site transportation planning at a large manufacturing plant be improved, by 1.) adding company KPIs and 2.) data-driven decision support based on the parameters of the locality and its constraints?

The application of increased decision support has a high potential in improving on-site transportation planning. The resulting plans made by the planning model out-performed the original plans made by the planners in terms of the KPIs. The planning model, through application of the quantitative KPI objectives, is able to potentially reduce combined locomotive and workforce usage per shift and half-shift, respectively, by up to 25%, while maintaining robustness by keeping wagon usage below 75% of capacity.

Usage of the planning model in real-life is expected to lead to a significant reduction in resource usage peaks and higher resource usage efficiency. The planning model can make better warehouse plans as it can simultaneously consider three KPIs. The formulated plans can be used as a starting point by the planners, as they are both feasible in practice and perform better in respect of the quantitative KPI insights. This reduces the workload and overall time needed to formulate the plans. The potential benefits of the planning model may also affect the port plan and rail plan and those planners positively. The planning model already partly considers rail operation constraints through the locomotive KPI and provides feasibility insights for port planners. These feasibility insights are important as the port plan is part of the inputs and constraints of the warehouse plan. If the port planners can quickly review whether their plan poses problems for the warehouse planners, complications can be prevented. Further development of the planning model enriches its potential, from planning further ahead to tactical on-site logistics resource decision making. On-site transportation planning can move from constraint-based planning towards KPI-based planning through the application of a data-driven decision support planning model.

As described in the research objective of chapter 1, the on-site transportation planning of large manufacturing sites will be enhanced by added decision support based on KPIs, providing opportunities to evaluate alternative plans quantitatively. The manufacturing sites will move from a slower manual planning process to a (partly) automated fast planning process, reduce planner workload and execute more optimal plans resulting in more effective and efficient logistics operations. The quality of plans become less dependent on the planner and their experience and the plans become more standardized. Most of all, through the application of KPI-driven decision support plans will move from being adapted to fit constraints and disturbances to being determined based on quantitative insights in its KPIs. In the past this has been proven difficult to achieve in practice.

8.1.1. Added scientific value

The literature study found large potential for applying decision support in real-life planning cases. There are expected performance gains to be made by combining human and automated decision making integrally, where the best of both is used. Combining this with proper performance measurement has been marked as a relevant avenue for further research. Currently research does not yet cover the full system analysis and KPI determination of real-world use cases in combination with the actual application of a real-world operable planning decision support model, which plans real-world-sized problems with real-world complexity in terms of constraints and decision making. This gap has been filled by this thesis as it does firstly fundamentally analyze the on-site logistics and planning process, continues with detailed performance measurement formulation for both general on-site transportation planning and the real-world use case, then a planning model is developed which can plan real-world data sets and finally achieves quantitative and qualitative results and insights into the application of decision support for on-site transportation planning.

The focus on on-site logistics of this thesis additionally adds scientific value to the current practice and body of knowledge as on-site logistics generally speaking does not put a large focus on cost minimization of its processes. This is caused by the fact that on-site logistics are viewed as a service provider for more costly processes such as manufacturing. Costs of on-site logistics are much less compared to for example manufacturing due to lacking on-site logistics service provision. Risk aversion in on-site logistics makes the move towards optimization and resource usage minimization difficult to prove as being of added value to the business.

In table 8.1 the most notable research opportunities that have been covered in this thesis are listed. This table is derived from table 2.1 from the literature study, showing only the literature gaps this thesis has put emphasis on.

8.1.2. Added societal/business value

It was expected by ORTEC consultants and Tata Steel IJmuiden management and planners that performance gains in the on-site transportation plans of Tata Steel IJmuiden could be made. This thesis has proven that this is indeed possible, by analyzing the earlier not explicitly known constraints and requirements of on-site transportation plans and most of all specifying the quantitative expression of the performance of these plans.

Table 8.1: Table with the covered literature research gaps and opportunities of this thesis.

Source: Lacked: Opportunity covered:	Van der Linden (2018) Detailed knowledge of the planning processes and accompanying performance Performance improvement in the planning process by mapping the planning process has been found
Source: Lacked: Opportunity covered:	Crainic and Roy (1988) - Potential improvements of added automation compared to strictly manual planning is confirmed
Source: Lacked: Opportunity covered:	Díaz-Madroñero et al. (2015) Focus on application of Tactical transportation planning models to realistic use cases Application of a planning model to realistic use case has been done
Source: Lacked: Opportunity covered:	Mostafa and Eltawil (2016) Limited to less complex situations, considering e.g. only a single plant or homogeneous fleets, limited use of real life studies Application on real-life use case has been done on a complex system
Source: Lacked: Opportunity covered:	Bouchard et al. (2017) Human planner aspects and consideration of Decision Support, KPI determining and evaluation Potential of application of integrated planning, with specified KPIs and their evaluation, shows higher planning performance
Source: Lacked: Opportunity covered:	McKay and Wiers (2003), Fleischmann et al. (2008) - An exact optimization planning model has been used to optimize and find alternatives to a planning problem, where the objective and constraints have been mapped first
Source: Lacked: Opportunity covered:	Ghiani et al. (2004) - Benchmarking and evaluation of performance through performance metric based comparison is done and shows proper configuration of the planing model

This thesis has made clear what makes a good on-site transportation plan and provides insights into the key performance indicators which determine this performance. Currently the derived operational KPIs can already be applied to the plans, adding insights for the planners into the expected locomotive and workforce usage of the upcoming shifts.

Furthermore these insights and the developed planning model may result in an implementable and daily operational planning tool that adds data-driven decision-making to the current planning process at Tata Steel IJmuiden. This tool leads to better plans, – that is plans that align automatically with Tata Steel's overall economic objectives by taking into account company KPIs. The model will also allow management to plan on a tactical level as the weight of any KPI or their relative weight within the model can be adjusted as required. Thus planning can move from a purely operational level based on constraints to become part of any overall tactical and strategic effort as defined by Tata Steel as a company given economic, environmental, or societal goals. The planning process will move from constraint- and disturbance-based to quantitative KPIs-based, where planners will experience decreased workload, easier and more efficient handling of exceptions and changes.

8.2. Discussion

This section covers, per core steps of this thesis, the discussion points of this research and its results.

System analysis:
The conclusions of this thesis are based on the results of the planning model which generates on-site transportation plans based on the use case of Tata Steel IJmuiden's warehouse plan. On-site logistics and transportation will have similar characteristics for different real-world cases, but ultimately different key elements will define the plans. Tata Steel IJmuiden is unique as a use case as it is one of the largest manufacturing sites in Western-Europe, with over 100km of rail track, a large number of site-locations and its own inland and seaport. Furthermore the type of goods, (semi-)finished steel products, which are transported in large quantities at the site, make Tata Steel IJmuiden a special use case. The conclusions and results of this thesis therefore need to be considered with the use case in mind.

Performance measurement:
The SCOR framework has been used in this thesis as the main foundation for the KPI determination. SCOR is a proper framework to use, as is discussed in this thesis, but other performance measurement systems could also have resulted in suitable KPIs, for example those performance measurement systems also scoring high in figure 5.1. This thesis thus does not imply that SCOR is the only right performance measurement system to use in case of on-site transportation planning.

Furthermore, as discussed in this thesis, the SCOR KPIs themselves still require molding to the real-world use case that is analyzed. As stated earlier, each use case is different and it is important to specify KPIs which capture the specifics of the system that is measured and are in line with the objectives of the stakeholders.

The specified KPIs for the warehouse plan of Tata Steel IJmuiden have shown to result in well-performing plans and their use has been proven. However there may be other formulations or specifications of the KPIs which will yield similar results. Furthermore it is noted that additional KPI(s) which would encourage sequential scheduling of jobs at the same site-location would be real additions to the current set of KPIs and would improve the plans further.

The planning model:
Firstly several assumptions and simplifications have been applied, as discussed in chapter 6, in the development of the planning model. These assumptions and simplifications do not hinder answering the research questions and the formulation of the conclusions of this thesis. However, these assumptions and simplifications need to be considered in light of the development of an implementable version of the planning model in real-world operations.

Besides the assumptions and simplifications, this thesis is also a learning journey, especially in the modeling of the planning model as a MILP, programming the mathematical formulation and solving real-world data sets with the model. The presented model may be formulated, programmed and solved tighter, more efficient and faster than the author of this work has done at this time.

Furthermore the planning model is developed based on a set of requirements. These requirements are formulated with the aim of this thesis in mind. Two key elements of the planning model requirements, the fixed horizon and run time, need to be considered in light of the development of a real-world planning model. For the application of the planning model in this thesis using fixed horizon planning is acceptable, however in the real-world application of the planning model at Tata Steel IJmuiden a combination of rolling horizon with rescheduling possibilities is preferable. This allows the plans to be modified as more tasks come in and resolves the issues fixed horizon planning has with continuity at the start and end of the planning horizon. Run time, i.e. the time it takes to make the plans, should be stabilized and rescheduling as the horizon is rolling should be quick, otherwise the planning model will hinder instead of enhance planners and operations. Furthermore the quality of the plans, i.e. the level of optimality of the planning model solutions, should be consistent otherwise planners will not trust the generated plans.

Results:
The planning model results are compared to plans made by warehouse planners. However, these warehouse planners did not base their plans on the formulated KPIs of this thesis. Therefore it is important to note that the comparison of the model results with old plans is in terms of non-KPI-based plans and KPI-based plans. In this comparison an element of human versus computer-based plans can be found, but this is not the base of the comparison.

The planning model results consist of three data sets. This is considered enough to answer the research questions of this thesis and to cover the possibility of a lucky hit in the performance. However it is encouraged to explore the model results of more data sets in the future. Furthermore the data sets which have been used are those of relatively calm days. This is due to the COVID-19 pandemic and its effect on the current economic climate.

In the end the real performance improvement in on-site transportation plans using data-driven decision support will depend on the real-world implementation and use of planning models such as the one developed in this thesis.

8.3. Recommendations

As discussed in this and previous chapters, there are several leads for further research and development. This section covers the recommendations for further scientific research and recommendations for the commissioner, ORTEC, and use case Tata Steel IJmuiden.

8.3.1. Recommendations for further research

Application of the research structure and approach of this thesis to other on-site transportation systems is advised. Determining their KPIs and evaluating their performance compared to an optimization planning model leads to relevant insights in the competencies of such models in practice. Furthermore this enables the comparison of this thesis's results to other use cases and further fills the current gap in scientific knowledge on real-world cases.

Performing more analysis on the balance of KPIs and their trade-offs should be done. This includes studying and incorporating real cost values for resources. In doing so, a better understanding of which KPIs make good plans is developed and the consideration which resources to optimize for first in on-site logistics becomes more clear. This ultimately improves (on-site) logistics as a whole.

Many studies on other mathematical formulations of RC(M)PSP problems can be found. Which formulation and solution algorithm are best suitable for on-site transportation problems is a topic for further research. These results can be compared to the results of the MILP of this thesis. Faster solution times and more stable result generation is needed for implementation of complex planning models in operational environments.

8.3.2. Recommendations for ORTEC and Tata Steel IJmuiden

Tata Steel operations:

Firstly it is recommended to determine the actual cost factors for each KPI as used in the model. This enables more detailed and realistic assessment of the KPI trade-offs and evaluation of the overall potential cost reduction. Furthermore this provides the ability to better compare alternative model solutions based on their costs, provided that the plans are robust for surrounding processes.

Secondly analysis on the planning process itself and the on-site logistics should be done, evaluating for example if half-shift operations with both locomotives and workforce is possible and what the impact of this would be on operations. Furthermore analysis on the bottlenecks for both the planning process and on-site logistics system as a whole could be done. This uncovers possible problems currently experienced by Tata Steel employees which hinders them in achieving the best possible performance. Bottlenecks could include information transfer between organizational layers or departments, but also limitations to the currently used planning software.

Thirdly more analysis on the disturbances and uncertainty in the plans and on-site transportation is relevant to better understand what determines current plans and how these could impact plans made by a planning model. For example shift efficiency of different workforce groups could impact the execution of by the planning model drafted plans. Now it is assumed that each group has the same efficiency, but it could be that different site locations are better capable of handling several sequential tasks.

Fourthly to enable plans to be made further ahead, it is advised to ensure transportation task information is shared earlier and consistently to the planners. Currently drafting plans further ahead is partly constrained by information throughput. Better information flow, which is standardized and incorporated automatically in the planning system could for example include all the hall-transfer tasks for the next 24 hours. These can than be planned already and this yields a plan which is more complete further ahead in time and thus better able to handle more incoming tasks and disturbances. Furthermore this enables further optimization of the plans and better alternative plan generation.

Model development:
Further model development could include incorporation of an on-time delivery KPI, which allows violation of task deadlines at the cost of a penalty. This better models real-life planning where this could be done at a trade-off. This KPI could include a cost function which increases as the delay of the task increases.

Furthermore a different robustness KPI, which focuses on scheduling with a margin, or slack, to the deadline of a task could be examined. This also represents a risk averse element in the model, where having 1 to 2 hours extra, i.e. being 1 hour 'early' at the on-site destination for unloading is preferable. At the same time being too early could be harmful to the flexibility of the operations, thus the KPI cost function should be bounded and could include higher costs if too much slack is included. In the current planning model the wagon usage KPI enforces preferable behavior in terms of robustness, with a cost function that ensures enough wagons are available to handle last-minute transportation tasks.

An addition to the current planning model would be a KPI which stimulates sequential job scheduling at the same site-location, or penalizes planning jobs closely after another in the same site cluster but not at the same site-location. Now the planning model could plan two jobs successively, first at location A and then at location B. This forces the team responsible of completing these jobs to switch locations very quickly. It is thus preferred to plan jobs successively at the same location. Penalizing the switching could be done by incorporating a switching time for the workforce teams and adding an objective to minimize the overall switching time.

The literature review of Hartmann and Briskorn (2010) provides an extensive overview of possible extensions of the basis Resource Constrained Project Scheduling Problem. Several of these extensions could be applicable to the use case of this thesis, these include: resource switch time, resource setup time, rescheduling capability, due date inclusion in the objective function and the activity-on-node representation. This source could be a good starting point for further research which focuses on extending the, in this thesis, presented RCMPSP formulation.

Finally in terms of model development, the current model should be expanded with a spatial element that better models the rail operations and the site's spatial layout. In this expansion the rail process is included in more detail with elements such as locomotive speeds and distance between site locations. The goal of this expansion would be to both better align the model results with the successive rail operations and rail plan, but also better model the locomotive resource. Now the locomotive resource is simplified to a tractive force capacity. However, the real locomotive operations are more complex and their complexity constrains the plan execution. Van der Linden (2018) has already studied the rail operations at Tata Steel IJmuiden and has developed a model of this process. Extending the planning model with a separate rail simulation model could result in a model that better includes the rail complexity, but this could also hinder the insightfulness of the current model and possible implementation issues could arise. Simpler solutions to include more of the rail process complexity could be the inclusion of track segments as resources, mimicking the rail network, or adding locomotives as agents in the model. Recent studies which incorporate routing in the Resource Constrained Project Scheduling Problem include Lacomme et al. (2018) and Hu et al. (2019).

Model capabilities:
Considering the current model capabilities, it is advised to shift the model from fixed horizon to a rolling horizon time base with rescheduling functionality. Rolling horizon better suits the continuing operations at Tata Steel IJmuiden and solves some continuity problems which could arise in application of the current model in real-world operations. Additionally including rescheduling greatly increases the strength of the model in real-world application.

More fundamentally the planning model should be extended to handle all, or nearly all, types of transportation tasks currently part of the warehouse plan. This includes inbound transports. Furthermore the overall number of assumptions and simplifications of the model should be reduced.

In light of future implementation of the model, a faster and more stable solution generation should be achieved. Partly these improvement could be made by evaluating the current formulation and improving this base, but also heuristic solution methods should be considered. Literature proposes several solution methods for RCPSPs (and extensions), including a genetic algorithm (Goncalves et al., 2008), priority rule heuristics (Browning & Yassine, 2010) (Villafanez et al., 2019) and very recently Constraint Programming by Hauder et al. (2020).

Model evaluation:
More analysis on the model results can be done by running more and more busy data sets. More data sets results in more founded conclusions and busier data sets are interesting to study as these represent more normal operations.

Furthermore analysis comparing the drafted model plans and ultimately executed plans should be done, where the drafted plans are taken as starting points for daily operations. It is interesting to note what of the plans was changed during the day by the dispatchers. This may result in insights on possible model extensions and improvements.

Model implementation:
Finally, working towards the implementation of a decision support KPI-based planning model at Tata Steel IJmuiden should start with determining, in cooperation with the stakeholders of the process at Tata Steel IJmuiden, the requirements of the envisioned planning tool. It is important to very clearly know which tasks should be planned, what time horizon and time step size should be considered and what run time is acceptable. An extensive set of requirements should be formulated and this will determine the next steps. The planning model needs to be suitable to use in an operating environment and the planners need to be properly instructed on its use. The current planning process with human planners needs to be aligned with any semi-automatic decision support planning tool, ensuring the planners properly use the planning model, know its limitations and its strengths.

Bibliography

Akyuz, G. A., & Erkan, T. E. (2010). Supply chain performance measurement: A literature review. International Journal of Production Research, 48(17), https://doi.org/10.1080/00207540903089536, 5137–5155. https://doi.org/10.1080/00207540903089536

Ardjmand, E., Ghalehkhondabi, I., Weckman, G., & Young, W. (2016). Application of decision support systems in scheduling/planning of manufacturing/service systems: A critical review. International Journal of Management and Decision Making, 15, 248. https://doi.org/10.1504/IJMDM.2016.080703

Barros, L. (1997). A global view of industrial logistics. Gestão & Produção, 4, 150–158. https://doi.org/10.1590/S0104-530X1997000200004

Beyer, T., Göhner, P., Yousefifar, R., & Wehking, K. (2016). Agent-based dimensioning to support the planning of intra-logistics systems, In 2016 IEEE 21st international conference on emerging technologies and factory automation (ETFA). https://doi.org/10.1109/ETFA.2016.7733647

Blazewicz, J., Lenstra, J., & Kan, A. (1983). Scheduling subject to resource constraints: Classification and complexity. Discrete Applied Mathematics, 5(1), 11–24. https://doi.org/https://doi.org/10.1016/0166-218X(83)90012-4

Błażewicz, J., Ecker, K. H., Pesch, E., Schmidt, G., & Węglarz, J. (2007a). Definition, analysis and classification of scheduling problems. In Handbook on scheduling: From theory to applications (pp. 57–72). Berlin, Heidelberg, Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-32220-7_3

Błażewicz, J., Ecker, K. H., Pesch, E., Schmidt, G., & Węglarz, J. (2007b). Scheduling under resource constraints. In Handbook on scheduling: From theory to applications (pp. 425–475). Berlin, Heidelberg, Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-32220-7_12

Bouchard, M., D'Amours, S., Rönnqvist, M., Azouzi, R., & Gunn, E. (2017). Integrated optimization of strategic and tactical planning decisions in forestry. European Journal of Operational Research, 259(3), 1132–1143. https://doi.org/10.1016/j.ejor.2016.11.022

Browning, T. R., & Yassine, A. A. (2010). Resource-constrained multi-project scheduling: Priority rule performance revisited. International Journal of Production Economics, 126(2), 212–228. https://doi.org/https://doi.org/10.1016/j.ijpe.2010.03.009

Caris, A., Macharis, C., & Janssens, G. K. (2008). Planning problems in intermodal freight transport: Accomplishments and prospects. Transportation Planning and Technology, 31(3), 277–302. https://doi.org/10.1080/03081060802086397

Caris, A., Macharis, C., & Janssens, G. K. (2013). Decision support in intermodal transport: A new research agenda [Decision Support for Intermodal Transport]. Computers in Industry, 64(2), 105–112. https://doi.org/10.1016/j.compind.2012.12.001

Clausen, U., & Rotmann, M. (2014). Measurement and optimization of delivery performance in industrial railway systems (U. Clausen, M. ten Hompel, & J. F. Meier, Eds.). In U. Clausen, M. ten Hompel, & J. F. Meier (Eds.), Efficiency and innovation in logistics, Cham, Springer International Publishing. https://link.springer.com/chapter/10.1007%2F978-3-319-01378-7_8

Crainic, T. G., & Laporte, G. (1997). Planning models for freight transportation. European Journal Of Operational Research, 97(3), 409–438. https://doi.org/10.1016/S0377-2217(96)00298-6

Crainic, T. G., & Roy, J. (1988). OR tools for tactical freight transportation planning. European Journal of Operational Research, 33(3), 290–297. https://doi.org/10.1016/0377-2217(88)90172-5

Cummings, M. L., & Bruni, S. (2010). Human-automated planner collaboration in complex resource allocation decision support systems. Int. Dec. Tech., 4(2), 101–114. https://doi.org/10.3233/IDT-2010-0072

Daganzo, C. F. (2005). Logistics systems analysis (4th ed.). Springer-Verlag Berlin Heidelberg. https://doi.org/10.1007/3-540-27516-9

Díaz-Madroñero, M., Peidro, D., & Mula, J. (2015). A review of tactical optimization models for integrated production and transport routing planning decisions. Computers & Industrial Engineering, 88, 518–535. https://doi.org/10.1016/j.cie.2015.06.010

Duinkerken, M. B., & Schulte, F. (2019). Lecture slides ME44305, System Analysis and Simulation [Lecture slides session 2 (2018/19 Q3), retrieved from brightspace.tudelft.nl].

Duinkerken, M. B., Dekker, R., Kurstjens, S., Ottjes, J., & Dellaert, N. (2006). Comparing transportation systems for inter-terminal transport at the maasvlakte container terminals. OR Spektrum, 28(4), 469–493. https://doi.org/10.1007/s00291-006-0056-1

Estampe, D., Lamouri, S., Paris, J.-L., & Brahim-Djelloul, S. (2013). A framework for analysing supply chain performance evaluation models [Anticipation of risks impacts and industrial performance evaluation in distributed organizations life cycles]. International Journal of Production Economics, 142(2), 247–258. https://doi.org/10.1016/j.ijpe.2010.11.024

Farahani, R., Rezapour, S., & Kardar, L. (2011). Logistics operations and management: Concepts and models. Elsevier Science.

Fleischmann, B., Meyr, H., & Wagner, M. (2008). Advanced planning. In H. Stadtler & C. Kilger (Eds.), Supply chain management and advanced planning: Concepts, models, software, and case studies (pp. 81–106). Berlin, Heidelberg, Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-74512-9_5

Fugate, B. S., Mentzer, J. T., & Stank, T. P. (2010). Logistics performance: Efficiency, effectiveness, and differentiation. Journal of Business Logistics, 31(1), 43–62. https://doi.org/10.1002/j.2158-1592.2010.tb00127.x

Ghiani, G., Laporte, G., & Musmanno, R. (2004). Introduction to logistics systems planning and control. Wiley.

Gleissner, H., & Femerling, J. C. (2013a). Logistical infrastructure. In Logistics: Basics — exercises — case studies (pp. 37–52). Cham, Springer International Publishing. https://doi.org/10.1007/978-3-319-01769-3_4

Gleissner, H., & Femerling, J. C. (2013b). Logistics network planning. In Logistics: Basics — exercises — case studies (pp. 161–188). Cham, Springer International Publishing. https://doi.org/10.1007/978-3-319-01769-3_8

Gleissner, H., & Femerling, J. C. (2013c). Logistics systems. In Logistics: Basics — exercises — case studies (pp. 19–35). Cham, Springer International Publishing. https://doi.org/10.1007/978-3-319-01769-3_3

Gleissner, H., & Femerling, J. C. (2013d). The principles of logistics. In Logistics: Basics — exercises — case studies (pp. 3–18). Cham, Springer International Publishing. https://doi.org/10.1007/978-3-319-01769-3_2

Gleissner, H., & Femerling, J. C. (2013e). Transport systems and logistics services. In Logistics: Basics — exercises — case studies (pp. 53–94). Cham, Springer International Publishing. https://doi.org/10.1007/978-3-319-01769-3_5

Goncalves, J., Mendes, J., & Resende, M. (2008). A genetic algorithm for the resource constrained multi-project scheduling problem. European Journal of Operational Research, 189(3), 1171–1190. https://doi.org/https://doi.org/10.1016/j.ejor.2006.06.074

Grossmann, I. E., & Furman, K. C. (2009). Challenges in enterprise wide optimization for the process industries. In W. Chaovalitwongse, K. C. Furman, & P. M. Pardalos (Eds.), Optimization and logistics challenges in the enterprise (pp. 3–59). Boston, MA, Springer US. https://doi.org/10.1007/978-0-387-88617-6_1

Habibi, F., Barzinpour, F., & Sadjadi, S. (2018). Resource-constrained project scheduling problem: Review of past and recent developments. Journal of Project Management, 3, 55–88. https://doi.org/10.5267/j.jpm.2018.1.005

Hartmann, S., & Briskorn, D. (2010). A survey of variants and extensions of the resource-constrained project scheduling problem. European Journal of Operational Research, 207(1), 1–14. https://doi.org/https://doi.org/10.1016/j.ejor.2009.11.005

Hauder, V. A., Beham, A., Raggl, S., Parragh, S. N., & Affenzeller, M. (2020). Resource-constrained multi-project scheduling with activity and time flexibility. Computers & Industrial Engineering, 150, 106857. https://doi.org/https://doi.org/10.1016/j.cie.2020.106857

Herroelen, W., Demeulemeester, E., & De Reyck, B. (1999). A classification scheme for project scheduling. In J. Węglarz (Ed.), Project scheduling: Recent models, algorithms and applications (pp. 1–26). Boston, MA, Springer US. https://doi.org/10.1007/978-1-4615-5533-9_1

Hillier, F. S. (Ed.). (2002a). Classification of project scheduling problems. In Project scheduling: A research handbook (pp. 71–93). Boston, MA, Springer US. https://doi.org/10.1007/0-306-48142-1_3

Hillier, F. S. (Ed.). (2002b). The project scheduling process. In Project scheduling: A research handbook (pp. 13–70). Boston, MA, Springer US. https://doi.org/10.1007/0-306-48142-1_2

Hillier, F. S. (Ed.). (2002c). Resource-constrained scheduling: Advanced topics. In Project scheduling: A research handbook (pp. 343–417). Boston, MA, Springer US. https://doi.org/10.1007/0-306-48142-1_7

Hu, S., Zhang, Z., Wang, S., Kao, Y., & Ito, T. (2019). A project scheduling problem with spatial resource constraints and a corresponding guided local search algorithm. Journal of the Operational Research Society, 70(8), 1349–1361. https://doi.org/10.1080/01605682.2018.1489340

Ittner, C., & Larcker, D. (2003). Coming up short on non-financial performance measurement. Harvard business review, 81, 88–95, 139.

Krauth, E., Moonen, H., Popova, V., & Schut, M. (2005). Performance measurement and control in logistics service providing., In ICEIS 2005 - proceedings of the 7th international conference on enterprise information systems.

L.A. van Vledder, & J.J. Nieuwenhuis. (2020). Personal communication [For more information, see appendix H.].

Lacomme, P., Moukrim, A., Quilliot, A., & Vinot, M. (2018). Integration of routing into resource constrained project scheduling problem. EURO Journal on Computational Optimization, 7. https://doi.org/10.1007/s13675-018-0104-z

Le-Anh, T. (2005). Intelligent control of vehicle-based internal transport systems (Doctoral dissertation). Rotterdam School of Management (RSM), Erasmus University. Rotterdam. http://hdl.handle.net/1765/6554

Li, K., & Tian, H. (2015). Integrated optimization of finished product logistics in iron and steel industry using a multi-objective variable neighborhood search. ISIJ International, 55(9), 1932–1941. https://doi.org/10.2355/isijinternational.ISIJINT-2015-007

Mar-Ortiz, J., Gracia, M. D., & Castillo-García, N. (2018). Challenges in the design of decision support systems for port and maritime supply chains. In R. Valencia-García, M. A. Paredes-Valverde, M. d. P. Salas-Zárate, & G. Alor-Hernández (Eds.), Exploring intelligent decision support systems: Current state and new trends (pp. 49–71). Cham, Springer International Publishing. https://doi.org/10.1007/978-3-319-74002-7_3

McKay, K. N., & Wiers, V. C. (2003). Integrated decision support for planning, scheduling, and dispatching tasks in a focused factory. Computers in Industry, 50(1), 5–14. https://doi.org/10.1016/S0166-3615(02)00146-X

Mentzer, J. T., & Konrad, B. P. (1991). An efficiency/effectiveness approach to logistics performance analysis [Copyright - Copyright Council of Logistics Management 1991; Last updated: 2015-01-03]. Journal of Business Logistics, 12(1), 33–62. http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)2158-1592

Mostafa, N., & Eltawil, A. (2016). Vertical supply chain integrated decisions: A critical review of recent literature and a future research perspective.

Neely, A., Gregory, M., & Platts, K. (1995). Performance measurement system design: A literature review and research agenda. International Journal of Operations & Production Management, 15, 80–116. https://doi.org/10.1108/01443570510633639

ORTEC. (n.d.-a). ORTEC Supply Chain Master Classes - Managing and Optimizing the SC [Internal document - Unpublished, version 2011-03-02].

ORTEC. (n.d.-b). Planwise cursus voor Tata Steel [Internal document - Unpublished].

ORTEC. (n.d.-c). Planwise user manual [Internal document - Unpublished].

ORTEC. (2020). Over ons. Retrieved January 14, 2020, from https://ortec.com/nl-nl/over-ons

Paché, G., & Spalanzani, A. (2007). La gestion des chaines logistiques multi-acteurs: Perspectives stratégiques (tech. rep.).

Piotrowicz, W., & Cuthbertson, R. (2015). Performance measurement and metrics in supply chains: An exploratory study. International Journal of Productivity and Performance Management, 64, 1068–1091. https://doi.org/10.1108/IJPPM-04-2014-0064

Pritsker, A. A. B., Watters, L. J., & Wolfe, P. M. (1969). Multiproject scheduling with limited resources: A zero-one programming approach. Management Science, 16(1), 93–108. http://www.jstor.org/stable/2628369

Pro Rail. (2013). Hoogovens IJmuiden op het spoor. Retrieved January 14, 2020, from https://www.prorail.nl/nieuws/hoogovens-ijmuiden-op-het-spoor

Reddy, K. J. M., Rao, A. N., & Krishnanand, L. (2019). A review on supply chain performance measurement systems [Digital Manufacturing Transforming Industry Towards Sustainable Growth]. Procedia Manufacturing, 30, 40–47. https://doi.org/10.1016/j.promfg.2019.02.007

Robertson, S. (2001). Requirements trawling: Techniques for discovering requirements. International Journal of Human-Computer Studies, 55(4), 405–421. https://doi.org/10.1006/ijhc.2001.0481

Rose, K. H. (1995). A performance measurement model. Quality progress, 28(2), 63.

SCC. (2010). Supply Chain Operations Reference Model v10.0 [SSC: Supply Chain Council, SCOR v10 manual].

Schoenmaker, H. (2016). Generating stowage plans in the steel industry (Master's thesis) [Retrieved from Tata Steel IJmuiden]. Delft University of Technology. Mekelweg 5, Delft, the Netherlands. Retrieved from Tata Steel IJmuiden.

Schönemann, R. (2016). Scheduling rail freight node operations through a slot allocation approach (Doctoral dissertation). Technischen Universität Berlin. https://doi.org/10.14279/depositonce-5452

Shim, J., Warkentin, M., Courtney, J. F., Power, D. J., Sharda, R., & Carlsson, C. (2002). Past, present, and future of decision support technology [Decision Support System: Directions for the Next Decade]. Decision Support Systems, 33(2), 111–126. https://doi.org/10.1016/S0167-9236(01)00139-7

Surie, C., & Wagner, M. (2008). Supply chain analysis. In H. Stadtler & C. Kilger (Eds.), Supply chain management and advanced planning: Concepts, models, software, and case studies (pp. 37–63). Berlin, Heidelberg, Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-74512-9_3

Tata Steel. (n.d.-a). Handboek opleiding halplanner [Internal document - Unpublished].

Tata Steel. (n.d.-b). Opvolging planwise - planwise 2.0 [Internal document - Unpublished].

Tata Steel. (2020). Tata steel in IJmuiden. Retrieved January 14, 2020, from https://www.tatasteel.nl/nl/over/organisatie/

Van Eynde, R., & Vanhoucke, M. (2020). Resource-constrained multi-project scheduling: Benchmark datasets and decoupled scheduling. Journal of Scheduling. https://doi.org/10.1007/s10951-020-00651-w

van der Linden, C. W. P. (2018). Capacity optimization of an industrial site freight railway system (Master's thesis). Delft University of Technology. Mekelweg 5, Delft, the Netherlands.

Veeke, H. P. M., Ottjes, J. A., & Lodewijks, G. (2008). The delft systems approach: Analysis and design of industrial systems. Springer London.

Villafanez, F., Poza, D., Lopez-Paredes, A., Pajares, J., & del Olmo, R. (2019). A generic heuristic for multi-project scheduling problems with global and local resource constraints (RCMPSP). Soft Computing, 23(10), 3465–3479.

Vleugel, J. M. (2019). Lecture slides TIL5050-12, Interdisciplinary Design Project [Instruction lecture 13-09-19, retrieved from brightspace.tudelft.nl].

Weber, J. (1995). Logistik-controlling: Leistungen, prozesskosten, kennzahlen. Schäffer-Poeschel.

Yazdani, M., Zarate, P., Coulibaly, A., & Zavadskas, E. K. (2017). A group decision making support system in logistics and supply chain management. Expert systems with Applications, 88, 376–392.

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Scientific Paper

The scientific paper starts on the next page.

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Data-Driven On-Site Transportation Planning: A study of a large manufacturing site in the steel industry

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Abstract

Planning the on-site transportation of large manufacturing sites is a complex process. Currently these plans are made based on the on-site logistics constraints rather than on KPIs. Research has been focused on either analysis of system parameters or generally on KPIs, but lacks the combination of both on real-life cases. This gap is closed by taking both system analysis and KPI development into account to develop a working planning tool that can assist planners in a real-life situation. The goal of this study is to gain insights in the on-site transportation planning of large manufacturing plants and their performance measurement. This study answers the question: How can the on-site transportation planning at a large manufacturing plant be improved, by 1.) adding company KPIs and 2.) data-driven decision support based on the parameters of the locality and its constraints? Through the application of the DMADE methodology, this research question is answered. The SCOR performance measurement framework is used to determine the KPIs of the on-site transportation plans. A planning model, classified as a Resource-Constrained Multi-Project Scheduling problem, is formulated as a Mixed-Integer Linear Program. This planning model optimizes the on-site transportation plans for the KPIs, proves the correctness of the KPIs and shows the potential performance increase of on-site transportation plans if constructed by the planning model.

Keywords: On-Site Logistics, On-Site Transportation Planning, Performance Measurement, RCMPSP, Data-Driven Decision Support, DMADE, System Analysis, Optimization, MILP.

1 Introduction

Large manufacturing sites have internal departments responsible for transporting large volumes of goods around the facility. The scale of these facilities and the accompanying amount of transported volumes result in complex logistic processes. Efficient and effective planning of these transports has a big impact on the surrounding processes.

On-site logistics generally speaking does not put a large focus on cost minimization of its processes. This is caused by the fact that on-site logistics are viewed as a service provider for more costly processes such as manufacturing. On-site logistics has a risk averse nature, therefore oftentimes the planning of the on-site transportation is done based on constraints of the logistics environment and not with a focus on optimality through Key Performance Indicators (KPIs).

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Research Goal and Research Questions

Literature review shows there is high potential in the application of decision support in planning on real-life use cases. Incorporating performance measurement and system analysis in the application of decision support is expected to result in performance improvements and is highlighted as relevant for further research. Current research has been narrow-focused on either analysis of system parameters or generally on KPIs and lacks the application of decision support on real-life use cases.

The goal of this study is to gain insights in the on-site transportation planning of large manufacturing plants and their performance measurement. These insights are used to determine to what extent improvements can be made in the on-site transportation planning by adding data-driven decision support with planning based on KPIs.

The combination of the found research gap and goal of this paper leads to the following main research question:

"How can the on-site transportation planning at a large manufacturing plant be improved, by 1.) adding company KPIs and 2.) data-driven decision support based on the parameters of the locality and its constraints?"

Use Case

To assess on-site transportation planning, a use case has been found in the steel manufacturing facilities of Tata Steel IJmuiden. The analysis of this use case is discussed in section 3.

Method

This research is structured using the DMADE design framework and a combination of process analysis methods and tools from the System Analysis field. The tools from the System Analysis field are used to define the current (planning) process at the use case, as described in Veeke et al. (2008) and Duinkerken and Schulte (2019). The DMADE (Define, Measure, Analyze, Design and Evaluate) framework is an adaptation of the better known DMAIC lean six sigma method for finding improvements in processes. DMADE represents the five key steps from first assessing the processes to designing the right solutions and evaluating these with the original situation. Therefore firstly the use case is analyzed, secondly the KPIs of this use case are specified, thirdly the KPIs are incorporated in a design in form of a planning model and lastly this planning model with the KPIs is evaluated.

Structure

The remainder of this paper is organized as follows. Firstly section 2 covers the literature review. Secondly section 3 discusses the use case of this paper. Thirdly section 4 covers the performance measurement of on-site transportation planning and the use case in particular. With the system analysis and performance measurement complete, section 5 presents the formulated planning model. Section 6 discusses the results of the planning model. Finally in section 7 concluding remarks are made and in section 8 the discussion and opportunities for future research are presented.

2 Literature Review

The literature review of this paper discusses the current gap in scientific knowledge based on relevant studies.

At complex freight hubs sub-optimal planning is found. Observations and interviews with experts show that there is poor coordination in tactical infrastructure utilization planning and the process coordination quality depends on individual actors' optimization strategies. Actors mainly plan and optimize only their assigned part, resulting in local optimization rather than global optimization (Schönemann, 2016).

A study by Van der Linden (2018) notes that the planning of the transports and the railway operations at Tata Steel IJmuiden are separated and detailed knowledge of the planning processes and accompanying performance is not available.

There is little research done on finished product logistics optimization in the steel industry (Li and Tian, 2015). In the iron and steel industry, the various types of finished products are stored separately in different warehouses on-site. Li and Tian (2015) formulate a mixed-integer programming model, which is solved using a two-layer multi-objective variable neighborhood search (TLMOVNS) algorithm. Lacking in their study is the human planner aspect and consideration of Decision Support in the planning. Furthermore no details are given into the KPI determination nor are the chosen KPIs evaluated for appropriateness.

Several studies have been found making the case for application of decision support systems, or more integrated planning, to aid the human planners and improve planning performance: McKay and Wiers (2003), Beyer et al. (2016) and Schönemann (2016).

Crainic and Roy (1988) study the tactical planning process as an optimization problem which is modeled and solved using mathematical modeling and programming. Their study is proof of the ability to solve such planning problems using mathematical programming and optimization and their potential on operational performance.

Furthermore several authors advocate research into real-world planning systems and studying the potential of decision support in their planning, leading to more integrated plans and thus better performance, e.g.: Caris et al. (2008), Mostafa and Eltawil (2016), Bouchard et al. (2017) and Díaz-Madroñero et al. (2015).

Caris et al. (2008) note there is a limited number of scientific publications on intermodal planning problems on operational decision level and a need for more integration of planning problems on multiple decision levels. Also Caris et al. (2013) found a lack of understanding by the various actors involved in the levels of the DSS, which leads to sub-optimal usage and solutions. The integration of objectives of the various actors should be done better.

Finally Ghiani et al. (2004), in their analysis of shipment consolidation and dispatching problems, advocate the use of benchmarking for comparison of performance to the best-practice current standard, i.e. use of internal benchmarking. For this performance evaluation the SCOR (Supply Chain Operations Reference) model is advised for both its high- and low-level KPIs.

An overview of the gaps and opportunities from the found relevant studies is given in table 3 of Appendix A1.

3 Use Case Analysis

The industrial railway system of Tata Steel IJmuiden is used for transport of inbound raw materials, outbound (semi-)

finished products to customers by train or ship and on-site repositioning of the steel.

The on-site transportation plans are made by the On-Site Planning (OSP) department, part of the larger On-Site Logistics (OSL) department. OSP makes three different on-site transportation plans: the port plan, rail plan and warehouse plan. This research focuses on the warehouse plan, which is governed by the warehouse planners and the dispatchers of the On-Site Planning (OSP) department.

The warehouse planners determine which load is transported using which wagon-subtype, at what time and govern the storage filling levels of the warehouses. Customers require a specified delivery moment, resulting in a departure time for either outbound vessel, train or truck. Other transport tasks are the internal repositioning of goods between site locations (warehouses, production facilities). Repositioning occurs for two reasons: storage capacity filling and environmental conditioning of the steel. Internal repositioning tasks are requested by site locations to the OSP department.

While making the plans, the planners need to consider parameters such as the arrival and departure plans of the outbound vessels and trains, wagon types, transit times, loading capacity, loading speeds and locomotive availability. Currently plans are made 24 hours to 48 hours in advance and are fixed for the next 4 to 8 hours. Dispatchers can adjust the planning to respond to possible disturbances, such as the malfunctioning of equipment, weather or faulty loading of a train resulting in delays.

System Analysis

In this section, a black box model representation, figure 1, of the planning process of the use case is presented. The black box under consideration here results in the warehouse plan as output.

The process parameters, process constraints, disturbances and output elements of the black box model are discussed more extensively below. The requirements and KPIs are discussed later on in this paper.

Process parameters

The process parameters are categorized into 3 categories: Time, prioritization and the site-locations. Time consists of the loading and unloading time stamps, travel time between site locations and shunting time. The locations consist of the various outbound and on-site terminals linked to each modality. Road transport is done directly at warehouses. Quay warehouses are used in the port for short term storage, production warehouses are in the process of producing goods and also only facilitate short term storage. Storage locations also include for example outdoor shunting areas where loaded wagons are positioned as a storage facility.

Warehouse clusters:

The Tata Steel IJmuiden site is divided into geographically-based clusters. Warehouses and workforce responsible for loading and unloading wagons at warehouses are also grouped in these clusters.

Process constraints

The process constraints are categorized into eight categories: safety, resource availability, resource capacity, operating speeds, production, network constraints and resource constraints. Furthermore, warehouses also plan their operations, constraining the warehouse plan and steel production limitations might constrain the planned operations of the warehouse plan.

Disturbances

Disturbances hinder the on-site logistics and warehouse plan after the plan has been made. This ranges from changing weather conditions to ships being rejected for loading.

Output

The warehouse plan consists of the following five main elements: transport task schedule (start time, end time), workforce operations at site locations, wagon allocation, wagon loading configuration and task prioritization.

Each task in the warehouse plan has a pick-up time window, delivery time window and cargo characteristics (number of wagons, number of coils and weight of the coils), illustrated in equation (1).

$$\text{Transport task} = \begin{cases} \text{Origin,} & [t_{o,1}, t_{o,2}] \\ \text{Destination,} & [t_{d,1}, t_{d,2}] \\ \text{Cargo data,} & [\text{\# Wagons,} \\ & \text{\# Coils, Weight]} \\ \text{Timing data,} & [\text{Start time,} \\ & \text{loading duration,} \\ & \text{unloading duration,} \\ & \text{due date]} \end{cases} \tag{1}$$

Warehouse Plan Objective

The following objective has been formulated for the warehouse plan, as part of the on-site transportation planning at Tata Steel IJmuiden:

Planning steel transports from warehouses to the rail yard, ports and internally between warehouses, within existing constraints, in such a way that yields the highest performance in terms of KPIs.

Requirements of the warehouse plan

The requirements of the warehouse plan are split into

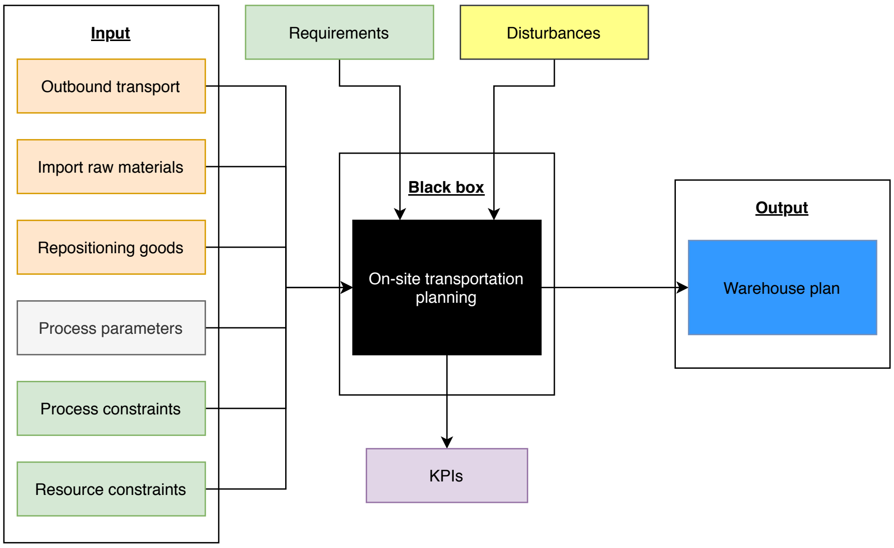


FIGURE 1: Black box representation of the on-site transportation planning of Tata Steel IJmuiden, resulting in the warehouse plan

functional and non-functional requirements:

Functional requirements:

1. The plan must adhere to all safety regulations.
2. The plan must comply with the predefined constraints.
3. The plan must specify which resources are assigned to each task, e.g. what wagon sub-type or which crane.
4. The plan must present every stakeholder with an overview of what is transported from origin to destination.

Non-functional requirements:

1. The plan must be in form of an activity schedule, i.e. assigning tasks to resources over time.
2. The plan must include the possibility of prioritization of tasks.
3. The plan must be adaptable for future changes to the system, providing long-term flexibility.
4. The plan must facilitate both rolling horizon and event-based planning.
5. The plan must be created based on a time frame with a 24 to 48 hours horizon, or 72 hours in case of weekends.

Current Performance Measurement

Currently it is not possible to clearly express the performance of the warehouse plan of Tata Steel IJmuiden. The OSL department operates in a service role, facilitating the transport and delivery of products to customers. Making sure the requested transports are done on-time and done safely is the main objective of the OSL department. The OSL department uses *Delivery on-time in full (DOTIF)* as core performance indicator. Furthermore Tata Steel IJmuiden operates based on a target throughput, or volume, in tonnes sold, and thus delivered, steel products. This target is yearly and translated to throughput targets on a monthly and weekly basis for the OSL department. Therefore the current key performance indicator of OSL is the achievement of the targeted throughput. There is no structure in place indicating and providing insight into the performance of the warehouse plan itself and for instance statistics on delayed vessel departures are unknown. Current performance measurement does not describe the efficiency and effectiveness of elements of the on-site transportation operations and warehouse plans, such as equipment usage and delayed operations.

4 KPI Specification

In this section the specification of the KPIs which determine the performance of on-site transportation plans and in particular those that determine the performance of the warehouse plan is done.

The SCOR (Supply Chain Operations Reference) model is used as a foundation for determining the use case KPIs. Usage of SCOR is based on the framework of Estampe et al. (2013) and SCOR is advocated by Surie and Wagner (2008), Akyuz and Erkan (2010) and ORTEC SCOR experts, due to its suitability in terms of various levels of consideration in light of performance measurement and its focus on the planning element of the supply chain.

Use Case KPIs

The main take-aways from the SCOR performance metrics are:

- A performance metric that measures the timing of the orders, making sure orders are planned as such that service levels and deadlines are met, is a useful metric for plans. This metric is then used to measure plans in terms of on-time delivery of orders.
- A performance metric similar to those of the Agility performance attribute is considered relevant. The Agility metrics measure the ability to handle increases in tasks to be planned. In terms of the warehouse plan, this is translated to the robustness of the warehouse plan. Robustness, in this case, describes the ability of a plan to handle possible disturbances or delays in operation and not have tasks miss their deadline as a result. There is a balance to be found in how much time ahead a task needs to be ready for unloading, whilst not being started too early as this results in less flexibility due to there being loaded wagons in the system. This robustness is also linked to the Agility performance metric as a metric dealing with the 'risk' in the plan.
- In measuring the performance of the plans the consideration of the amount of resources used should be included. This should be done in light of limiting the costs of the on-site logistics operations.
- The consideration of peak loads in the on-site logistics system, not directly found in SCOR, needs to be made. The warehouse plan heavily dictates the workload at warehouses and other site locations. It is favorable to spread the workloads if possible, limiting workload peaks. This is relevant both from robustness and a worker perspective.

Thus the warehouse plan needs KPIs that measure:

- How many tasks are scheduled on-time,
- How able the plan is to handle possible disturbances,
- How many resources are required to execute the plan, and
- How much workload is experienced in the on-site logistics system.

Illustrated in figure 2 the performance of the warehouse plan can be measured using four main KPIs. These four KPIs are ranked based on their importance.

KPI implementation

In the planning model the four KPIs are translated to three operational and measurable KPIs. On-time delivery is considered fixed, i.e. the planning model must adhere to the set deadlines of tasks. Costs are represented by a locomotive usage KPI and a workforce usage KPI and workload peaks and robustness are combined in a wagon usage KPI. The combination of the KPIs results in a weighted function that determines the performance of the on-site transportation plans, as shown in equation 2.

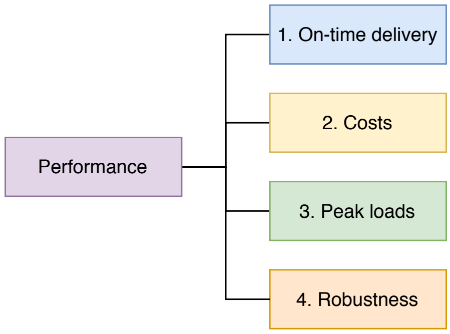


FIGURE 2: Key performance indicators, describing the performance of the warehouse plan.

$$\text{Performance} = \text{Weight}_1 \cdot \text{KPI}_1 + \text{Weight}_2 \cdot \text{KPI}_2 \ldots \quad (2)$$

Cost functions are used to express the metrics consistently and provide a basis for combining the metrics into one performance score. There are no direct costs available expressing the resource usage, therefore the cost function values are fictional.

Considering safety

Safety is noted in the objective of On-Site Logistics at Tata Steel IJmuiden, however not included as a KPI for the warehouse plan. Safety cannot be considered as a trade-off or KPI and therefore safety is included as a constraint.

5 Model Formulation

With the use case analysis and KPI specification steps complete, this section of the paper discusses the developed planning model. The planning model is developed as such that the old warehouse plans from Tata Steel IJmuiden planners can be compared to optimized plans generated by the planning model in terms of the KPIs.

Planning Model Requirements

The envisaged planning model comes with a set of requirements. These requirements specify what the model needs to do and build upon the requirements of the warehouse plan. The functional and non-functional requirements for the planning model are as follows:

Functional requirements:

1. The planning model must comply with the warehouse plan functional requirements.
2. The planning model must create plans based on quantitative KPIs.
3. The planning model must create plans based on data from original, real-world, data sets.
4. The planning model must be able to plan representative data sets in terms of size and complexity; planning outbound shipments, export trains and hall transfer tasks ('omrijzendingen').
5. The planning model must have a time scale resolution which is compliant with the level of detail at which currently warehouse plans are made.
6. The planning model must be able to generate warehouse plans from different days, i.e. handle different data sets.
7. The planning model must maintain the structure of transportation tasks as these currently are, i.e. consisting of four main steps (jobs): wagon-supply, loading, transit, unloading.

Non-functional requirements:

1. The planning model must plan a full day's data set in a fixed horizon planning manner.
2. The output of the planning model must be as such that it is importable into the current planning tool for expert validation.
3. Solving of the planning model must be finished within a reasonable time (0 - 1 hour) and at a reasonably high level of optimality (80+% optimal).

Scheduling Problem Classification

The scheduling problem as encountered in the use-case of Tata Steel IJmuiden's warehouse plan is identified as a type of Resource-Constrained Project Scheduling Problem (RCPSP). RCPSPs are scheduling problems where several activities, part of a project and subject to precedence constraints, need to be scheduled subject to resource constraints (Hillier, 2002) (Habibi et al., 2018) (Van Eynde and Vanhoucke, 2020).

In the case of the warehouse plan, multiple projects (transport tasks) which consume the same resources are considered, extending the standard RCPSP to a multi-project RCPSP: Resource-Constrained Multi-Project Scheduling Problem (RCMPSP) (Van Eynde and Vanhoucke, 2020).

Time base and Event representation

Based on the by Grossmann and Furman (2009) discussed time base and event representation advantages and disadvantages, a discrete-time base with global time intervals of 30 minutes as event representation is used for the planning model. Using time intervals leads to the problem becoming an allocation problem of start times of tasks to an interval or time stamp.

Scheduling Problem Elements

The scheduling problem consists of six main elements: tasks I with jobs J, resources R, time T, objective function Z and decision variables X.

Transportation tasks (I), referred to as *tasks*, consist of four **jobs** j: wagon-supply, loading, transit and unloading. These jobs each require a specific amount of resources (site location cranes, site location track space, wagons, workforce and locomotives) and have a specific process duration and job due date. Furthermore precedence constraints, meaning the jobs are subsequent and can only start after the predecessor is completed, characterize the scheduling problem.

Resources (R) consist of the cranes at site locations (i.e. origin and destination on transport tasks), track space at site locations, the workforce needed to load the wagons at site locations (grouped in the clusters along with the site locations), the various possible wagon types and their availability and the available tractive force of the locomotives used for moving the wagons on-site. The resources are classified as renewable, i.e. after a wagon set or locomotive has been used in a job, it will become available again for use in another job. Wagons will be in use for the entirety of a task, i.e. all jobs, whereas locomotives are only in use during the wagon-supply and transit job. The cranes and the workforce are used during the respective loading and unloading jobs of a task.

Time (T) is modeled discretely as a vector with the length of the planning horizon and segmented into 30 minute sized time steps. The planning horizon runs from 00:00h till 06:00h the following day. This results in a time vector which contains $(30 * 2 =)$ 60 entries. Thus $T = \{0, 1, ..., 59\}$.

Objective function (Z) of the model is a combination of the formulated KPIs.

Finally the **decision variables** X of the problem are the starting times of all the jobs of all the tasks, x_{ijt}. All variables and parameters are non-negative and integers.

MILP Formulation

The warehouse plan is modeled in form of a Mixed Integer Linear Problem (MILP). The MILP formulation is based on the foundations of the in Pritsker et al. (1969) presented MILP formulation for multi-project scheduling problems with resource limitations. In table 4 of Appendix A2 an overview of the elements of the MILP is given. In this paper only the most notable additions of this study to the MILP formulation of the base RCMPSP formulation are discussed: the auxiliary variables, objective function, resource constraint and dummy tracker formulation.

Auxiliary variables
Several auxiliary variables are introduced to model the warehouse plan: dummy trackers y and objective function auxiliary variables. The objective function auxiliary variables are used to compute the KPI metrics of the warehouse plan, based on the decision variable x of each job.

The dummy trackers are binary. These trackers represent the time between the regular jobs, similar to a waiting time. The dummy trackers make sure the model takes the wagon and site-location track space usage between regular jobs into account. Dummy trackers have value 1 at each time instance where that dummy activity is ongoing and 0 if not, as described in equation 3. Similar formulation is used for the other two dummy tracker variables (y_1 and y_2).

$$y_{0_{it}} = \begin{cases} 1, & \text{if at } t \ y_0 \text{ is between job } j = 0 \text{ and } j = 1 \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

$$\forall i \in I, \forall t \in T$$

Objective function
The objective function of the planning model consists of multiple KPIs which are optimized at the same time, resulting in a multi-objective problem. The objective function is the weighted sum of multiple objectives, as presented in equation 4. The objective function is threefold: the KPI metric for the locomotive usage per shift objective (equation 5), the workforce usage per half-shift objective (equation 7) and the wagon[1] objective (equation 9). Each of these metrics makes use of piece-wise linear functions to approximate exponential cost functions. The used values in the cost functions for all KPIs are fictional. The cost functions for each KPI are setup[2] as presented in table 1. In figure 3 the cost functions are illustrated graphically. The threshold value is the starting value of the cost function, i.e. from this value onward costs are computed.

Resource usage above the threshold yields in exponentially growing KPI cost values, following the shape of the KPI cost function. If the model achieves little to no resulting costs in the its plans, the plans are considered as high quality in terms of KPI performance. For the base model setting the threshold values are chosen as such that the weight of each KPI is set equal to one. With the defined cost functions, having lower boundaries where no costs are made which balance the KPIs, there is no need to assign specific weights to any of the KPIs yet, thus the KPI weights in the base model are all set equal to one.

Note that the objective function values are calculated for all workforce groups (each site cluster) and wagon types separately. Below these computations are generalized in their formulation.

$$\text{MIN } Z_{tot} \quad (4)$$

$$Z_{tot} = W_1 \cdot Z_{loc} + W_2 \cdot Z_{workforce} + W_3 \cdot Z_{wagons}$$

$$Z_{loc} = \sum_{s \in S} C_s(U_{loc_s}) \quad (5)$$

$$\text{with} \quad U_{loc_s} = \max_{t \in s}(U_{loc_t}) \quad (6)$$

$$Z_{workforce} = \sum_{hs \in HS} C_{hs}(U_{workforce_{hs}}) \quad (7)$$

$$\text{with} \quad U_{workforce_{hs}} = \max_{t \in hs}(U_{workforce_t}) \quad (8)$$

$$Z_{wagons} = \sum_{t \in T} C(U_{frac-wagon_t}) \quad (9)$$

$$\text{with} \quad U_{frac-wagon_t} = \frac{U_{wagon_t}}{R_t} \quad (10)$$

Resource constraint
Constraint 11 defines the resource usage. This prescribes that the sum of all resources of type k required at time t for all activities scheduled at that time subject to x_{iju} must be less than or equal to the total available resources of that type at that time. The u period defines the period that a job is being processed.

$$\sum_{i \in I} \sum_{j \in J} \sum_{u=\max(0,t+1-p_{ij})}^{t} r_{ijk} \cdot x_{iju} + \sum_{i \in I} r_{0ik} \cdot y_{0_{it}} + \sum_{i \in I} r_{1ik} \cdot y_{1_{it}} + \sum_{i \in I} r_{2ik} \cdot y_{2_{it}} \leq R_{kt} \quad (11)$$

$$\forall k \in K, \ \forall t \in T$$

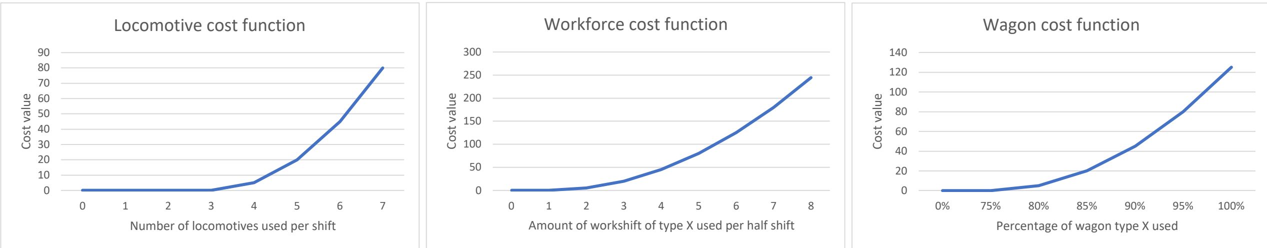
Dummy tracker constraints
For the dummy trackers y_0, y_1 and y_2 three sets of constraints are added. Firstly the lower bound of the interval of t, based on the start time and processing time of the prior job of each task, for which the values of the dummy trackers are allowed

[1] Out of the used wagon types at Tata Steel, 4 types with corresponding coding in the planning system are considered in this study: PLWG, VWWG, GHUIF and SETJE.

[2] Cost function shape is piece-wise linear within step size in case of the wagon usage, and the cost functions continue after the capacity of five locomotives as in the original plans these limiting values may have been violated.

TABLE 1: Overview of the cost function specification for each KPI

KPI	Cost function shape	Unit	Threshold	Time Scale	KPI value
Locomotive usage	Quadratic	Per locomotive	3	Per shift	Summation over all shifts
Workforce usage	Quadratic	Per workforce group, per cluster	1	Per half-shift	Summation over all half-shifts, per cluster
Wagon usage	Quadratic	Per 5% wagon capacity, per wagon type	75%	Per time step	Summation over all time steps, per wagon type



(A) Locomotive cost function (B) Workforce cost function (C) Wagon cost function

FIGURE 3: Cost functions for each of the KPIs

to be 1 needs to be defined. Secondly the upper bound of the interval needs to be defined and finally the exact amount of times y_0, y_1 and y_2 have to be the value 1 needs to be constrained. This makes sure that the entire gap between regular jobs is filled with value 1 for the tracker variables. Constraint 12 prescribes the lower bound, constraint 13 the upper bound and constraint 14 the summation of the y_0 tracker. The same computations are done for the other two tracker variables.

$$\sum_{t\in T} t\cdot x_{i0t} + p_{i0} \leq t\cdot y_{0it} + M\cdot(1-y_{0it}) \quad \forall i\in I,\ \forall t\in T \qquad (12)$$

$$t\cdot y_{0it} + 1 \leq \sum_{t\in T} t\cdot x_{i1t} \quad \forall i\in I,\ \forall t\in T \qquad (13)$$

$$\sum_{t\in T} t\cdot x_{i0t} + p_{i0} + \sum_{t\in T} y_{0it} - \sum_{t\in T} t\cdot x_{i1t} = 0 \quad \forall i\in I \qquad (14)$$

Modeling Tool

The planning model is solved using the Gurobi mathematical optimization solver, version 9.0.2, build v9.0.2.rc0 (win64), on an Intel Core i7-8650U processor.

6 Results and Evaluation

This section of this paper discusses and evaluates the results of the planning model. The planning model generates warehouse plans of Tata Steel IJmuiden and present quantitative results based on the determined KPIs and performance metrics of on-site transportation plans.

Data Sets

The used data sets are exported from the current planning tool. Three planned days have been chosen: August 21st 2020, August 23rd 2020 and August 25th 2020. The August 21st set is the smallest of the three, and 23rd and 25th are similar in size, as seen in table 2. Most tasks are the Hall-transfer tasks, which only slightly outnumber the shipment tasks. The train tasks consist of the fewest tasks per category.

In practice warehouse plans are continuously updated and do not start or end at a specific time. As the planning model has a finite planning horizon, small discontinuities occur, e.g. there are tasks falling partly out of the planning horizon. These are manually set to the start and end time steps of the planning horizon.

Note that these data sets are smaller in terms of size compared to 'normal' operations as these are taken during the COVID-19 pandemic.

Results Per KPI

For each of the data sets the original, manual, plans are compared quantitatively based on their KPI score and performance to the results of the planning model. In this section the results per KPI are discussed.

KPI 1: Locomotive usage

Figure 4 shows the clearly different results for the orig-

TABLE 2: Overview of the number of tasks, per type and totals, for each data set.

	21-8-2020	23-8-2020	25-8-2020
Shipment tasks	26	31	30
Train tasks	11	20	20
Hall-transfers	33	38	36
Total number of tasks	70	89	86
Total number of jobs	280	356	344

inal plan and new plan of August 23rd. The planning model succeeds in spreading the locomotive usage and optimizing the usage within shifts. Returning in all data sets is the large peak of locomotive usage at the start of the time horizon, in the 01:00 - 01:30h time step, in the original plans. This peak usage is due to manually adjusting the tasks which fall partly out of the planning horizon. The noted peak is thus not realistic, but the load on the resource does needs to be handled by the planning model.

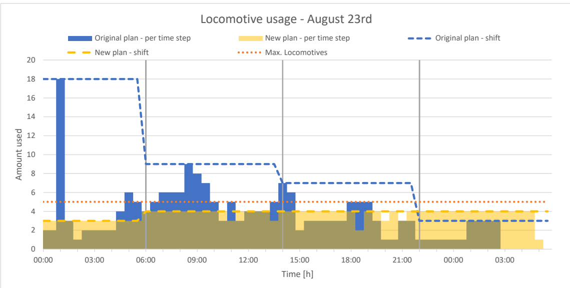


FIGURE 4: Locomotive usage - August 23rd

KPI 2: Workforce usage

As seen with the locomotive usage, the planning model also succeeds in achieving low and spread out workforce usage over time and per half shift. The less busy clusters of site-locations result in similar usage of workforce for both the original and new plans, but with the busy clusters the new plans very much show less and more spread workforce usage, e.g. at the *Cluster Midden*, illustrated in figure 5.

KPI 3: Wagon usage

In terms of the wagon usage KPI, there are both similarities and differences in the results comparing the original and new plans of August 23rd. The PLWG and VWWG wagons usage have very similar results for both the original and new plans. Main differences are noted in the GHUIF usage graph, where the planning model keeps these wagons in use for much longer and in doing so better balances the other resource loads, shown in figure 6a. Furthermore the SETJE wagon type yields for both the original and the new plans KPI costs, shown in figure 6b.

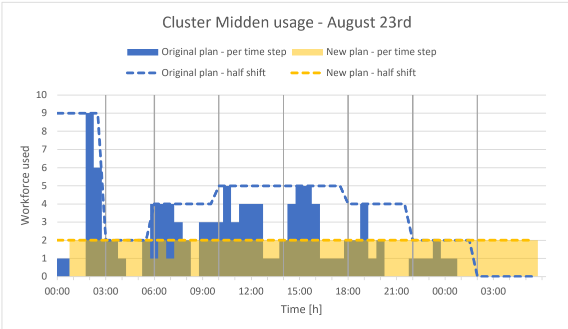
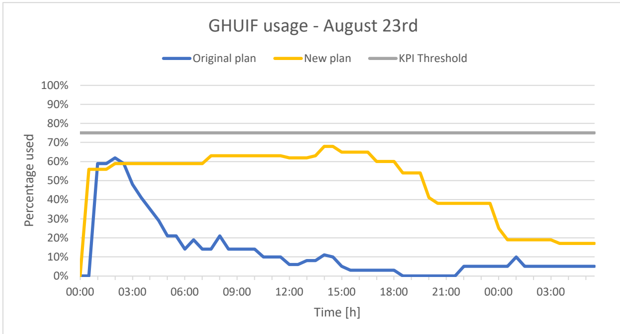
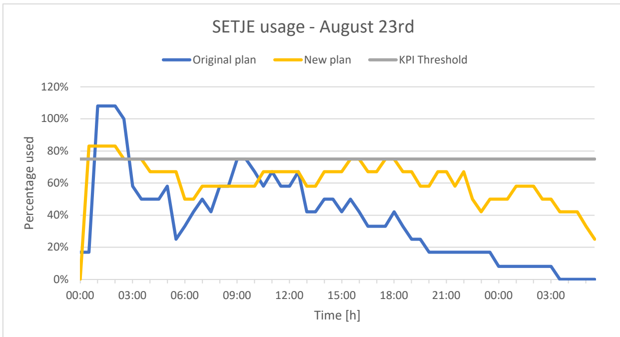


FIGURE 5: Workforce Cluster Midden usage - August 23rd



(A) GHUIF usage - August 23rd



(B) SETJE usage - August 23rd

FIGURE 6: Wagon usage per type - August 23rd

Results Full Plans

Per data set the difference in resource type usage is shown graphically in figure 7. The original, manual, plans are compared to the base model results based on the total amount of resources used per plan. For each plan, the number of locomotives per shift are added up, the total workforce per half-shift for all clusters are added up and finally the average percentage wagon capacity used per wagon type is computed. In these computations, the first shift (00:00h - 06:00h) is excluded. The comparison of original and new plans is thus based on the regular three planning shifts: 06:00h - 14:00h, 14:00h - 22:00h and 22:00h - 06:00h.

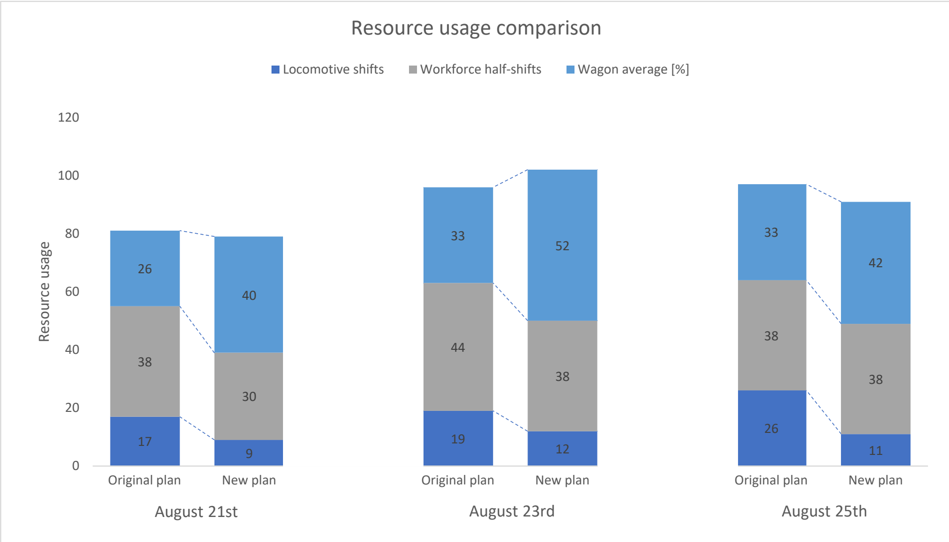


FIGURE 7: Graphical representation of the resource usage results per data set, comparing original plans to optimized plans by the planning model

The combined locomotive and workforce totals of the new plans are much reduced. In terms of the wagon average the new plans have a higher average, however this is not a problem as the wagon usage percentage per type generally remains well below their KPI threshold of 75% for each plan. Table 5 of Appendix A3 shows the overview of the full plan results with, additionally, the calculated difference per original and new plan. The results show that the planning model is able to reduce combined locomotive and workforce usage up to 25% on average.

Evaluation of the Planning Model

The planning model complies with all the functional requirements as formulated. In terms of the non-functional requirements the model does not fully comply with the last requirement on the model run time and solution stability. The planning model run times vary over the different model run settings and data set sizes. This ranges from within reasonable time (less than one hour) to much longer (several hours), and optimality[3] of results is not guaranteed.

However, application of the planning model will result in reduced and more efficient resource usage. There will be fewer peak loads and the planning model will be able to create schedules considering three or more KPIs, which govern resource usage over many resources, at the same time. At the least, the planning model enables planners to start from a feasible plan early on with quantitative insights on the performance of the plan. This reduces planner workload and has the potential to decrease overall time planners need to spend on the warehouse plans. This potential echoes through to surrounding planning and operations as the warehouse model better considers these. Further development of the planning model potentially allows to plan further ahead, including maintenance planning and tactical decision on the on-site logistics resources. The data-driven decision support model allows moving from constraint-based planning to KPI-based planning.

[3] 80+% near-optimal solutions

7 Conclusions

With the gained insights into the on-site transportation planning of large manufacturing plans and their performance measurements insights, this research has determined to what extent on-site transportation planning can improve by applying data-driven decision support. Ultimately the following main research question is answered: *How can the on-site transportation planning at a large manufacturing plant be improved, by 1.) adding company KPIs and 2.) data-driven decision support based on the parameters of the locality and its constraints?*

The application of increased decision support has a high potential in improving on-site transportation planning. The resulting plans made by the planning model out-performed the original plans made by the planners in terms of the KPIs. The planning model, through application of the quantitative KPI objectives, is able to reduce combined locomotive and workforce usage per shift and half-shift, respectively, by up to 25%, while maintaining robustness by keeping wagon usage below 75% of capacity.

Usage of the planning model in real-life is expected to lead to a significant reduction in resource usage peaks and higher resource usage efficiency. The planning model can make better warehouse plans as it can simultaneously consider three KPIs. The formulated plans can be used as a starting point by the planners, as they are both feasible in practice and perform better in respect of the quantitative KPI insights. This reduces the workload and overall time needed to formulate the plans. The potential benefits of the planning model may also affect surrounding logistics operations and plans positively as the planning model is able to consider their constraints simultaneously. Further development of the planning model enriches its potential, from planning further ahead to tactical on-site logistics resource decision making. On-site transportation planning can move from constraint-based planning towards KPI-based planning through the application of a data-driven decision support planning model.

In literature a large potential for applying decision support in real-life planning cases was found. Performance gains by combining human and automated decision making integrally were expected. The found literature gap has been filled by this paper as it firstly fundamentally analyzes the on-site logistics and planning process, continues with detailed performance measurement formulation for both general on-site transportation planning and the real-world use case, then a planning model is developed which can plan real-world data sets and finally achieves quantitative and qualitative results and insights into the application of decision support for on-site transportation planning.

The on-site transportation planning of large manufacturing sites will be enhanced by added decision support based on KPIs. The manufacturing sites will be able to move from a slower manual planning process to a (partly) automated fast planning process, reduce planner workload and execute more optimal plans resulting in more effective and efficient logistics operations. The quality of plans will become less dependent on the planner and their experience and the plans will become more standardized. Most of all, through the application of KPI-driven decision support plans will move from being adapted to fit constraints and disturbances to being determined based on quantitative insights in its KPIs.

8 Discussion and Further Research

There are several considerations to be made in light of the results and conclusions of this paper.

Firstly the conclusions of this paper are based on the results of the planning model which generates on-site transportation plans based on the use case of Tata Steel IJmuiden's warehouse plan. On-site logistics and transportation will have similar characteristics for different real-world cases, but ultimately different key elements will define the plans.

Secondly the SCOR framework has been used in this study as the main foundation for the KPI determination. SCOR is a proper framework to use, but other performance measurement systems could also have resulted in suitable KPIs.

Thirdly the specified KPIs for the warehouse plan of Tata Steel IJmuiden have shown to result in well-performing plans and their use has been proven. However there may be other formulations or specifications of the KPIs which will yield similar results.

Fourthly the planning model results are compared to plans made by warehouse planners. However, these warehouse planners did not base their plans on the formulated KPIs of this study. Thus non-KPI-based plans are compared to KPI-based plans.

Finally the results of the planning model should be interpreted knowing there is a wide set of assumptions and simplifications in the modeling. Ultimately the real performance improvement in on-site transportation plans using data-driven decision support will depend on the real-world implementation and use of planning models as developed in this paper.

Recommendations for further research

It is encouraged to apply this research structure and approach to other on-site transportation systems. This enables the comparison of this paper's results to other use cases and further fills the current gap in scientific knowledge on real-world cases.

Additionally more analysis on the balance of KPIs and their trade-offs should be done, also by studying and incorporating real cost values for resources. In doing so better understanding of which KPIs make good plans, considerations which resources to optimize for first, and ultimately improves (on-site) logistics as a whole.

Other mathematical formulations of the warehouse planning problem and other (heuristic) solution methods should be examined. Faster solution times and more stable result generation is needed for implementation of complex planning models in operational environments.

Finally the current planning process with the planners themselves should be studied more in-depth. It is important to study if there are other issues that impact the quality of warehouse plans. This gives insights into the current beliefs of planners in what a good on-site transportation plan is and will uncover what the current bottlenecks are in improving the plans.

References

Akyuz, G. A. and Erkan, T. E. (2010). Supply chain performance measurement: a literature review. *International Journal of Production Research*, 48(17):5137–5155.

Beyer, T., Göhner, P., Yousefifar, R., and Wehking, K. (2016). Agent-based dimensioning to support the planning of intra-logistics systems. In *2016 IEEE 21st Interna-*

tional Conference on Emerging Technologies and Factory Automation (ETFA), pages 1–4.

Bouchard, M., D'Amours, S., Rönnqvist, M., Azouzi, R., and Gunn, E. (2017). Integrated optimization of strategic and tactical planning decisions in forestry. *European Journal of Operational Research*, 259(3):1132 – 1143.

Caris, A., Macharis, C., and Janssens, G. K. (2008). Planning problems in intermodal freight transport: Accomplishments and prospects. *Transportation Planning and Technology*, 31(3):277–302.

Caris, A., Macharis, C., and Janssens, G. K. (2013). Decision support in intermodal transport: A new research agenda. *Computers in Industry*, 64(2):105 – 112. Decision Support for Intermodal Transport.

Crainic, T. G. and Roy, J. (1988). Or tools for tactical freight transportation planning. *European Journal of Operational Research*, 33(3):290 – 297.

Duinkerken, M. B. and Schulte, F. (2019). Lecture slides ME44305, System Analysis and Simulation. Lecture slides session 2 (2018/19 Q3), retrieved from brightspace.tudelft.nl.

Díaz-Madroñero, M., Peidro, D., and Mula, J. (2015). A review of tactical optimization models for integrated production and transport routing planning decisions. *Computers & Industrial Engineering*, 88:518 – 535.

Estampe, D., Lamouri, S., Paris, J.-L., and Brahim-Djelloul, S. (2013). A framework for analysing supply chain performance evaluation models. *International Journal of Production Economics*, 142(2):247 – 258. Anticipation of risks impacts and industrial performance evaluation in distributed organizations life cycles.

Fleischmann, B., Meyr, H., and Wagner, M. (2008). *Advanced Planning*, pages 81–106. Springer Berlin Heidelberg, Berlin, Heidelberg.

Ghiani, G., Laporte, G., and Musmanno, R. (2004). *Introduction to Logistics Systems Planning and Control*. Wiley-Interscience Series in Systems and Optimization. Wiley.

Grossmann, I. E. and Furman, K. C. (2009). *Challenges in Enterprise Wide Optimization for the Process Industries*, pages 3–59. Springer US, Boston, MA.

Habibi, F., Barzinpour, F., and Sadjadi, S. (2018). Resource-constrained project scheduling problem: review of past and recent developments. *Journal of Project Management*, 3:55–88.

Hillier, F. S., editor (2002). *Resource-Constrained Scheduling: Advanced Topics*, pages 343–417. Springer US, Boston, MA.

Li, K. and Tian, H. (2015). Integrated optimization of finished product logistics in iron and steel industry using a multi-objective variable neighborhood search. *ISIJ International*, 55(9):1932–1941.

McKay, K. N. and Wiers, V. C. (2003). Integrated decision support for planning, scheduling, and dispatching tasks in a focused factory. *Computers in Industry*, 50(1):5 – 14.

Mostafa, N. and Eltawil, A. (2016). *Vertical Supply Chain Integrated Decisions: A Critical Review of Recent Literature and a Future Research Perspective*, page In press.

Pritsker, A. A. B., Watters, L. J., and Wolfe, P. M. (1969). Multiproject scheduling with limited resources: A zero-one programming approach. *Management Science*, 16(1):93–108.

Schönemann, R. (2016). *Scheduling rail freight node operations through a slot allocation approach*. PhD thesis, Technischen Universität Berlin.

Surie, C. and Wagner, M. (2008). *Supply Chain Analysis*, pages 37–63. Springer Berlin Heidelberg, Berlin, Heidelberg.

Van der Linden, C. W. P. (2018). Capacity optimization of an industrial site freight railway system. Master's thesis, Delft University of Technology, Mekelweg 5, Delft, the Netherlands.

Van Eynde, R. and Vanhoucke, M. (2020). Resource-constrained multi-project scheduling: benchmark datasets and decoupled scheduling. *Journal of Scheduling*.

Veeke, H. P. M., Ottjes, J. A., and Lodewijks, G. (2008). *The Delft Systems Approach: Analysis and Design of Industrial Systems*. Springer London.

Appendix

A1: Literature table

TABLE 3: Relevant literature overview, number of checkmarks per source indicate the focus areas of this study in terms of the presented research opportunities

Source	Focus	Lacking	Opportunities	This study
Schönemann (2016)	Performance complex freight hubs	Coordination among actors & processes.	Collaborative yard planning approach	✓
Van der Linden (2018)	Capacity of the IRS of Tata Steel IJmuiden	Detailed knowledge of the planning processes and accompanying performance	Performance improvement of the planning process by mapping the planning process	✓✓✓
Crainic and Roy (1988)	Tactical planning process as an optimization problem	-	Potential improvements of added automation compared to strictly manual planning	✓✓✓
Li and Tian (2015)	The potential of integrated optimization	Human planner aspects and consideration of Decision Support elements. KPI determination and evaluation.	Extend the scope of what they did with the considerations of DSS, human planner and focus on performance measurement	✓
Caris et al. (2008), Caris et al. (2013)	Research agenda on decision support in intermodal transport	Understanding of the actors on multiple levels of DSS, leading to sub-optimal usage and solutions	Integrating objectives of the various actors better	✓
Bouchard et al. (2017)	Combination of strategic and tactical level planning decision making	Human planner aspects and consideration of Decision Support, KPI determining and evaluation	Application of integrated planning with higher planning performance	✓✓
Díaz-Madroñero et al. (2015)	Tactical transportation planning	Focus on application of these models to realistic use cases	Application of these models to realistic use cases	✓✓✓
Mostafa and Eltawil (2016)	Literature review on PIDRP problems	Research limited to less complex situations, considering e.g. only a single plant or homogeneous fleets. Limited use real life studies	Application on real life use case	✓✓✓
McKay and Wiers (2003), Fleischmann et al. (2008)	Integrated planning approach	-	Optimizing by finding and defining the alternatives, objectives and constraints of the planning problems and using either exact or heuristic optimizing planning methods	✓✓
Ghiani et al. (2004)	Shipment Consolidation and Dispatching problems	-	Evaluate specified alternatives, generate optimal configuration or policy with respect to a given performance measure and use benchmarking for performance comparison.	✓✓

A2: Overview of MILP elements

TABLE 4: Overview of MILP elements of the Resource-Constrained Multi-Project Scheduling Problem

Indices & sets	**Description**
T: $t = \{1, \ldots, T_{end}\}$	Time horizon, with index t, divided into discrete time segments
I: $i = \{1, \ldots, I_{end}\}$	Tasks, with index i, i.e. transport tasks
J: $j = \{0, \ldots, 3\}$	Jobs, with index j, part of each task i
Y: $y = \{0, 1, 2\}$	Dummy jobs: y_0, y_1 and y_2
K: $k = \{1, \ldots, k_{end}\}$	Resource types
S: $s = \{1, \ldots, s_{end}\}$	Shifts: 00:00 - 06:00h, 06:00 - 14:00h, 14:00 - 22:00h, 22:00 - 06:00h
HS: $hs = \{1, \ldots, hs_{end}\}$	Half-shifts: regular shifts split in half
Parameters	
r_{ijk}	Resource requirement of resource type k of job j of task i
d_{ij}	Due date of job j of task i
p_{ij}	Processing duration of job j of task i
l_{ij}	Release date of job j of task i
R_{kt}	Resource availability of resource k at time t
Time step size	Size of each time step
Cost function values	Resulting cost for each KPI as a function of the resource usage
Decision Variables	
x_{ijt}	Starting time of job j of task i at time t
Auxiliary Variables	
y_{0it}	Tracker dummy job 0: time between wagon-supply and loading
y_{1it}	Tracker dummy job 1: time between loading and transit
y_{2it}	Tracker dummy job 2: time between transit and unloading
$U_{loc\,t}$ & $U_{loc\,s}$	Locomotive auxiliary variables
$U_{workforce_t}$ & $U_{workforce_{hs}}$	Workforce auxiliary variables
U_{wagon_t} & $U_{frac-wagon_t}$	Wagon auxiliary variables
Objective Function	
Locomotive usage	Equation: 5
Workforce usage	Equation: 7
Wagon usage	Equation: 9
Constraints	
Tasks are scheduled precisely once	
Resource usage	Equation: 11
Precedence constraints	
Earliest start time	
Latest start time	
Dummy tracker lower bound	Equation: 12
Dummy tracker upper bound	Equation: 13
Dummy tracker sum	Equation: 14

A3: Quantitative Results

TABLE 5: Resource usage results & percentage change per data set, comparing original plans to optimized plans

	August 21st			August 23rd			August 25th		
	Man. plan	New plan	Delta	Man. plan	New plan	Delta	Man. plan	New plan	Delta
Locomotive shifts	17	9	-47%	19	12	-37%	26	11	-58%
Workforce half-shifts	38	30	-21%	44	38	-14%	38	38	0%
Wagon average [%]	26	40	+54%	33	52	+58%	38	42	+11%
Total	81	79	-2%	96	102	+6%	102	91	-11%
Total without wagons	55	39	-29%	63	50	-21%	64	49	-23%

B

Requirement Techniques

Robertson (2001) discusses techniques and methods for determining requirements. Requirements are categorized into conscious, unconscious and undreamed requirements. Conscious requirements are those that the stakeholder is very aware of being a requirement. Unconscious requirements are requirements that a stakeholder would not mention upfront as they are not aware of the requirement and undreamed requirements are those the stakeholder does not see as a possibility.

Robertson (2001) presents a number of trawling techniques to uncover conscious, unconscious and undreamed requirements:

- Abstraction
- Apprenticing
- Business events
- Brainstorming
- Family therapy
- Interviewing
- Mind mapping
- Neurolinguistic programming
- Reusing requirements
- Simulation models (scenarios, prototypes)
- Soft systems
- Systems archaeology
- Use case workshops
- Video
- Viewpoints

Furthermore, requirements are split into functional and non-functional requirements, relating to the things a system has to do and what qualities a system has to have. It is emphasized that besides determining system requirements, goals and constraints need to be determined too. Goals can be seen as a high-level objective to which all other requirements contribute, whereas constraints on the other hand influence the way requirements are met.

Based upon the distinction of three different requirements, a combination of techniques can be made that will successfully uncover all relevant requirements. The following requirement techniques are used in this research:

- Interviewing: captures conscious requirements
- Brainstorming: captures undreamed requirements
- Systems archaeology: captures unconscious requirements

These are chosen based on the applicability table from Robertson (2001), current research possibilities and the expected results of their combination.

Interviewing is a proper technique for conscious requirements due to the chance it gives actors to tell what comes to mind. Brainstorming works well for undreamed requirements due to its nature to release preconceived ideas and notions. And finally systems archaeology mainly digs into current business process documentation and based thereupon conceptualizes requirements. If there are any questions or doubts raised on requirements based on the documentation, these can be verified in the interviews.

C

Daily Schedule Warehouse Planner

Time	Activity	Description
7:00h	Start-up	• Check past 24 hours • Consultation with port planner • Adjust current plan • Look ahead for disturbances • Collect hot strip rolling mill storage filling rate
8:45h	Morning meeting OSL	• Note deviations from the current plan for planners consultation
9:15h	Planners consultation	• Pass down wagon availability • Report on warehouse availability
9:40h	Start work on warehouse plan	• Start-up meeting with port planner • Plan internal repositioning transports • Discuss internal repositioning with OTB • Plan outbound rail transport
12:00h	12-hour consultation	• Discuss added internal repositioning transports
12:00 - 14:45h	Finishing warehouse plan	• Planning of added internal repositioning work • Process changes caused by port plan modifications • Check length-of-stay of coils in unconditioned warehouse & arrange internal repositioning • Check for possible bundling of transport tasks to one locomotive
14:45h	Afternoon meeting OSL	• Transfer the warehouse plan to shift work

Table C.1: Warehouse planner daily schedule, from Tata Steel (n.d.-a)

D

Resource Data

Note that the used resource data may differ in real life operations. E.g. a greater number of wagons could be available or a different workforce schedule could apply.

Table D.1: Resource data: locomotives, workforce and wagons. Including workforce groups, wagon types and capacity.

Category	**Type**	**Capacity**
Locomotives	Locomotives	5 (30 wagons)
Workforce	WAW	2, (0 at night)
	CPR	4
	Cluster Zuid	2
	TSP	2
	Cluster Midden	7
	Cluster Noord	3
Wagons	GHUIF	63
	PLWG	55
	SETJE	12
	VWWG	74

Table D.2: Site location data: Locations used, their site cluster and track capacity.

Location	**Site Cluster**	**Track capacity**
TRH S5	HAV	8
TRH	HAV	8
TRH S4 / Deur	HAV	8
BI3	HAV	5
BU1	HAV	5
BU3	HAV	5
BUO	HAV	5
BUW	HAV	5
Z	ZD1 WAW	5
ZT	ZD1 WAW	5
MO	ZD1 WAW	5

MOC	ZD1 WAW	5
N	ZD1 WAW	5
CHN	CPR	4
CH	CPR	4
LA	CPR	12
LAO	CPR	12
LAW	CPR	12
CC	CPR	0
F	Cluster Zuid	6
RW	Cluster Zuid	5
RWT	Cluster Zuid	5
WBH	Cluster Zuid	7
CPP	TSP	10
E	TSP	5
T	TSP	5
T2	TSP	5
W	TSP	5
Wt(truck)	TSP	0
V	TSP	4
WB2	Cluster Midden	8
BVM	Cluster Midden	5
BOS	Cluster Midden	12
PAA	Cluster Midden	8
PAW	Cluster Midden	5
PAO	Cluster Midden	8
PAB	Cluster Midden	5
PCW	Cluster Midden	5
PAC	Cluster Midden	7
PAD	Cluster Midden	5
PAF	Cluster Midden	6
KB2	Cluster Noord	10
BM3	Cluster Noord	4
BM	Cluster Noord	8
BO	Cluster Noord	8
BR	Cluster Noord	8
BT	Cluster Noord	8
C Empl	RVE	200

E

Python Code - Planning Model

```
# %% ----------------- Imports -----------------
import gurobipy as gp
from gurobipy import GRB
import numpy as np

# %% ----------------- Model -----------------
model = gp.Model("Planning Model")

# %% ----------------- Shipment Variables -----------------
x_ship = {}
for i in I_ship:
    for j in J:
        for t in T:
            x_ship[i,j,t] = model.addVar(vtype=GRB.BINARY, name = 'x_ship[' + str(i)+
                                    ',' + str(j)+ ',' + str(t)+']')
# Dummy trackers
y_0_ship = {}
for i in I_ship:
    for t in T:
        y_0_ship[i,t] = model.addVar(vtype = GRB.BINARY, name = 'y_0_ship[' + str(i)+ ',' + str(t)+ ']')
y_1_ship = {}
for i in I_ship:
    for t in T:
        y_1_ship[i,t] = model.addVar(vtype = GRB.BINARY, name = 'y_1_ship[' + str(i)+ ',' + str(t)+ ']')
y_2_ship = {}
for i in I_ship:
    for t in T:
        y_2_ship[i,t] = model.addVar(vtype = GRB.BINARY, name = 'y_2_ship[' + str(i)+ ',' + str(t)+ ']')

# %% ----------------- Train Variables -----------------
x_train = {}
for i in I_train:
    for j in J:
        for t in T:
            x_train[i,j,t] = model.addVar(vtype=GRB.BINARY, name = 'x_train[' + str(i)+
                                    ',' + str(j)+ ',' + str(t)+']')
y_0_train = {}
for i in I_train:
    for t in T:
        y_0_train[i,t] = model.addVar(vtype = GRB.BINARY, name = 'y_0_train[' + str(i)+ ',' + str(t)+ ']')
y_1_train = {}
for i in I_train:
    for t in T:
        y_1_train[i,t] = model.addVar(vtype = GRB.BINARY, name = 'y_1_train[' + str(i)+ ',' + str(t)+ ']')
y_2_train = {}
for i in I_train:
```

```
    for t in T:
        y_2_train[i,t] = model.addVar(vtype = GRB.BINARY, name = 'y_2_train[' + str(i)+ ',' + str(t)+ ']')
# %% ----------------- Hall Transfer Variables -----------------
x_hall = {}
for i in I_hall:
    for j in J:
        for t in T:
            x_hall[i,j,t] = model.addVar(vtype=GRB.BINARY, name = 'x_hall[' + str(i)+
                                        ',' + str(j)+ ',' + str(t)+']')
y_0_hall = {}
for i in I_hall:
    for t in T:
        y_0_hall[i,t] = model.addVar(vtype = GRB.BINARY, name = 'y_0_hall[' + str(i)+ ',' + str(t)+ ']')
y_1_hall = {}
for i in I_hall:
    for t in T:
        y_1_hall[i,t] = model.addVar(vtype = GRB.BINARY, name = 'y_1_hall[' + str(i)+ ',' + str(t)+ ']')
y_2_hall = {}
for i in I_hall:
    for t in T:
        y_2_hall[i,t] = model.addVar(vtype = GRB.BINARY, name = 'y_2_hall[' + str(i)+ ',' + str(t)+ ']')

# %% ----------------- Constraints -----------------
con1_ship = {}
for i in I_ship:
    for j in J:
        con1_ship[i] = model.addConstr((gp.quicksum(x_ship[i,j,t] for t in T)
                                        == 1), name = 'Task_once_ship[' +str(i)+ ',' +str(j)+ ']')
con1_train = {}
for i in I_train:
    for j in J:
        con1_train[i] = model.addConstr((gp.quicksum(x_train[i,j,t] for t in T)
                                        == 1), name = 'Task_once_train[' +str(i)+ ',' +str(j)+ ']')
con1_hall = {}
for i in I_hall:
    for j in J:
        con1_hall[i] = model.addConstr((gp.quicksum(x_hall[i,j,t] for t in T)
                                        == 1), name = 'Task_once_hall[' +str(i)+ ',' +str(j)+ ']')
con2_loc_comb = {}
for t in T:
    for k in K_locs:
        con2_loc_comb[t,k] = model.addConstr(gp.quicksum(r_loc_ijk_ship[i,j,k]*x_ship[i,j,u]
                                    for i in I_ship for j in J
                                    for u in range(max(0, int(t+1 - P_ij_ship[i,j] )), t+1))
                            + gp.quicksum(r_loc_ijk_train[i,j,k]*x_train[i,j,u]
                                    for i in I_train for j in J
                                    for u in range(max(0, int(t+1 - P_ij_train[i,j] )), t+1))
                            + gp.quicksum(r_loc_ijk_hall[i,j,k]*x_hall[i,j,u]
                                    for i in I_hall for j in J
                                    for u in range(max(0, int(t+1 - P_ij_hall[i,j] )), t+1))
                            <= RA_loc_kt[k,t] , name = 'Loc_Resource_Req[' +str(k)+ ',' +str(t)+ ']')
con2_wags_comb = {}
for t in T:
    for k in K_wagons:
        con2_wags_comb[t,k] = model.addConstr(gp.quicksum(r_wagons_ijk_ship[i,j,k]*x_ship[i,j,u]
                                    for i in I_ship for j in J
                                    for u in range(max(0, int(t+1 - P_ij_ship[i,j] )), t+1))
                            + gp.quicksum(r_y0_wag_ship[i,k]*y_0_ship[i,t] for i in I_ship)
                            + gp.quicksum(r_y1_wag_ship[i,k]*y_1_ship[i,t] for i in I_ship)
                            + gp.quicksum(r_y2_wag_ship[i,k]*y_2_ship[i,t] for i in I_ship)
                            + gp.quicksum(r_wagons_ijk_train[i,j,k]*x_train[i,j,u]
                                    for i in I_train for j in J
                                    for u in range(max(0, int(t+1 - P_ij_train[i,j] )), t+1))
                            + gp.quicksum(r_y0_wag_train[i,k]*y_0_train[i,t] for i in I_train)
```

```
                                + gp.quicksum(r_y1_wag_train[i,k]*y_1_train[i,t] for i in I_train)
                                + gp.quicksum(r_y2_wag_train[i,k]*y_2_train[i,t] for i in I_train)
                                + gp.quicksum(r_wagons_ijk_hall[i,j,k]*x_hall[i,j,u]
                                            for i in I_hall for j in J
                                            for u in range(max(0, int(t+1 - P_ij_hall[i,j] )), t+1))
                                + gp.quicksum(r_y0_wag_hall[i,k]*y_0_hall[i,t] for i in I_hall)
                                + gp.quicksum(r_y1_wag_hall[i,k]*y_1_hall[i,t] for i in I_hall)
                                + gp.quicksum(r_y2_wag_hall[i,k]*y_2_hall[i,t] for i in I_hall)
                                <= RA_wag_kt[k,t] , name = 'Wagon_Resource_Req[' +str(k)+ ',' +str(t)+ ']')
con2_hKraan_comb = {}
for t in T:
    for k in K_hallen:
        con2_hKraan_comb[t,k] = model.addConstr(gp.quicksum(r_hKraan_ijk_ship[i,j,k]*x_ship[i,j,u]
                                            for i in I_ship for j in J
                                            for u in range(max(0, int(t+1 - P_ij_ship[i,j] )), t+1))
                                + gp.quicksum(r_hKraan_ijk_train[i,j,k]*x_train[i,j,u]
                                            for i in I_train for j in J
                                            for u in range(max(0, int(t+1 - P_ij_train[i,j] )), t+1))
                                + gp.quicksum(r_hKraan_ijk_hall[i,j,k]*x_hall[i,j,u]
                                            for i in I_hall for j in J
                                            for u in range(max(0, int(t+1 - P_ij_hall[i,j] )), t+1))
                                <= RA_hKraan_kt[k,t] , name = 'hKraan_Resource_Req[' +str(k)+ ',' +str(t)+ ']')
con2_hSpoor_comb = {}
for t in T:
    for k in K_hallen:
        con2_hSpoor_comb[t,k] = model.addConstr(gp.quicksum(r_hSpoor_ijk_ship[i,j,k]*x_ship[i,j,u]
                                            for i in I_ship for j in J
                                            for u in range(max(0, int(t+1 - P_ij_ship[i,j] )), t+1))
                                + gp.quicksum(r_y0_hSpoor_ship[i,k]*y_0_ship[i,t] for i in I_ship)
                                + gp.quicksum(r_y1_hSpoor_ship[i,k]*y_1_ship[i,t] for i in I_ship)
                                + gp.quicksum(r_y2_hSpoor_ship[i,k]*y_2_ship[i,t] for i in I_ship)
                                + gp.quicksum(r_hSpoor_ijk_train[i,j,k]*x_train[i,j,u]
                                            for i in I_train for j in J
                                            for u in range(max(0, int(t+1 - P_ij_train[i,j] )), t+1))
                                + gp.quicksum(r_y0_hSpoor_train[i,k]*y_0_train[i,t] for i in I_train)
                                + gp.quicksum(r_y1_hSpoor_train[i,k]*y_1_train[i,t] for i in I_train)
                                + gp.quicksum(r_y2_hSpoor_train[i,k]*y_2_train[i,t] for i in I_train)
                                + gp.quicksum(r_hSpoor_ijk_hall[i,j,k]*x_hall[i,j,u]
                                            for i in I_hall for j in J
                                            for u in range(max(0, int(t+1 - P_ij_hall[i,j] )), t+1))
                                + gp.quicksum(r_y0_hSpoor_hall[i,k]*y_0_hall[i,t] for i in I_hall)
                                + gp.quicksum(r_y1_hSpoor_hall[i,k]*y_1_hall[i,t] for i in I_hall)
                                + gp.quicksum(r_y2_hSpoor_hall[i,k]*y_2_hall[i,t] for i in I_hall)
                                <= RA_hSpoor_kt[k,t] , name = 'hSpoor_Resource_Req[' +str(k)+ ',' +str(t)+ ']')
con2_hPloeg_comb = {}
for t in T:
    for k in K_clus:
        con2_hPloeg_comb[t,k] = model.addConstr(gp.quicksum(r_hPloeg_ijk_ship[i,j,k]*x_ship[i,j,u]
                                            for i in I_ship for j in J
                                            for u in range(max(0, int(t+1 - P_ij_ship[i,j] )), t+1))
                                + gp.quicksum(r_hPloeg_ijk_train[i,j,k]*x_train[i,j,u]
                                            for i in I_train for j in J
                                            for u in range(max(0, int(t+1 - P_ij_train[i,j] )), t+1))
                                + gp.quicksum(r_hPloeg_ijk_hall[i,j,k]*x_hall[i,j,u]
                                            for i in I_hall for j in J
                                            for u in range(max(0, int(t+1 - P_ij_hall[i,j] )), t+1))
                                <= RA_hPloeg_kt[k,t] , name = 'hPloeg_Resource_Req[' +str(k)+ ',' +str(t)+ ']')
con3_ship = {}
for i in I_ship:
    for j in range(len(Jobs)-1):
        con3_ship[i,j] = model.addConstr(gp.quicksum(t*x_ship[i,j,t] for t in T) + P_ij_ship[i,j]
                              <= gp.quicksum(t* x_ship[i,j+1,t] for t in T),
                              name = 'Precedence_Jobs_ship[' +str(i)+ ',' +str(j)+ ']')
con3_train = {}
```

```
for i in I_train:
    for j in range(len(Jobs)-1):
        con3_train[i,j] = model.addConstr(gp.quicksum(t*x_train[i,j,t] for t in T) + P_ij_train[i,j]
                                <= gp.quicksum(t* x_train[i,j+1,t] for t in T),
                                name = 'Precedence_Jobs_train[' +str(i)+ ',' +str(j)+ ']')
con3_hall = {}
for i in I_hall:
    for j in range(len(Jobs)-1):
        con3_hall[i,j] = model.addConstr(gp.quicksum(t*x_hall[i,j,t] for t in T) + P_ij_hall[i,j]
                                <= gp.quicksum(t* x_hall[i,j+1,t] for t in T),
                                name = 'Precedence_Jobs_hall[' +str(i)+ ',' +str(j)+ ']')
con4_hall = {}
for i in I_hall:
    con4_hall[i,j] = model.addConstr(gp.quicksum(t * x_hall[i,1,t] for t in T) >= L_ij_hall[i,1],
                                      name = 'Releasetime_HH_taak[' +str(i)+ ']')
con5_1_hall = {}
for i in I_hall:
    con5_1_hall[i,j] = model.addConstr(gp.quicksum(t * x_hall[i,1,t] for t in T) <= d_i_laden_hall[i],
                                      name = 'Deadline_HH_laad_taak[' +str(i)+ ']')
con5_2_hall = {}
for i in I_hall:
    con5_2_hall[i,j] = model.addConstr(gp.quicksum(t * x_hall[i,3,t] for t in T)
                                        + P_ij_hall[i,3] - 1 <= d_i_lossen_hall[i],
                                      name = 'Deadline_HH_los_taak[' +str(i)+ ']')
# Dummy Trackers
con6_01_ship =  {}
for i in I_ship:
    for t in T:
        con6_01_ship[i,t] = model.addConstr((gp.quicksum(t * x_ship[i,0,t] for t in T ) + P_ij_ship[i,0])
                                  <= t * y_0_ship[i,t] + M * (1 - y_0_ship[i,t]),
                                  name = 'Y_0_lower_ship[' +str(i)+ ','  +str(t)+  ']')
con6_01_train =  {}
for i in I_train:
    for t in T:
        con6_01_train[i,t] = model.addConstr((gp.quicksum(t * x_train[i,0,t] for t in T ) + P_ij_train[i,0])
                                  <= t * y_0_train[i,t] + M * (1 - y_0_train[i,t]),
                                  name = 'Y_0_lower_train[' +str(i)+ ','  +str(t)+  ']')
con6_01_hall =  {}
for i in I_hall:
    for t in T:
        con6_01_hall[i,t] = model.addConstr((gp.quicksum(t * x_hall[i,0,t] for t in T ) + P_ij_hall[i,0])
                                  <= t * y_0_hall[i,t] + M * (1 - y_0_hall[i,t]),
                                  name = 'Y_0_lower_hall[' +str(i)+ ','  +str(t)+  ']')
con6_02_ship =  {}
for i in I_ship:
    for t in T:
        con6_02_ship[i,t] = model.addConstr( t * y_0_ship[i,t] + 1
                                  <= gp.quicksum(t * x_ship[i,1,t] for t in T) ,
                                  name = 'Y_0_upper_ship[' +str(i)+ ','  +str(t)+ ']')
con6_02_train =  {}
for i in I_train:
    for t in T:
        con6_02_train[i,t] = model.addConstr( t * y_0_train[i,t] + 1
                                  <= gp.quicksum(t * x_train[i,1,t] for t in T) ,
                                  name = 'Y_0_upper_train[' +str(i)+ ','  +str(t)+ ']')
con6_02_hall =  {}
for i in I_hall:
    for t in T:
        con6_02_hall[i,t] = model.addConstr( t * y_0_hall[i,t] + 1
                                  <= gp.quicksum(t * x_hall[i,1,t] for t in T) ,
                                  name = 'Y_0_upper_hall[' +str(i)+ ','  +str(t)+ ']')
con6_1_ship =  {}
for i in I_ship:
    for t in T:
```

```
        con6_1_ship[i,t] = model.addConstr((gp.quicksum(t * x_ship[i,1,t] for t in T ) + P_ij_ship[i,1])
                              <= t * y_1_ship[i,t] + M * (1 - y_1_ship[i,t]),
                              name = 'Y_1_lower_ship[' +str(i)+ ',' +str(t)+ ']')
con6_1_train = {}
for i in I_train:
    for t in T:
        con6_1_train[i,t] = model.addConstr((gp.quicksum(t * x_train[i,1,t] for t in T ) + P_ij_train[i,1])
                              <= t * y_1_train[i,t] + M * (1 - y_1_train[i,t]),
                              name = 'Y_1_lower_train[' +str(i)+ ',' +str(t)+ ']')
con6_1_hall = {}
for i in I_hall:
    for t in T:
        con6_1_hall[i,t] = model.addConstr((gp.quicksum(t * x_hall[i,1,t] for t in T ) + P_ij_hall[i,1])
                              <= t * y_1_hall[i,t] + M * (1 - y_1_hall[i,t]),
                              name = 'Y_1_lower_hall[' +str(i)+ ',' +str(t)+ ']')
con6_2_ship = {}
for i in I_ship:
    for t in T:
        con6_2_ship[i,t] = model.addConstr( t * y_1_ship[i,t] + 1
                              <= gp.quicksum(t * x_ship[i,2,t] for t in T) ,
                              name = 'Y_1_upper_ship[' +str(i)+ ',' +str(t)+ ']')
con6_2_train = {}
for i in I_train:
    for t in T:
        con6_2_train[i,t] = model.addConstr( t * y_1_train[i,t] + 1
                              <= gp.quicksum(t * x_train[i,2,t] for t in T) ,
                              name = 'Y_1_upper_train[' +str(i)+ ',' +str(t)+ ']')
con6_2_hall = {}
for i in I_hall:
    for t in T:
        con6_2_hall[i,t] = model.addConstr( t * y_1_hall[i,t] + 1
                              <= gp.quicksum(t * x_hall[i,2,t] for t in T) ,
                              name = 'Y_1_upper_hall[' +str(i)+ ',' +str(t)+ ']')
con7_1_ship = {}
for i in I_ship:
    for t in T:
        con7_1_ship[i,t] = model.addConstr((gp.quicksum(t * x_ship[i,2,t] for t in T ) + P_ij_ship[i,2])
                              <= t * y_2_ship[i,t] + M * (1 - y_2_ship[i,t]),
                              name = 'Y_2_lower_ship[' +str(i)+ ',' +str(t)+ ']')
con7_1_train = {}
for i in I_train:
    for t in T:
        con7_1_train[i,t] = model.addConstr((gp.quicksum(t * x_train[i,2,t] for t in T ) + P_ij_train[i,2])
                              <= t * y_2_train[i,t] + M * (1 - y_2_train[i,t]),
                              name = 'Y_2_lower_train[' +str(i)+ ',' +str(t)+ ']')
con7_1_hall = {}
for i in I_hall:
    for t in T:
        con7_1_hall[i,t] = model.addConstr((gp.quicksum(t * x_hall[i,2,t] for t in T ) + P_ij_hall[i,2])
                              <= t * y_2_hall[i,t] + M * (1 - y_2_hall[i,t]),
                              name = 'Y_2_lower_hall[' +str(i)+ ',' +str(t)+ ']')
con7_2_ship = {}
for i in I_ship:
    for t in T:
        con7_2_ship[i,t] = model.addConstr( t * y_2_ship[i,t] + 1
                              <= gp.quicksum(t * x_ship[i,3,t] for t in T) ,
                              name = 'Y_2_upper_ship[' +str(i)+ ',' +str(t)+ ']')
con7_2_train = {}
for i in I_train:
    for t in T:
        con7_2_train[i,t] = model.addConstr( t * y_2_train[i,t] + 1
                              <= gp.quicksum(t * x_train[i,3,t] for t in T) ,
                              name = 'Y_2_upper_train[' +str(i)+ ',' +str(t)+ ']')
con7_2_hall = {}
```

```
for i in I_hall:
    for t in T:
        con7_2_hall[i,t] = model.addConstr( t * y_2_hall[i,t] + 1
                                <= gp.quicksum(t * x_hall[i,3,t] for t in T) ,
                                name = 'Y_2_upper_hall[' +str(i)+ ',' +str(t)+ ']')
con8_0_ship = {}
for i in I_ship:
    con8_0_ship[i] = model.addConstr(gp.quicksum(y_0_ship[i,t] for t in T)
                                    - gp.quicksum(t*x_ship[i,1,t] for t in T)
                              + gp.quicksum(t*x_ship[i,0,t] for t in T) + P_ij_ship[i,0] == 0,
                              name = 'Sum_y0_ship[' +str(i)+ ']')
con8_0_train = {}
for i in I_train:
    con8_0_train[i] = model.addConstr(gp.quicksum(y_0_train[i,t] for t in T)
                                     - gp.quicksum(t*x_train[i,1,t] for t in T)
                              + gp.quicksum(t*x_train[i,0,t] for t in T) + P_ij_train[i,0] == 0,
                              name = 'Sum_y0_train[' +str(i)+ ']')
con8_0_hall = {}
for i in I_hall:
    con8_0_hall[i] = model.addConstr(gp.quicksum(y_0_hall[i,t] for t in T)
                                    - gp.quicksum(t*x_hall[i,1,t] for t in T)
                              + gp.quicksum(t*x_hall[i,0,t] for t in T) + P_ij_hall[i,0] == 0,
                              name = 'Sum_y0_hall[' +str(i)+ ']')
con8_1_ship = {}
for i in I_ship:
    con8_1_ship[i] = model.addConstr(gp.quicksum(y_1_ship[i,t] for t in T)
                                    - gp.quicksum(t*x_ship[i,2,t] for t in T)
                              + gp.quicksum(t*x_ship[i,1,t] for t in T) + P_ij_ship[i,1] == 0,
                              name = 'Sum_y1_ship[' +str(i)+ ']')
con8_1_train = {}
for i in I_train:
    con8_1_train[i] = model.addConstr(gp.quicksum(y_1_train[i,t] for t in T)
                                     - gp.quicksum(t*x_train[i,2,t] for t in T)
                              + gp.quicksum(t*x_train[i,1,t] for t in T) + P_ij_train[i,1] == 0,
                              name = 'Sum_y1_train[' +str(i)+ ']')
con8_1_hall = {}
for i in I_hall:
    con8_1_hall[i] = model.addConstr(gp.quicksum(y_1_hall[i,t] for t in T)
                                    - gp.quicksum(t*x_hall[i,2,t] for t in T)
                              + gp.quicksum(t*x_hall[i,1,t] for t in T) + P_ij_hall[i,1] == 0,
                              name = 'Sum_y1_hall[' +str(i)+ ']')
con8_2_ship = {}
for i in I_ship:
    con8_2_ship[i] = model.addConstr(gp.quicksum(y_2_ship[i,t] for t in T)
                                    - gp.quicksum(t*x_ship[i,3,t] for t in T)
                              + gp.quicksum(t*x_ship[i,2,t] for t in T) + P_ij_ship[i,2] == 0,
                              name = 'Sum_y2_ship[' +str(i)+ ']')
con8_2_train = {}
for i in I_train:
    con8_2_train[i] = model.addConstr(gp.quicksum(y_2_train[i,t] for t in T)
                                     - gp.quicksum(t*x_train[i,3,t] for t in T)
                              + gp.quicksum(t*x_train[i,2,t] for t in T) + P_ij_train[i,2] == 0,
                              name = 'Sum_y2_train[' +str(i)+ ']')
con8_2_hall = {}
for i in I_hall:
    con8_2_hall[i] = model.addConstr(gp.quicksum(y_2_hall[i,t] for t in T)
                                    - gp.quicksum(t*x_hall[i,3,t] for t in T)
                              + gp.quicksum(t*x_hall[i,2,t] for t in T) + P_ij_hall[i,2] == 0,
                              name = 'Sum_y2_hall[' +str(i)+ ']')
con9_ship = {}
for i in I_ship:
    con9_ship[i] = model.addConstr(gp.quicksum( t * x_ship[i,3,t] for t in T)  == ST_crane_ship[i],
                                   name = 'defining_cranetask[' +str(i)+ ']')
con9_train = {}
```

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for i in I_train:
    con9_train[i] = model.addConstr(gp.quicksum( t * x_train[i,3,t] for t in T)  == ST_crane_train[i],
                                name = 'defining_departuretask[' +str(i)+ ']')

# %% KPI Locs auxiliary variables
U_Locs_t = {}
for t in T:
    U_Locs_t[t] = model.addVar(vtype = GRB.INTEGER, name = 'U_Locs_t[' +str(t)+ ']')
U_Locs_s = {}
for s in S:
    U_Locs_s[s] = model.addVar(vtype = GRB.INTEGER, name = 'U_Locs_s[' +str(s)+ ']')
Cost_locs = {}
for s in S:
    Cost_locs[s] = model.addVar(vtype = GRB.INTEGER, name = 'Cost_locs[' +str(s)+ ']')

# %% KPI Wagons auxiliary variables
Frac_Wags_PLWG_t = {}
for t in T:
    Frac_Wags_PLWG_t[t] = model.addVar(vtype = GRB.CONTINUOUS, name = 'Frac_Wags_PLWG_t[' +str(t)+ ']')
Cost_wags_PLWG_t = {}
for t in T:
    Cost_wags_PLWG_t[t] = model.addVar(vtype = GRB.CONTINUOUS, name = 'Cost_wags_PLWG[' +str(t)+ ']')
Frac_Wags_GHUIF_t = {}
for t in T:
    Frac_Wags_GHUIF_t[t] = model.addVar(vtype = GRB.CONTINUOUS, name = 'Frac_Wags_GHUIF_t[' +str(t)+ ']')
Cost_wags_GHUIF_t = {}
for t in T:
    Cost_wags_GHUIF_t[t] = model.addVar(vtype = GRB.CONTINUOUS, name = 'Cost_wags_GHUIF[' +str(t)+ ']')
Frac_Wags_VWWG_t = {}
for t in T:
    Frac_Wags_VWWG_t[t] = model.addVar(vtype = GRB.CONTINUOUS, name = 'Frac_Wags_VWWG_t[' +str(t)+ ']')
Cost_wags_VWWG_t = {}
for t in T:
    Cost_wags_VWWG_t[t] = model.addVar(vtype = GRB.CONTINUOUS, name = 'Cost_wags_VWWG[' +str(t)+ ']')
Frac_Wags_SETJE_t = {}
for t in T:
    Frac_Wags_SETJE_t[t] = model.addVar(vtype = GRB.CONTINUOUS, name = 'Frac_Wags_SETJE_t[' +str(t)+ ']')
Cost_wags_SETJE_t = {}
for t in T:
    Cost_wags_SETJE_t[t] = model.addVar(vtype = GRB.CONTINUOUS, name = 'Cost_wags_SETJE[' +str(t)+ ']')

# %% KPI workforce auxiliary variables
U_WAW_t = {}
for t in T:
    U_WAW_t[t] = model.addVar(vtype = GRB.CONTINUOUS, name = 'U_WAW_t[' +str(t)+ ']')
U_WAW_hs = {}
for hs in HS:
    U_WAW_hs[hs] = model.addVar(vtype = GRB.CONTINUOUS, name = 'U_WAW_hs[' +str(hs)+ ']')
Cost_WAW = {}
for hs in HS:
    Cost_WAW[hs] = model.addVar(vtype = GRB.CONTINUOUS, name = 'Cost_WAW[' +str(hs)+ ']')
U_CPR_t = {}
for t in T:
    U_CPR_t[t] = model.addVar(vtype = GRB.CONTINUOUS, name = 'U_CPR_t[' +str(t)+ ']')
U_CPR_hs = {}
for hs in HS:
    U_CPR_hs[hs] = model.addVar(vtype = GRB.CONTINUOUS, name = 'U_CPR_hs[' +str(hs)+ ']')
Cost_CPR = {}
for hs in HS:
    Cost_CPR[hs] = model.addVar(vtype = GRB.CONTINUOUS, name = 'Cost_CPR[' +str(hs)+ ']')
U_CLUSTER_ZUID_t = {}
for t in T:
    U_CLUSTER_ZUID_t[t] = model.addVar(vtype = GRB.CONTINUOUS, name = 'U_CLUSTER_ZUID_t[' +str(t)+ ']')
U_CLUSTER_ZUID_hs = {}
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for hs in HS:
    U_CLUSTER_ZUID_hs[hs] = model.addVar(vtype = GRB.CONTINUOUS, name = 'U_CLUSTER_ZUID_hs[' +str(hs)+ ']')
Cost_CLUSTER_ZUID = {}
for hs in HS:
    Cost_CLUSTER_ZUID[hs] = model.addVar(vtype = GRB.CONTINUOUS, name = 'Cost_CLUSTER_ZUID[' +str(hs)+ ']')
U_CPP_t = {}
for t in T:
    U_CPP_t[t] = model.addVar(vtype = GRB.CONTINUOUS, name = 'U_CPP_t[' +str(t)+ ']')
U_CPP_hs = {}
for hs in HS:
    U_CPP_hs[hs] = model.addVar(vtype = GRB.CONTINUOUS, name = 'U_CPP_hs[' +str(hs)+ ']')
Cost_CPP = {}
for hs in HS:
    Cost_CPP[hs] = model.addVar(vtype = GRB.CONTINUOUS, name = 'Cost_CPP[' +str(hs)+ ']')
U_WB2_t = {}
for t in T:
    U_WB2_t[t] = model.addVar(vtype = GRB.CONTINUOUS, name = 'U_WB2_t[' +str(t)+ ']')
U_WB2_hs = {}
for hs in HS:
    U_WB2_hs[hs] = model.addVar(vtype = GRB.CONTINUOUS, name = 'U_WB2_hs[' +str(hs)+ ']')
Cost_WB2 = {}
for hs in HS:
    Cost_WB2[hs] = model.addVar(vtype = GRB.CONTINUOUS, name = 'Cost_WB2[' +str(hs)+ ']')
U_KB2_t = {}
for t in T:
    U_KB2_t[t] = model.addVar(vtype = GRB.CONTINUOUS, name = 'U_KB2_t[' +str(t)+ ']')
U_KB2_hs = {}
for hs in HS:
    U_KB2_hs[hs] = model.addVar(vtype = GRB.CONTINUOUS, name = 'U_KB2_hs[' +str(hs)+ ']')
Cost_KB2 = {}
for hs in HS:
    Cost_KB2[hs] = model.addVar(vtype = GRB.CONTINUOUS, name = 'Cost_KB2[' +str(hs)+ ']')

# %% KPI constraints
con10_1_1 = {}
for t in T:
    con10_1_1[t] = model.addConstr(U_Locs_t[t] >= (1/6)*(gp.quicksum(r_loc_ijk_ship[i,j,0]*x_ship[i,j,u]
                                            for i in I_ship for j in J
                                            for u in range(max(0, int(t+1 - P_ij_ship[i,j] )), t+1))
                                  + gp.quicksum(r_loc_ijk_train[i,j,0]*x_train[i,j,u]
                                            for i in I_train for j in J
                                            for u in range(max(0, int(t+1 - P_ij_train[i,j] )), t+1))
                                  + gp.quicksum(r_loc_ijk_hall[i,j,0]*x_hall[i,j,u]
                                            for i in I_hall for j in J
                                            for u in range(max(0, int(t+1 - P_ij_hall[i,j] )), t+1))),
                                name = 'Loco_usage_t_low[' +str(t)+ ']')
con10_1_2 = {}
for t in T:
    con10_1_2[t] = model.addConstr(U_Locs_t[t] <= .99 + (1/6)*(gp.quicksum(r_loc_ijk_ship[i,j,0]*x_ship[i,j,u]
                                            for i in I_ship for j in J
                                            for u in range(max(0, int(t+1 - P_ij_ship[i,j] )), t+1))
                                  + gp.quicksum(r_loc_ijk_train[i,j,0]*x_train[i,j,u]
                                            for i in I_train for j in J
                                            for u in range(max(0, int(t+1 - P_ij_train[i,j] )), t+1))
                                  + gp.quicksum(r_loc_ijk_hall[i,j,0]*x_hall[i,j,u]
                                            for i in I_hall for j in J
                                            for u in range(max(0, int(t+1 - P_ij_hall[i,j] )), t+1))),
                                name = 'Loco_usage_t_up[' +str(t)+ ']')
con10_2 = {}
for s in S:
    con10_2[s] = model.addGenConstrMax(U_Locs_s[s], [U_Locs_t[t] for t in
                                                    range(shift_vector[s][0],shift_vector[s][-1]+1)],
                                       name = 'Max_shift_loc['+str(s)+']')
con10_3 = {}
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for s in S:
    con10_3[s] = model.addGenConstrPWL(U_Locs_s[s], Cost_locs[s], Num_locs_vec, C_locs,
                                       name = 'PWL_Costs_Locs[' +str(s)+ ']' )
con11_1_PLWG = {}
for t in T:
    con11_1_PLWG[t] = model.addConstr(Frac_Wags_PLWG_t[t] == (gp.quicksum(r_wagons_ijk_ship[i,j,10]*x_ship[i,j,u]
                                            for i in I_ship for j in J
                                            for u in range(max(0, int(t+1 - P_ij_ship[i,j] )), t+1))
                                + gp.quicksum(r_y0_wag_ship[i,10]*y_0_ship[i,t] for i in I_ship)
                                + gp.quicksum(r_y1_wag_ship[i,10]*y_1_ship[i,t] for i in I_ship)
                                + gp.quicksum(r_y2_wag_ship[i,10]*y_2_ship[i,t] for i in I_ship)
                                + gp.quicksum(r_wagons_ijk_train[i,j,10]*x_train[i,j,u]
                                            for i in I_train for j in J
                                            for u in range(max(0, int(t+1 - P_ij_train[i,j] )), t+1))
                                + gp.quicksum(r_y0_wag_train[i,10]*y_0_train[i,t] for i in I_train)
                                + gp.quicksum(r_y1_wag_train[i,10]*y_1_train[i,t] for i in I_train)
                                + gp.quicksum(r_y2_wag_train[i,10]*y_2_train[i,t] for i in I_train)
                                + gp.quicksum(r_wagons_ijk_hall[i,j,10]*x_hall[i,j,u]
                                            for i in I_hall for j in J
                                            for u in range(max(0, int(t+1 - P_ij_hall[i,j] )), t+1))
                                + gp.quicksum(r_y0_wag_hall[i,10]*y_0_hall[i,t] for i in I_hall)
                                + gp.quicksum(r_y1_wag_hall[i,10]*y_1_hall[i,t] for i in I_hall)
                                + gp.quicksum(r_y2_wag_hall[i,10]*y_2_hall[i,t] for i in I_hall))
                                / RA_wag_kt[10,t], name = 'Wagon_PLWG_usage[' +str(t)+ ']')
con11_2_PLWG = {}
for t in T:
    con11_2_PLWG[t] = model.addGenConstrPWL(Frac_Wags_PLWG_t[t], Cost_wags_PLWG_t[t], Frac_Wags_vec, C_wags,
                                            name = 'PLWG_cost[' +str(t)+ ']' )
con11_1_GHUIF = {}
for t in T:
    con11_1_GHUIF[t] = model.addConstr(Frac_Wags_GHUIF_t[t] == (gp.quicksum(r_wagons_ijk_ship[i,j,7]*x_ship[i,j,u]
                                            for i in I_ship for j in J
                                            for u in range(max(0, int(t+1 - P_ij_ship[i,j] )), t+1))
                                + gp.quicksum(r_y0_wag_ship[i,7]*y_0_ship[i,t] for i in I_ship)
                                + gp.quicksum(r_y1_wag_ship[i,7]*y_1_ship[i,t] for i in I_ship)
                                + gp.quicksum(r_y2_wag_ship[i,7]*y_2_ship[i,t] for i in I_ship)
                                + gp.quicksum(r_wagons_ijk_train[i,j,7]*x_train[i,j,u]
                                            for i in I_train for j in J
                                            for u in range(max(0, int(t+1 - P_ij_train[i,j] )), t+1))
                                + gp.quicksum(r_y0_wag_train[i,7]*y_0_train[i,t] for i in I_train)
                                + gp.quicksum(r_y1_wag_train[i,7]*y_1_train[i,t] for i in I_train)
                                + gp.quicksum(r_y2_wag_train[i,7]*y_2_train[i,t] for i in I_train)
                                + gp.quicksum(r_wagons_ijk_hall[i,j,7]*x_hall[i,j,u]
                                            for i in I_hall for j in J
                                            for u in range(max(0, int(t+1 - P_ij_hall[i,j] )), t+1))
                                + gp.quicksum(r_y0_wag_hall[i,7]*y_0_hall[i,t] for i in I_hall)
                                + gp.quicksum(r_y1_wag_hall[i,7]*y_1_hall[i,t] for i in I_hall)
                                + gp.quicksum(r_y2_wag_hall[i,7]*y_2_hall[i,t] for i in I_hall))
                                / RA_wag_kt[7,t], name = 'Wagon_GHUIF_usage[' +str(t)+ ']')
con11_2_GHUIF = {}
for t in T:
    con11_2_GHUIF[t] = model.addGenConstrPWL(Frac_Wags_GHUIF_t[t], Cost_wags_GHUIF_t[t], Frac_Wags_vec, C_wags,
                                             name = 'GHUIF_cost[' +str(t)+ ']' )
con11_1_VWWG = {}
for t in T:
    con11_1_VWWG[t] = model.addConstr(Frac_Wags_VWWG_t[t] == (gp.quicksum(r_wagons_ijk_ship[i,j,20]*x_ship[i,j,u]
                                            for i in I_ship for j in J
                                            for u in range(max(0, int(t+1 - P_ij_ship[i,j] )), t+1))
                                + gp.quicksum(r_y0_wag_ship[i,20]*y_0_ship[i,t] for i in I_ship)
                                + gp.quicksum(r_y1_wag_ship[i,20]*y_1_ship[i,t] for i in I_ship)
                                + gp.quicksum(r_y2_wag_ship[i,20]*y_2_ship[i,t] for i in I_ship)
                                + gp.quicksum(r_wagons_ijk_train[i,j,20]*x_train[i,j,u]
                                            for i in I_train for j in J
                                            for u in range(max(0, int(t+1 - P_ij_train[i,j] )), t+1))
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                              + gp.quicksum(r_y0_wag_train[i,20]*y_0_train[i,t] for i in I_train)
                              + gp.quicksum(r_y1_wag_train[i,20]*y_1_train[i,t] for i in I_train)
                              + gp.quicksum(r_y2_wag_train[i,20]*y_2_train[i,t] for i in I_train)
                              + gp.quicksum(r_wagons_ijk_hall[i,j,20]*x_hall[i,j,u]
                                          for i in I_hall for j in J
                                          for u in range(max(0, int(t+1 - P_ij_hall[i,j] )), t+1))
                              + gp.quicksum(r_y0_wag_hall[i,20]*y_0_hall[i,t] for i in I_hall)
                              + gp.quicksum(r_y1_wag_hall[i,20]*y_1_hall[i,t] for i in I_hall)
                              + gp.quicksum(r_y2_wag_hall[i,20]*y_2_hall[i,t] for i in I_hall))
                              / RA_wag_kt[20,t], name = 'Wagon_VWWG_usage[' +str(t)+ ']')
con11_2_VWWG = {}
for t in T:
    con11_2_VWWG[t] = model.addGenConstrPWL(Frac_Wags_VWWG_t[t], Cost_wags_VWWG_t[t], Frac_Wags_vec, C_wags,
                                          name = 'VWWG_cost[' +str(t)+ ']' )
con11_1_SETJE = {}
for t in T:
    con11_1_SETJE[t] = model.addConstr(Frac_Wags_SETJE_t[t] == (gp.quicksum(r_wagons_ijk_ship[i,j,15]*x_ship[i,j,u]
                                          for i in I_ship for j in J
                                          for u in range(max(0, int(t+1 - P_ij_ship[i,j] )), t+1))
                              + gp.quicksum(r_y0_wag_ship[i,15]*y_0_ship[i,t] for i in I_ship)
                              + gp.quicksum(r_y1_wag_ship[i,15]*y_1_ship[i,t] for i in I_ship)
                              + gp.quicksum(r_y2_wag_ship[i,15]*y_2_ship[i,t] for i in I_ship)
                              + gp.quicksum(r_wagons_ijk_train[i,j,15]*x_train[i,j,u]
                                          for i in I_train for j in J
                                          for u in range(max(0, int(t+1 - P_ij_train[i,j] )), t+1))
                              + gp.quicksum(r_y0_wag_train[i,15]*y_0_train[i,t] for i in I_train)
                              + gp.quicksum(r_y1_wag_train[i,15]*y_1_train[i,t] for i in I_train)
                              + gp.quicksum(r_y2_wag_train[i,15]*y_2_train[i,t] for i in I_train)
                              + gp.quicksum(r_wagons_ijk_hall[i,j,15]*x_hall[i,j,u]
                                          for i in I_hall for j in J
                                          for u in range(max(0, int(t+1 - P_ij_hall[i,j] )), t+1))
                              + gp.quicksum(r_y0_wag_hall[i,15]*y_0_hall[i,t] for i in I_hall)
                              + gp.quicksum(r_y1_wag_hall[i,15]*y_1_hall[i,t] for i in I_hall)
                              + gp.quicksum(r_y2_wag_hall[i,15]*y_2_hall[i,t] for i in I_hall))
                              / RA_wag_kt[15,t], name = 'Wagon_SETJE_usage['  +str(t)+ ']')
con11_2_SETJE = {}
for t in T:
    con11_2_SETJE[t] = model.addGenConstrPWL(Frac_Wags_SETJE_t[t], Cost_wags_SETJE_t[t], Frac_Wags_vec, C_wags,
                                           name = 'SETJE_cost[' +str(t)+ ']' )
con12_1_WAW = {}
for t in T:
    con12_1_WAW[t] = model.addConstr(U_WAW_t[t] == (gp.quicksum(r_hPloeg_ijk_ship[i,j,1]*x_ship[i,j,u]
                                          for i in I_ship for j in J
                                          for u in range(max(0, int(t+1 - P_ij_ship[i,j] )), t+1))
                              + gp.quicksum(r_hPloeg_ijk_train[i,j,1]*x_train[i,j,u]
                                          for i in I_train for j in J
                                          for u in range(max(0, int(t+1 - P_ij_train[i,j] )), t+1))
                              + gp.quicksum(r_hPloeg_ijk_hall[i,j,1]*x_hall[i,j,u]
                                          for i in I_hall for j in J
                                          for u in range(max(0, int(t+1 - P_ij_hall[i,j] )), t+1))),
                              name = 'WAW_ploeg_usage_t[' +str(t)+ ']')
con12_2_WAW = {}
for hs in HS:
    con12_2_WAW[hs] = model.addGenConstrMax(U_WAW_hs[hs], [U_WAW_t[t]
                        for t in range(Hshift_vector[hs][0],Hshift_vector[hs][-1]+1)],
                                          name = 'Max_Hshift_WAW['+str(hs)+']')
con12_3_WAW = {}
for hs in HS:
    con12_3_WAW[hs] = model.addGenConstrPWL(U_WAW_hs[hs], Cost_WAW[hs], Num_WAW_vec, Costs_WAW,
                                          name = 'PWL_Costs_WAW[' +str(hs)+ ']' )
con12_1_CPR = {}
for t in T:
    con12_1_CPR[t] = model.addConstr(U_CPR_t[t] == (gp.quicksum(r_hPloeg_ijk_ship[i,j,2]*x_ship[i,j,u]
                                          for i in I_ship for j in J
```

```
                                                  for u in range(max(0, int(t+1 - P_ij_ship[i,j] )), t+1))
                                    + gp.quicksum(r_hPloeg_ijk_train[i,j,2]*x_train[i,j,u]
                                                  for i in I_train for j in J
                                                  for u in range(max(0, int(t+1 - P_ij_train[i,j] )), t+1))
                                    + gp.quicksum(r_hPloeg_ijk_hall[i,j,2]*x_hall[i,j,u]
                                                  for i in I_hall for j in J
                                                  for u in range(max(0, int(t+1 - P_ij_hall[i,j] )), t+1))),
                                    name = 'CPR_ploeg_usage_t[' +str(t)+ ']')
con12_2_CPR = {}
for hs in HS:
    con12_2_CPR[hs] = model.addGenConstrMax(U_CPR_hs[hs], [U_CPR_t[t]
                        for t in range(Hshift_vector[hs][0],Hshift_vector[hs][-1]+1)],
                                                  name = 'Max_Hshift_CPR['+str(hs)+']')
con12_3_CPR = {}
for hs in HS:
    con12_3_CPR[hs] = model.addGenConstrPWL(U_CPR_hs[hs], Cost_CPR[hs], Num_CPR_vec, Costs_CPR,
                                                  name = 'PWL_Costs_CPR[' +str(hs)+ ']' )
con12_1_CLUSTER_ZUID = {}
for t in T:
    con12_1_CLUSTER_ZUID[t] = model.addConstr(U_CLUSTER_ZUID_t[t] == (gp.quicksum(r_hPloeg_ijk_ship[i,j,3]*x_ship[i,j,u]
                                                  for i in I_ship for j in J
                                                  for u in range(max(0, int(t+1 - P_ij_ship[i,j] )), t+1))
                                    + gp.quicksum(r_hPloeg_ijk_train[i,j,3]*x_train[i,j,u]
                                                  for i in I_train for j in J
                                                  for u in range(max(0, int(t+1 - P_ij_train[i,j] )), t+1))
                                    + gp.quicksum(r_hPloeg_ijk_hall[i,j,3]*x_hall[i,j,u]
                                                  for i in I_hall for j in J
                                                  for u in range(max(0, int(t+1 - P_ij_hall[i,j] )), t+1))),
                                    name = 'CLUSTER_ZUID_ploeg_usage_t[' +str(t)+ ']')
con12_2_CLUSTER_ZUID = {}
for hs in HS:
    con12_2_CLUSTER_ZUID[hs] = model.addGenConstrMax(U_CLUSTER_ZUID_hs[hs], [U_CLUSTER_ZUID_t[t]
                        for t in range(Hshift_vector[hs][0],Hshift_vector[hs][-1]+1)],
                                                          name = 'Max_Hshift_CLUSTER_ZUID['+str(hs)+']')
con12_3_CLUSTER_ZUID = {}
for hs in HS:
    con12_3_CLUSTER_ZUID[hs] = model.addGenConstrPWL(U_CLUSTER_ZUID_hs[hs], Cost_CLUSTER_ZUID[hs],
                                                          Num_CLUSTER_ZUID_vec, Costs_CLUSTER_ZUID,
                                                          name = 'PWL_Costs_CLUSTER_ZUID[' +str(hs)+ ']' )
con12_1_CPP = {}
for t in T:
    con12_1_CPP[t] = model.addConstr(U_CPP_t[t] == (gp.quicksum(r_hPloeg_ijk_ship[i,j,4]*x_ship[i,j,u]
                                                  for i in I_ship for j in J
                                                  for u in range(max(0, int(t+1 - P_ij_ship[i,j] )), t+1))
                                    + gp.quicksum(r_hPloeg_ijk_train[i,j,4]*x_train[i,j,u]
                                                  for i in I_train for j in J
                                                  for u in range(max(0, int(t+1 - P_ij_train[i,j] )), t+1))
                                    + gp.quicksum(r_hPloeg_ijk_hall[i,j,4]*x_hall[i,j,u]
                                                  for i in I_hall for j in J
                                                  for u in range(max(0, int(t+1 - P_ij_hall[i,j] )), t+1))),
                                    name = 'CPP_ploeg_usage_t[' +str(t)+ ']')
con12_2_CPP = {}
for hs in HS:
    con12_2_CPP[hs] = model.addGenConstrMax(U_CPP_hs[hs], [U_CPP_t[t]
                        for t in range(Hshift_vector[hs][0],Hshift_vector[hs][-1]+1)],
                                                  name = 'Max_Hshift_CPP['+str(hs)+']')
con12_3_CPP = {}
for hs in HS:
    con12_3_CPP[hs] = model.addGenConstrPWL(U_CPP_hs[hs], Cost_CPP[hs], Num_CPP_vec, Costs_CPP,
                                                  name = 'PWL_Costs_CPP[' +str(hs)+ ']' )
con12_1_WB2 = {}
for t in T:
    con12_1_WB2[t] = model.addConstr(U_WB2_t[t] == (gp.quicksum(r_hPloeg_ijk_ship[i,j,5]*x_ship[i,j,u]
                                                  for i in I_ship for j in J
```

```
                                                for u in range(max(0, int(t+1 - P_ij_ship[i,j] )), t+1))
                                    + gp.quicksum(r_hPloeg_ijk_train[i,j,5]*x_train[i,j,u]
                                                for i in I_train for j in J
                                                for u in range(max(0, int(t+1 - P_ij_train[i,j] )), t+1))
                                    + gp.quicksum(r_hPloeg_ijk_hall[i,j,5]*x_hall[i,j,u]
                                                for i in I_hall for j in J
                                                for u in range(max(0, int(t+1 - P_ij_hall[i,j] )), t+1))),
                                    name = 'WB2_ploeg_usage_t[' +str(t)+ ']')
con12_2_WB2 = {}
for hs in HS:
    con12_2_WB2[hs] = model.addGenConstrMax(U_WB2_hs[hs], [U_WB2_t[t]
                        for t in range(Hshift_vector[hs][0],Hshift_vector[hs][-1]+1)],
                                                name = 'Max_Hshift_WB2['+str(hs)+']')
con12_3_WB2 = {}
for hs in HS:
    con12_3_WB2[hs] = model.addGenConstrPWL(U_WB2_hs[hs], Cost_WB2[hs], Num_WB2_vec, Costs_WB2,
                                                name = 'PWL_Costs_WB2[' +str(hs)+ ']' )
con12_1_KB2 = {}
for t in T:
    con12_1_KB2[t] = model.addConstr(U_KB2_t[t] == (gp.quicksum(r_hPloeg_ijk_ship[i,j,6]*x_ship[i,j,u]
                                                for i in I_ship for j in J
                                                for u in range(max(0, int(t+1 - P_ij_ship[i,j] )), t+1))
                                    + gp.quicksum(r_hPloeg_ijk_train[i,j,6]*x_train[i,j,u]
                                                for i in I_train for j in J
                                                for u in range(max(0, int(t+1 - P_ij_train[i,j] )), t+1))
                                    + gp.quicksum(r_hPloeg_ijk_hall[i,j,6]*x_hall[i,j,u]
                                                for i in I_hall for j in J
                                                for u in range(max(0, int(t+1 - P_ij_hall[i,j] )), t+1))),
                                    name = 'KB2_ploeg_usage_t[' +str(t)+ ']')
con12_2_KB2 = {}
for hs in HS:
    con12_2_KB2[hs] = model.addGenConstrMax(U_KB2_hs[hs], [U_KB2_t[t]
                        for t in range(Hshift_vector[hs][0],Hshift_vector[hs][-1]+1)],
                                                name = 'Max_Hshift_KB2['+str(hs)+']')
con12_3_KB2 = {}
for hs in HS:
    con12_3_KB2[hs] = model.addGenConstrPWL(U_KB2_hs[hs], Cost_KB2[hs], Num_KB2_vec, Costs_KB2,
                                                name = 'PWL_Costs_KB2[' +str(hs)+ ']' )
con12_1_AOV = {}
for t in T:
    con12_1_AOV[t] = model.addConstr(U_AOV_t[t] == (gp.quicksum(r_hPloeg_ijk_ship[i,j,7]*x_ship[i,j,u]
                                                for i in I_ship for j in J
                                                for u in range(max(0, int(t+1 - P_ij_ship[i,j] )), t+1))
                                    + gp.quicksum(r_hPloeg_ijk_train[i,j,7]*x_train[i,j,u]
                                                for i in I_train for j in J
                                                for u in range(max(0, int(t+1 - P_ij_train[i,j] )), t+1))
                                    + gp.quicksum(r_hPloeg_ijk_hall[i,j,7]*x_hall[i,j,u]
                                                for i in I_hall for j in J
                                                for u in range(max(0, int(t+1 - P_ij_hall[i,j] )), t+1))),
                                    name = 'AOV_ploeg_usage_t[' +str(t)+ ']')
con12_2_AOV = {}
for hs in HS:
    con12_2_AOV[hs] = model.addGenConstrMax(U_AOV_hs[hs], [U_AOV_t[t]
                        for t in range(Hshift_vector[hs][0],Hshift_vector[hs][-1]+1)],
                                                name = 'Max_Hshift_AOV['+str(hs)+']')
con12_3_AOV = {}
for hs in HS:
    con12_3_AOV[hs] = model.addGenConstrPWL(U_AOV_hs[hs], Cost_AOV[hs], Num_AOV_vec, Costs_AOV,
                                                name = 'PWL_Costs_AOV[' +str(hs)+ ']' )

# %% ----------------- Objective Function -----------------

model.ModelSense = GRB.MINIMIZE

```

```
model.setObjectiveN(gp.quicksum(Cost_locs[s] for s in S), 1, weight=weight_Locs,
                    name = 'Loco_costs')
model.setObjectiveN(gp.quicksum(Cost_wags_PLWG_t[t] for t in T), 2, weight=weight_Locs,
                    name = 'PLWG_usage')
model.setObjectiveN(gp.quicksum(Cost_wags_GHUIF_t[t] for t in T), 3, weight=weight_Locs,
                    name = 'GHUIF_usage')
model.setObjectiveN(gp.quicksum(Cost_wags_VWWG_t[t] for t in T), 4, weight=weight_Locs,
                    name = 'VWWG_usage')
model.setObjectiveN(gp.quicksum(Cost_wags_SETJE_t[t] for t in T), 5, weight=weight_Locs,
                    name = 'SETJE_usage')
model.setObjectiveN(gp.quicksum(Cost_WAW[hs] for hs in HS), 6, weight=weight_Locs,
                    name = 'Ploeg_WAW_costs')
model.setObjectiveN(gp.quicksum(Cost_CPR[hs] for hs in HS), 7, weight=weight_Locs,
                    name = 'Ploeg_CPR_costs')
model.setObjectiveN(gp.quicksum(Cost_CLUSTER_ZUID[hs] for hs in HS), 8, weight=weight_Locs,
                    name = 'Ploeg_CLUSTER_ZUID_costs')
model.setObjectiveN(gp.quicksum(Cost_CPP[hs] for hs in HS), 9, weight=weight_Locs,
                    name = 'Ploeg_CPP_costs')
model.setObjectiveN(gp.quicksum(Cost_WB2[hs] for hs in HS), 10, weight=weight_Locs,
                    name = 'Ploeg_WB2_costs')
model.setObjectiveN(gp.quicksum(Cost_KB2[hs] for hs in HS), 11, weight=weight_Locs,
                    name = 'Ploeg_KB2_costs')
model.setObjectiveN(gp.quicksum(Cost_AOV[hs] for hs in HS), 12, weight=weight_Locs,
                    name = 'Ploeg_AOV_costs')

# %% ----------------- Solving -----------------
model.setParam ('OutputFlag', True)
model.setParam ("MIPFocus" , 0)
model.setParam ('MIPGap', .10)
model.setParam ('Presolve', 2)
model.setParam ('Cuts', 2)
model.setParam ('TimeLimit', 60 * 60 * 5)
model.update()
model.optimize()
```

F

Results: Tables with KPI Scores

Data set: August 21st

Table F.1: Locomotives per shift - August 21st - original

Shift	Locomotives used	Costs
0	14	605
1	8	125
2	6	45
3	3	0
Total	31	775

Table F.2: Locomotives per shift - August 21st - new

Shift	Locomotives used	Costs
0	3	0
1	3	0
2	3	0
3	3	0
Total	12	0

Table F.3: Wagons costs - August 21st - original

Wagon type	Costs
PLWG	0
VWWG	0
GHUIF	0
SETJE	167
Total	167

Table F.4: Wagons costs - August 21st - new

Wagon type	Costs
PLWG	0
VWWG	0
GHUIF	0
SETJE	0
Total	0

Table F.5: Workforce per half shift - August 21st - original

Half shift	ZD1 WAW Amount used	ZD1 WAW Costs	CPR Amount used	CPR Costs	Cluster Zuid Amount used	Cluster Zuid Costs	TSP Amount used	TSP Costs	Cluster Midden Amount used	Cluster Midden Costs	Cluster Noord Amount used	Cluster Noord Costs
0	0	0	5	80	0	0	5	80	5	80	3	20
1	0	0	1	0	0	0	5	80	4	45	3	20
2	0	0	1	0	2	5	3	20	5	80	2	5
3	0	0	2	5	1	0	0	0	4	45	2	5
4	0	0	2	5	1	0	0	0	2	5	1	0
5	0	0	2	5	2	5	0	0	2	5	4	45
6	0	0	1	0	1	0	1	0	1	0	1	0
7	0	0	0	0	1	0	1	0	0	0	0	0
Total	0	0	14	95	8	10	15	180	23	260	16	95

Table F.6: Workforce per half shift - August 21st - new

Half shift	ZD1 WAW Amount used	ZD1 WAW Costs	CPR Amount used	CPR Costs	Cluster Zuid Amount used	Cluster Zuid Costs	TSP Amount used	TSP Costs	Cluster Midden Amount used	Cluster Midden Costs	Cluster Noord Amount used	Cluster Noord Costs
0	0	0	1	0	1	0	1	0	1	0	1	0
1	0	0	1	0	1	0	1	0	1	0	1	0
2	0	0	1	0	1	0	1	0	1	0	1	0
3	0	0	1	0	1	0	1	0	2	5	1	0
4	0	0	1	0	1	0	1	0	1	0	1	0
5	0	0	0	0	1	0	1	0	1	0	1	0
6	0	0	1	0	1	0	0	0	1	0	1	0
7	0	0	1	0	1	0	1	0	2	5	1	0
Total	0	0	7	0	8	0	7	0	10	10	8	0

Data set: August 23rd

Table F.7: Locomotives per shift - August 23rd - original

Shift	Locomotives used	Costs
0	18	1125
1	9	180
2	7	80
3	3	0
Total	37	1385

Table F.8: Locomotives per shift - August 23rd - new

Shift	Locomotives used	Costs
0	3	0
1	4	5
2	4	5
3	4	5
Total	15	15

Table F.9: Wagons costs - August 23rd - original

Wagon type	Costs
PLWG	0
VWWG	0
GHUIF	0
SETJE	500
Total	500

Table F.10: Wagons costs - August 23rd - new

Wagon type	Costs
PLWG	0
VWWG	0
GHUIF	0
SETJE	60
Total	60

Table F.11: Workforce per half shift - August 23rd - original

Half shift	ZD1 WAW Amount used	ZD1 WAW Costs	CPR Amount used	CPR Costs	Cluster Zuid Amount used	Cluster Zuid Costs	TSP Amount used	TSP Costs	Cluster Midden Amount used	Cluster Midden Costs	Cluster Noord Amount used	Cluster Noord Costs
0	0	0	3	20	4	45	5	80	9	320	3	20
1	0	0	2	5	2	5	5	80	2	5	3	20
2	1	0	1	0	1	0	0	0	4	45	2	5
3	1	0	2	5	1	0	2	5	5	80	1	0
4	0	0	1	0	1	0	1	0	5	80	1	0
5	0	0	0	0	1	0	1	0	4	45	2	5
6	0	0	1	0	0	0	2	5	2	5	0	0
7	0	0	0	0	0	0	1	0	0	0	0	0
Total	2	0	10	30	10	50	17	170	31	580	12	50

Table F.12: Workforce per half shift - August 23rd - new

Half shift	ZD1 WAW Amount used	ZD1 WAW Costs	CPR Amount used	CPR Costs	Cluster Zuid Amount used	Cluster Zuid Costs	TSP Amount used	TSP Costs	Cluster Midden Amount used	Cluster Midden Costs	Cluster Noord Amount used	Cluster Noord Costs
0	0	0	0	0	1	0	1	0	2	5	1	0
1	0	0	1	0	1	0	1	0	2	5	1	0
2	0	0	1	0	0	0	1	0	2	5	1	0
3	0	0	1	0	0	0	2	5	2	5	0	0
4	1	0	1	0	1	0	1	0	2	5	1	0
5	1	0	1	0	1	0	1	0	2	5	1	0
6	0	0	1	0	1	0	1	0	2	5	1	0
7	0	0	1	0	1	0	1	0	2	5	1	0
Total	2	0	7	0	6	0	9	5	16	40	7	0

Data set: August 25th

Table F.13: Locomotives per shift - August 25th - original

Shift	Locomotives used	Costs
0	14	605
1	8	125
2	5	20
3	3	0
Total	30	750

Table F.14: Locomotives per shift - August 25th - new

Shift	Locomotives used	Costs
0	4	5
1	4	5
2	4	5
3	3	0
Total	15	15

Table F.15: Wagons costs - August 25th - original

Wagon type	Costs
PLWG	0
VWWG	0
GHUIF	0
SETJE	60
Total	60

Table F.16: Wagons costs - August 25th - new

Wagon type	Costs
PLWG	0
VWWG	0
GHUIF	0
SETJE	0
Total	0

Table F.17: Workforce per half shift - August 25th - original

Half shift	ZD1 WAW Amount used	ZD1 WAW Costs	CPR Amount used	CPR Costs	Cluster Zuid Amount used	Cluster Zuid Costs	TSP Amount used	TSP Costs	Cluster Midden Amount used	Cluster Midden Costs	Cluster Noord Amount used	Cluster Noord Costs
0	1	0	4	45	1	0	4	45	7	180	2	0
1	1	0	1	0	2	5	4	45	4	45	3	0
2	0	0	2	5	2	5	1	0	5	80	3	0
3	1	0	0	0	0	0	0	0	3	20	1	0
4	1	0	0	0	2	5	2	5	4	45	1	0
5	1	0	0	0	1	0	1	0	2	5	0	0
6	2	5	0	0	0	0	2	5	0	0	0	0
7	1	0	0	0	0	0	0	0	0	0	0	0
Total	8	5	7	50	8	15	14	100	25	375	10	0

Table F.18: Workforce per half shift - August 25th - new

Half shift	ZD1 WAW Amount used	ZD1 WAW Costs	CPR Amount used	CPR Costs	Cluster Zuid Amount used	Cluster Zuid Costs	TSP Amount used	TSP Costs	Cluster Midden Amount used	Cluster Midden Costs	Cluster Noord Amount used	Cluster Noord Costs
0	0	0	1	0	0	0	1	0	1	0	1	0
1	0	0	1	0	1	0	1	0	2	5	1	0
2	1	0	1	0	1	0	2	5	2	5	1	0
3	1	0	1	0	1	0	1	0	2	5	1	0
4	1	0	0	0	1	0	1	0	2	5	1	0
5	2	5	1	0	1	0	1	0	2	5	1	0
6	0	0	0	0	1	0	1	0	2	5	1	0
7	0	0	0	0	0	0	1	0	2	5	1	0
Total	5	5	5	0	6	0	9	5	15	35	8	0

Results Scenario 1 - Tables

Table F.19: Locomotives per shift - Scenario 1

Shift	Locomotives used	Costs
0	3	0
1	5	20
2	4	5
3	4	5
Total	16	30

Table F.20: Locomotives per shift - Base results

Shift	Locomotives used	Costs
0	3	0
1	4	5
2	4	5
3	4	5
Total	15	15

Table F.21: Wagons costs - Scenario 1

Wagon type	Costs
PLWG	0
VWWG	0
GHUIF	0
SETJE	60
Total	60

Table F.22: Wagons costs - Base results

Wagon type	Costs
PLWG	0
VWWG	0
GHUIF	0
SETJE	60
Total	60

Table F.23: Workforce per half shift - Scenario 1

Half shift	ZD1 WAW		CPR		Cluster Zuid		TSP		Cluster Midden		Cluster Noord	
	Amount used	Costs	Amount used	Costs	Amount used	Costs	Amount used	Costs	Amount used	Costs	Amount used	Costs
0	0	0	1	0	1	0	1	0	2	5	0	0
1	0	0	1	0	1	0	1	0	2	5	1	0
2	1	0	1	0	1	0	1	0	2	5	1	0
3	1	0	1	0	0	0	1	0	2	5	1	0
4	0	0	1	0	1	0	2	5	3	20	1	0
5	1	0	1	0	1	0	1	0	2	5	1	0
6	0	0	1	0	1	0	2	5	2	5	1	0
7	0	0	1	0	0	0	1	0	2	5	1	0
Total	3	0	8	0	6	0	10	10	17	55	7	0

Table F.24: Workforce per half shift - Base results

Half shift	ZD1 WAW		CPR		Cluster Zuid		TSP		Cluster Midden		Cluster Noord	
	Amount used	Costs	Amount used	Costs	Amount used	Costs	Amount used	Costs	Amount used	Costs	Amount used	Costs
0	0	0	0	0	1	0	1	0	2	5	1	0
1	0	0	1	0	1	0	1	0	2	5	1	0
2	0	0	1	0	0	0	1	0	2	5	1	0
3	0	0	1	0	0	0	2	5	2	5	0	0
4	1	0	1	0	1	0	1	0	2	5	1	0
5	1	0	1	0	1	0	1	0	2	5	1	0
6	0	0	1	0	1	0	1	0	2	5	1	0
7	0	0	1	0	1	0	1	0	2	5	1	0
Total	2	0	7	0	6	0	9	5	16	40	7	0

Results Scenario 2 - Tables

Table F.25: Locomotives per shift - Scenario 2

Shift	Locomotives used	Costs
0	4	5
1	4	5
2	4	5
3	4	5
Total	16	20

Table F.26: Locomotives per shift - Base results

Shift	Locomotives used	Costs
0	3	0
1	4	5
2	4	5
3	4	5
Total	15	15

Table F.27: Wagons costs - Scenario 2

Wagon type	Costs
PLWG	0
VWWG	0
GHUIF	33
SETJE	60
Total	93

Table F.28: Wagons costs - Base results

Wagon type	Costs
PLWG	0
VWWG	0
GHUIF	0
SETJE	60
Total	60

Table F.29: Workforce per half shift - Scenario 2

Half shift	ZD1 WAW Amount used	ZD1 WAW Costs	CPR Amount used	CPR Costs	Cluster Zuid Amount used	Cluster Zuid Costs	TSP Amount used	TSP Costs	Cluster Midden Amount used	Cluster Midden Costs	Cluster Noord Amount used	Cluster Noord Costs
0	0	0	1	0	1	0	1	0	2	5	0	0
1	0	0	1	0	1	0	1	0	2	5	1	0
2	0	0	1	0	1	0	1	0	2	5	1	0
3	1	0	0	0	1	0	2	5	2	5	1	0
4	1	0	0	0	1	0	1	0	2	5	1	0
5	1	0	1	0	1	0	1	0	2	5	1	0
6	0	0	1	0	0	0	1	0	2	5	1	0
7	0	0	1	0	1	0	1	0	2	5	1	0
Total	3	0	6	0	7	0	9	5	16	40	7	0

Table F.30: Workforce per half shift - Base results

Half shift	ZD1 WAW Amount used	ZD1 WAW Costs	CPR Amount used	CPR Costs	Cluster Zuid Amount used	Cluster Zuid Costs	TSP Amount used	TSP Costs	Cluster Midden Amount used	Cluster Midden Costs	Cluster Noord Amount used	Cluster Noord Costs
0	0	0	0	0	1	0	1	0	2	5	1	0
1	0	0	1	0	1	0	1	0	2	5	1	0
2	0	0	1	0	0	0	1	0	2	5	1	0
3	0	0	1	0	0	0	2	5	2	5	0	0
4	1	0	1	0	1	0	1	0	2	5	1	0
5	1	0	1	0	1	0	1	0	2	5	1	0
6	0	0	1	0	1	0	1	0	2	5	1	0
7	0	0	1	0	1	0	1	0	2	5	1	0
Total	2	0	7	0	6	0	9	5	16	40	7	0

G

Results: Quantitative graphs

Data set: August 21st

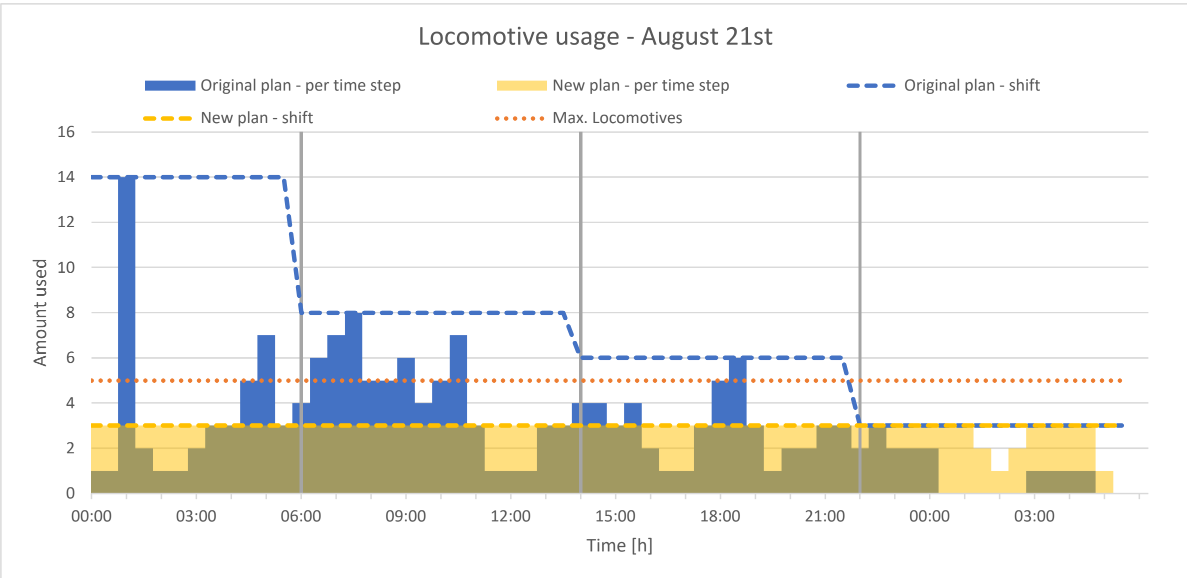
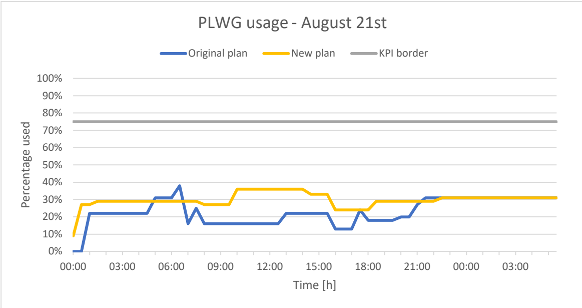
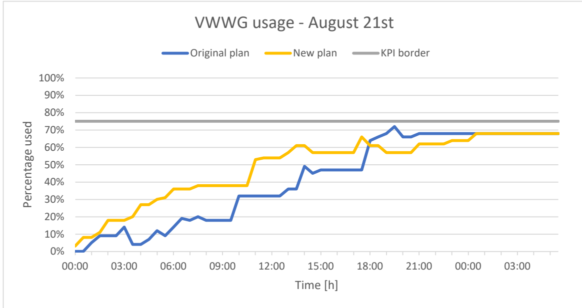


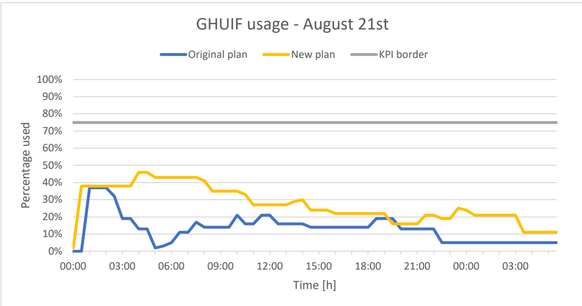
Figure G.1: Locomotive usage - August 21st



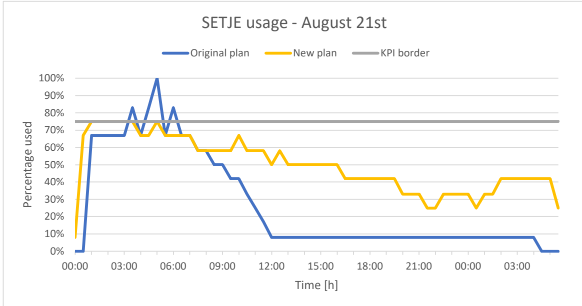
(a) PLWG usage - August 21st



(b) VWWG usage - August 21st

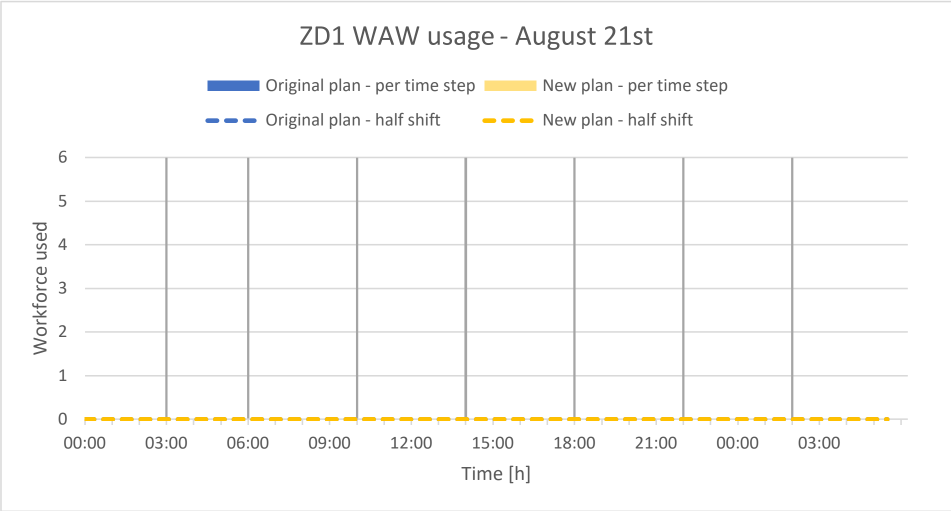


(c) GHUIF usage - August 21st

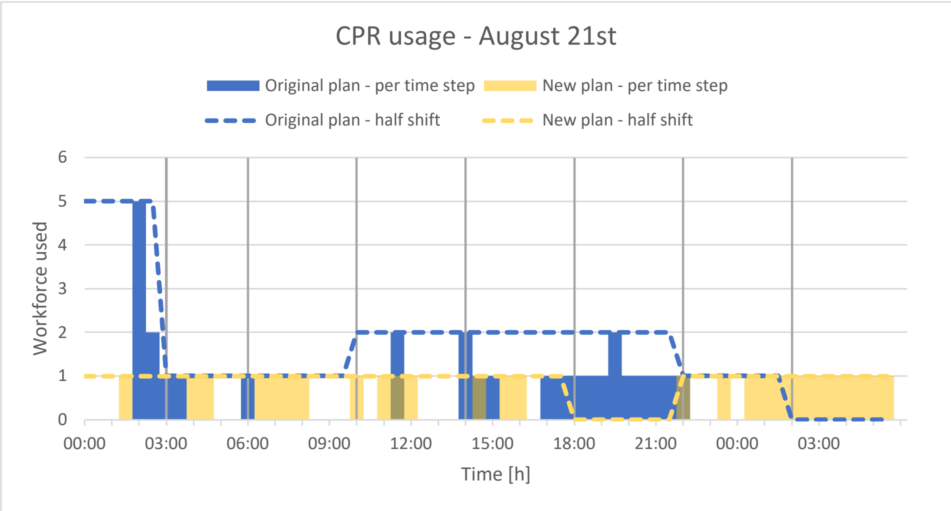


(d) SETJE usage - August 21st

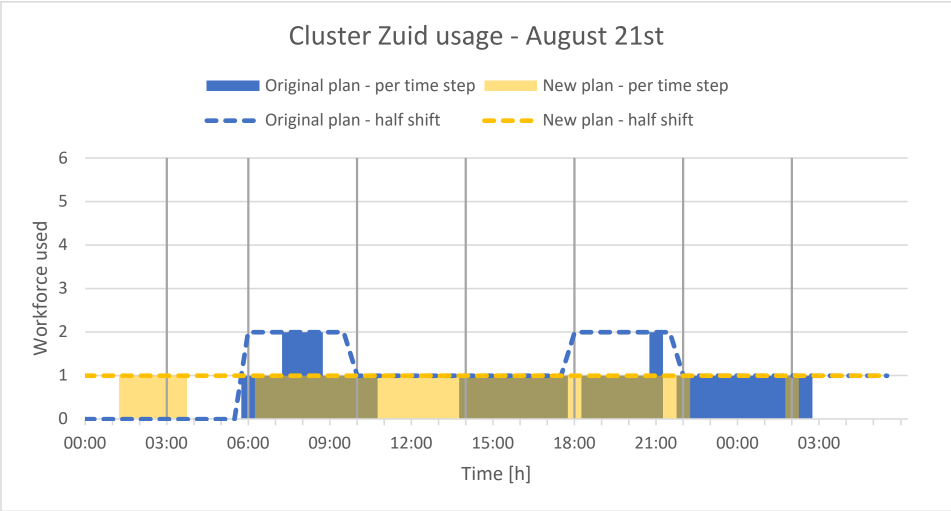
Figure G.2: Wagon usage per type - August 21st



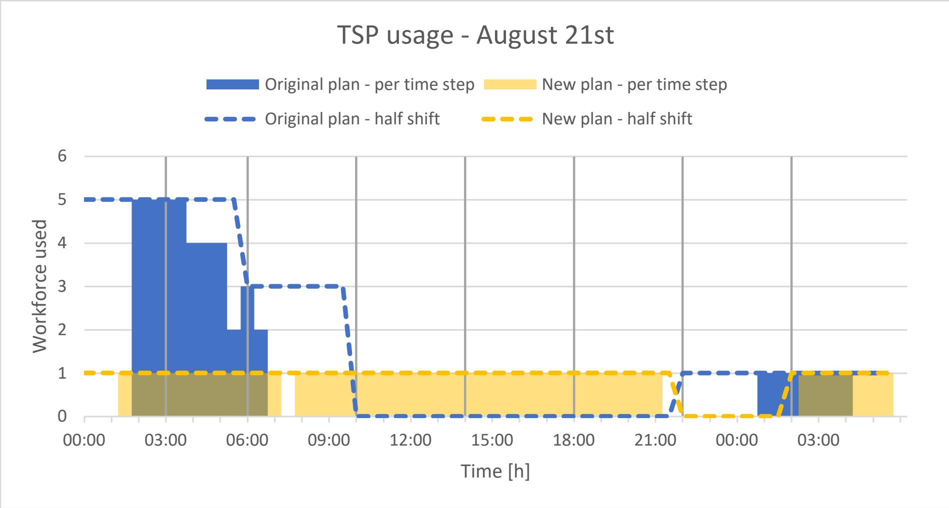
(a) Workforce WAW cluster usage - August 21st



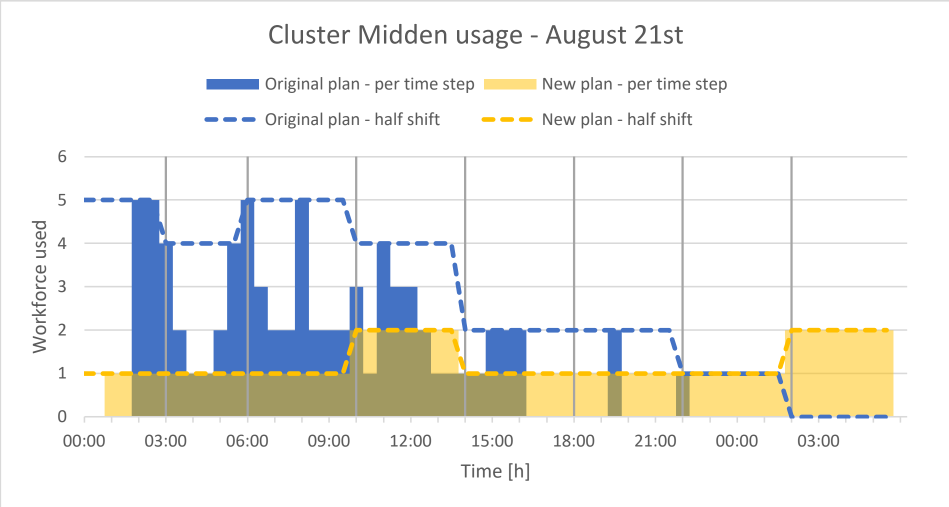
(b) Workforce CPR cluster usage - August 21st



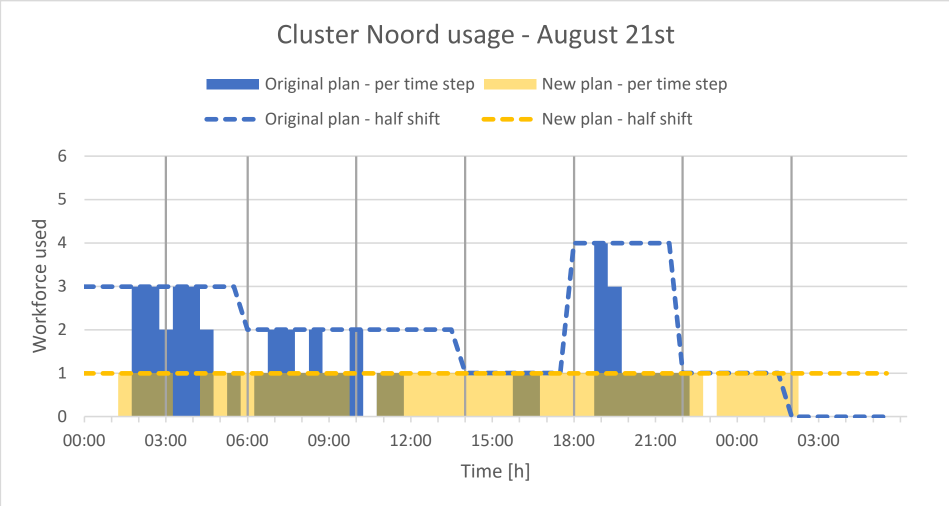
(c) Workforce Cluster Zuid usage - August 21st



(d) Workforce TSP cluster usage - August 21st



(e) Workforce Cluster Midden usage - August 21st



(f) Workforce Cluster Noord usage - August 21st

Figure G.3: Workforce usage per cluster - August 21st

Data set: August 23rd

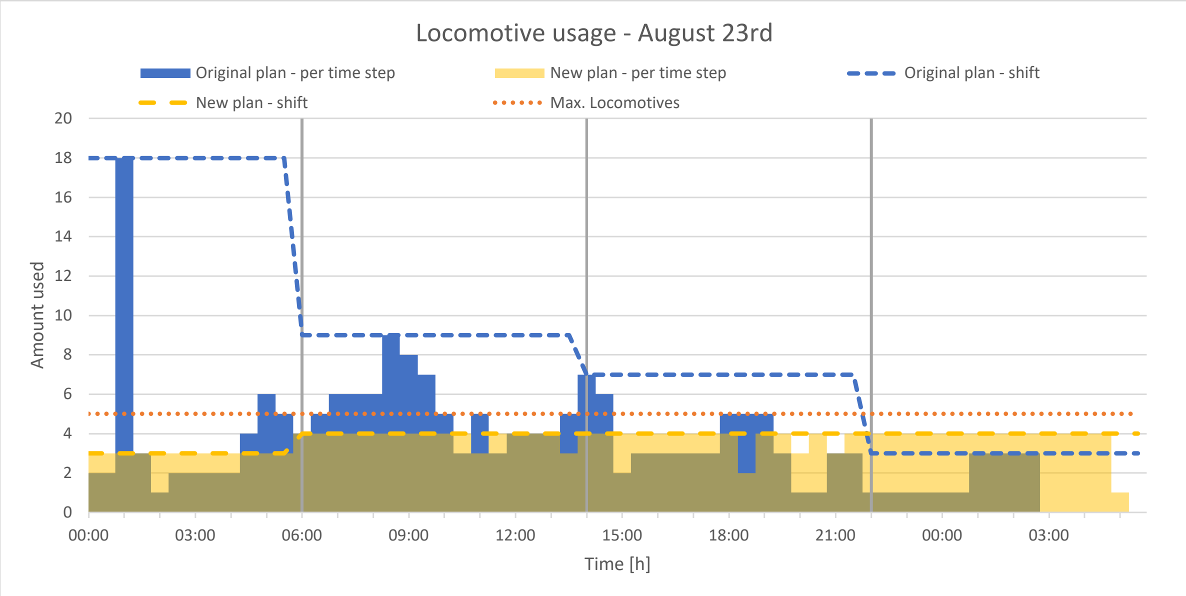
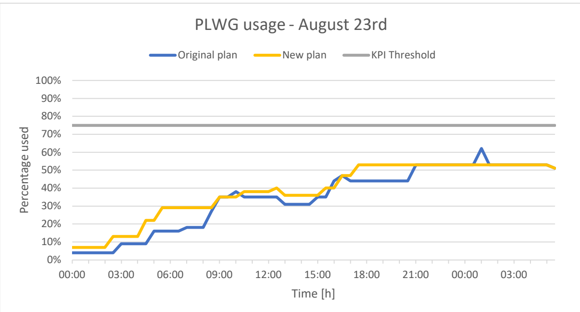
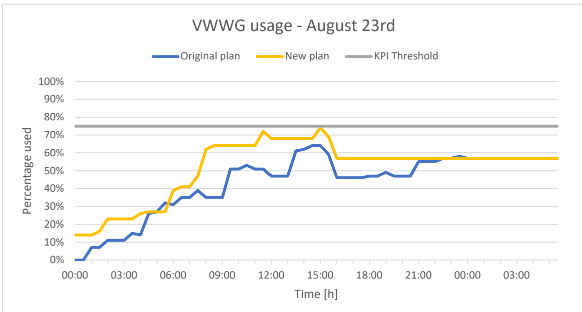


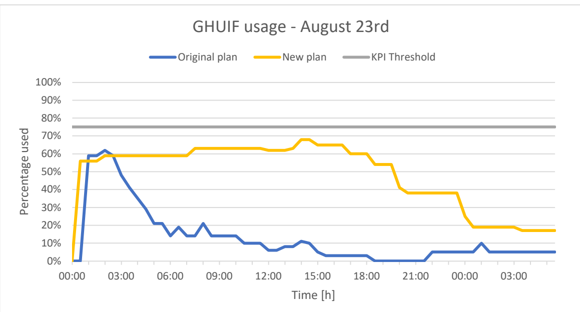
Figure G.4: Locomotive usage - August 23rd



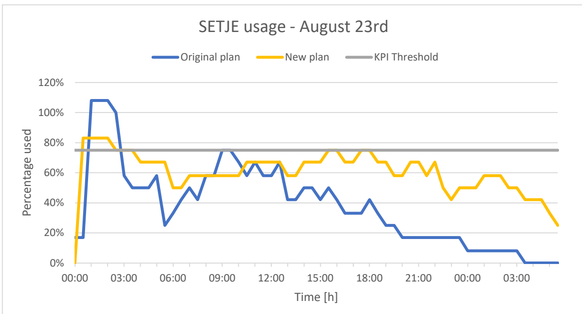
(a) PLWG usage - August 23rd



(b) VWWG usage - August 23rd

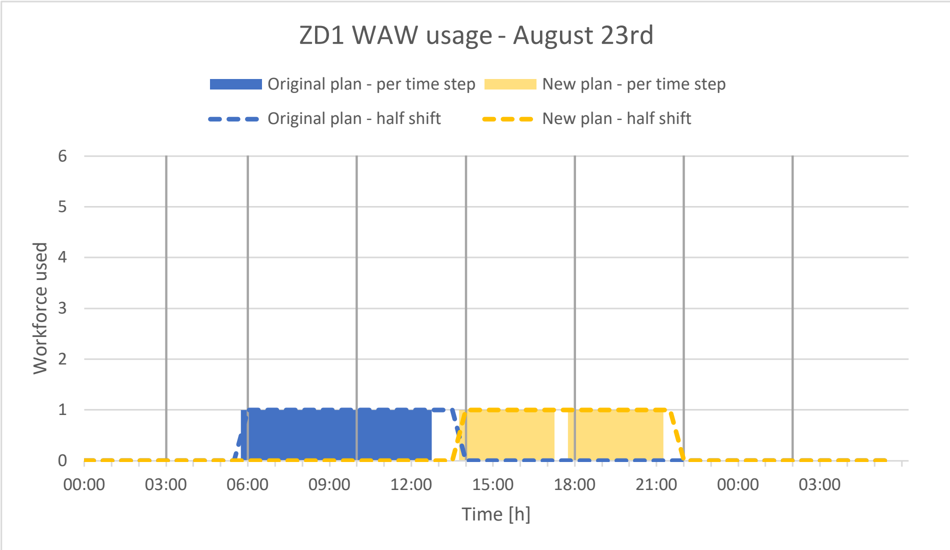


(c) GHUIF usage - August 23rd

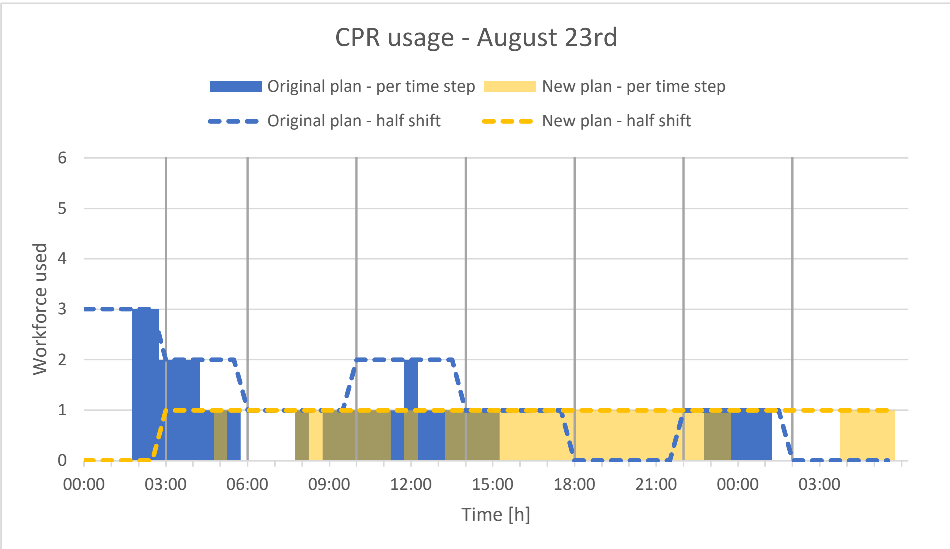


(d) SETJE usage - August 23rd

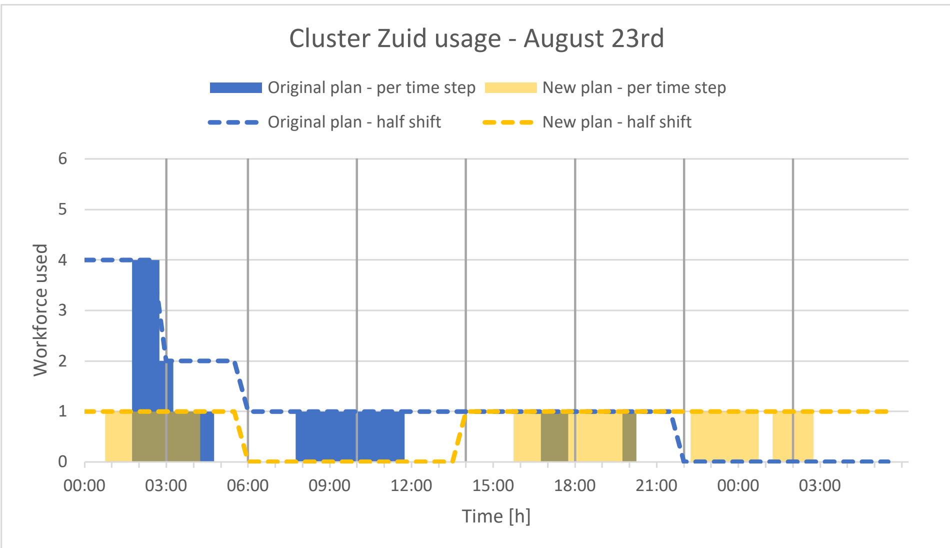
Figure G.5: Wagon usage per type - August 23rd



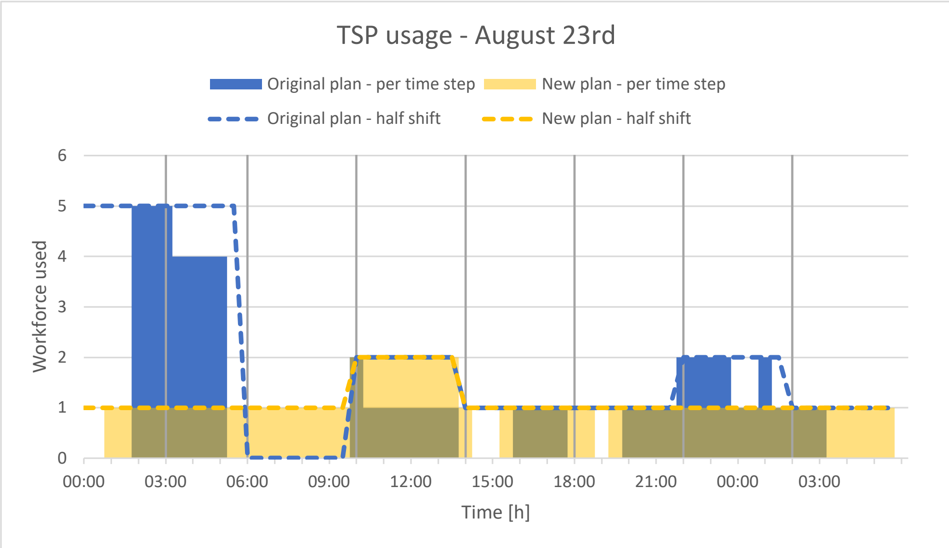
(a) Workforce WAW cluster usage - August 23rd



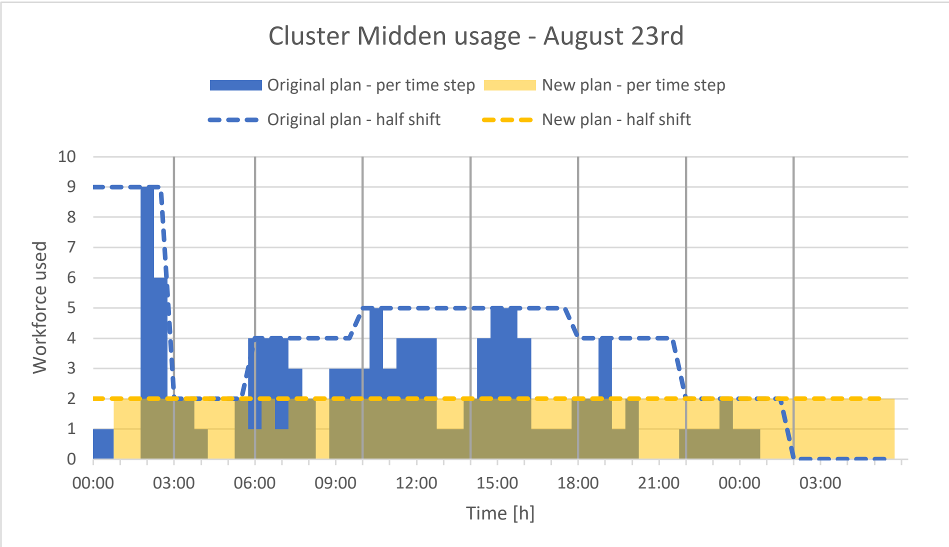
(b) Workforce CPR cluster usage - August 23rd



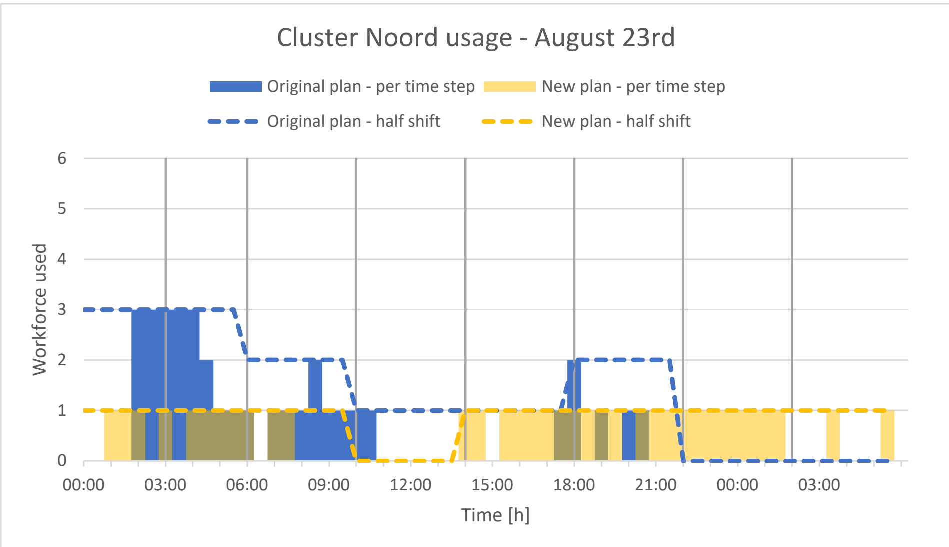
(c) Workforce Cluster Zuid usage - August 23rd



(d) Workforce TSP cluster usage - August 23rd



(e) Workforce Cluster Midden usage - August 23rd



(f) Workforce Cluster Noord usage - August 23rd

Figure G.6: Workforce usage per cluster - August 23rd

Data set: August 25th

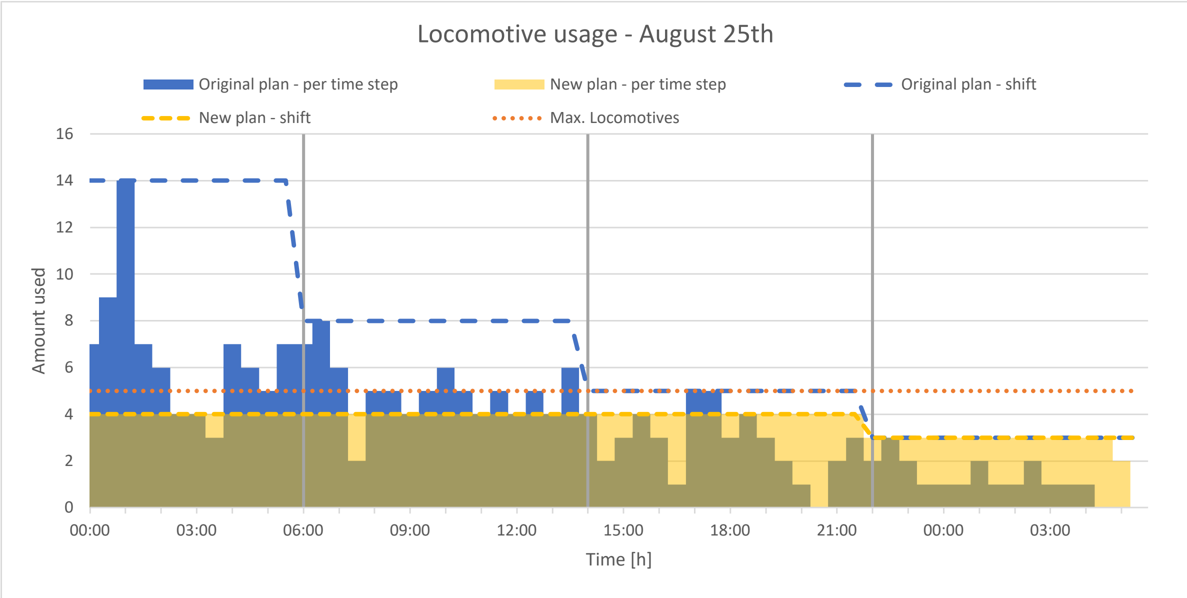
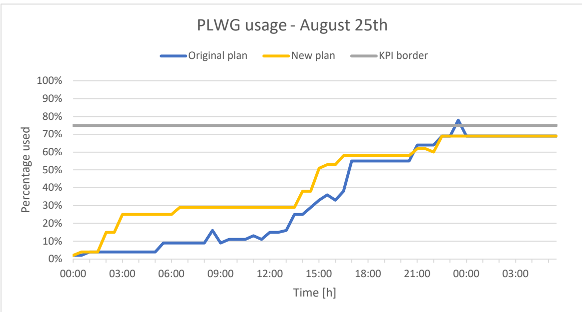
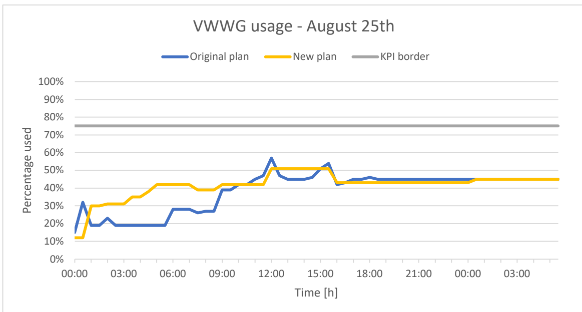


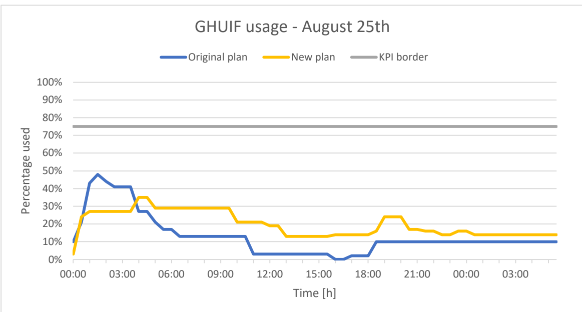
Figure G.7: Locomotive usage - August 25th



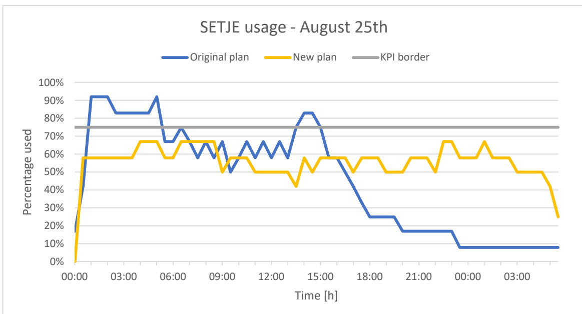
(a) PLWG usage - August 25th



(b) VWWG usage - August 25th

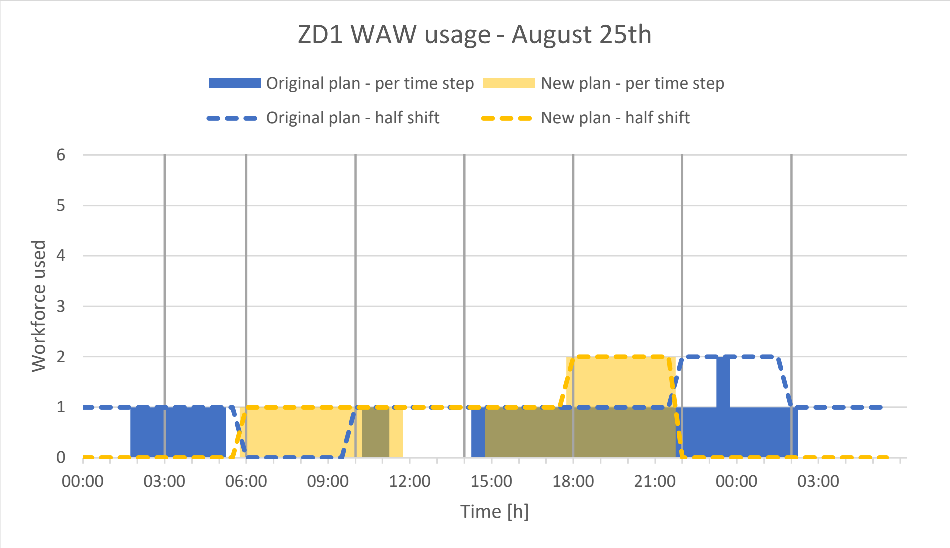


(c) GHUIF usage - August 25th

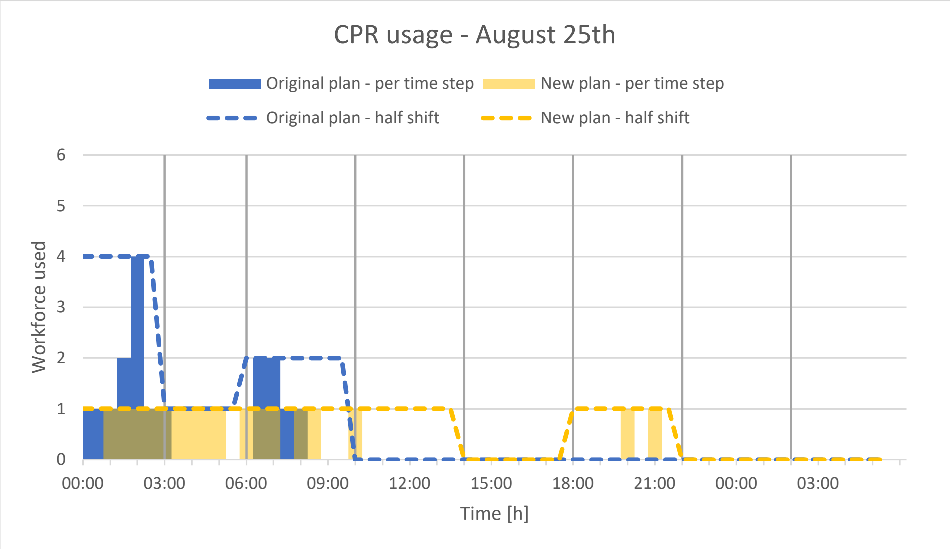


(d) SETJE usage - August 25th

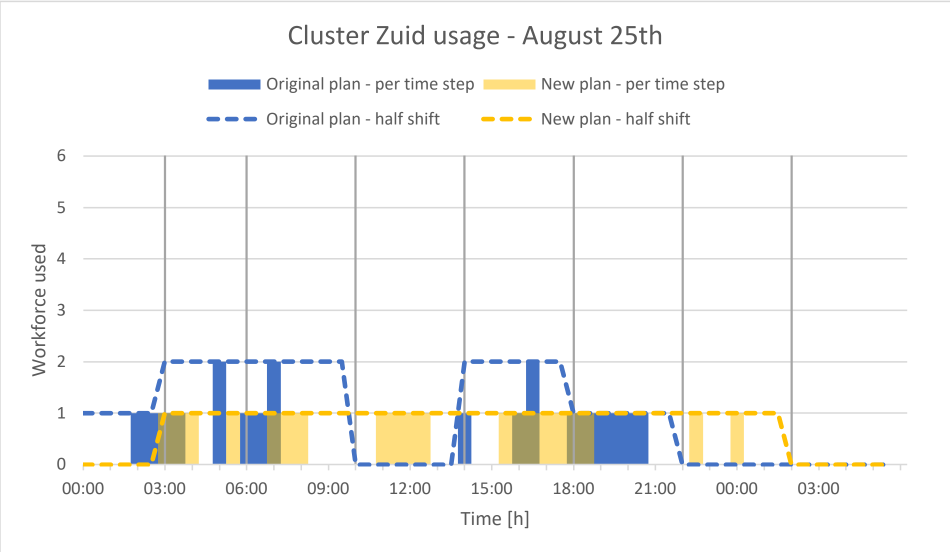
Figure G.8: Wagon usage per type - August 25th



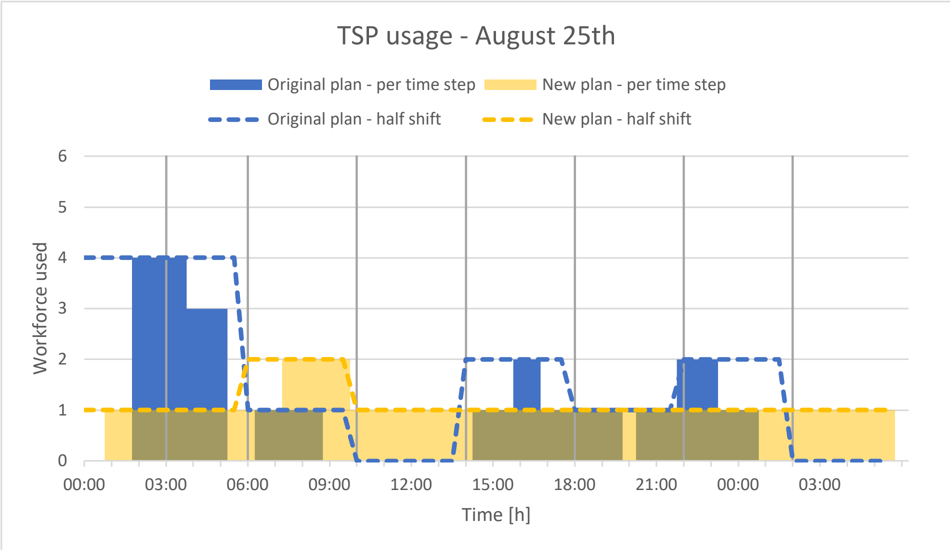
(a) Workforce WAW cluster usage - August 25th



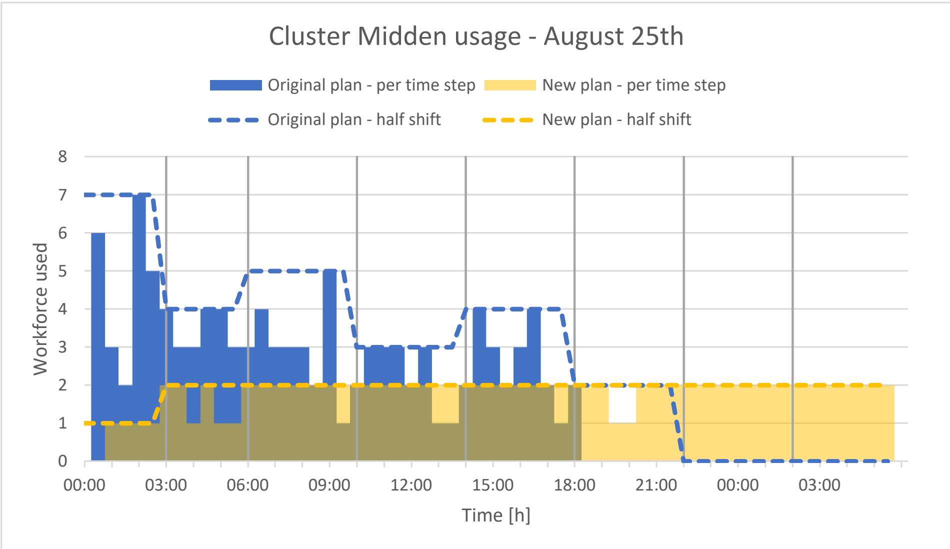
(b) Workforce CPR cluster usage - August 25th



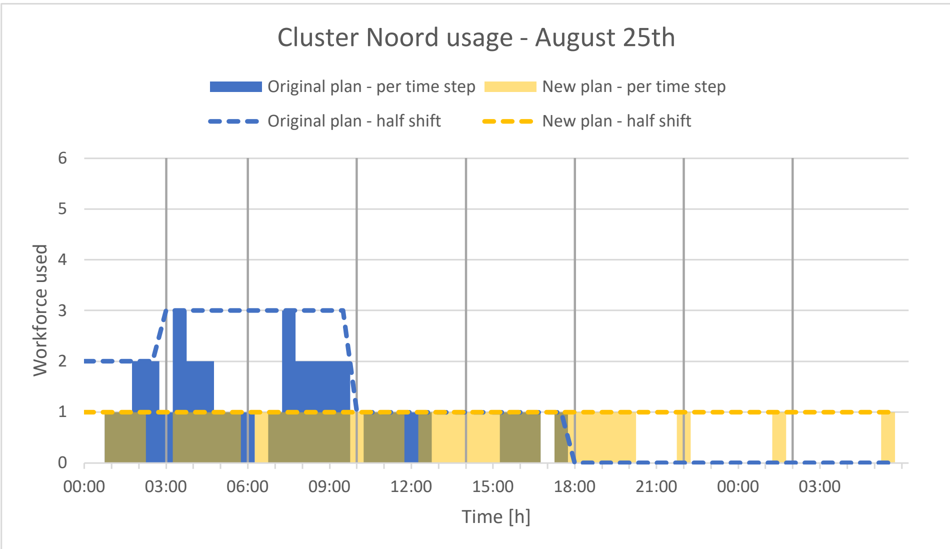
(c) Workforce Cluster Zuid usage - August 25th



(d) Workforce TSP cluster usage - August 25th



(e) Workforce Cluster Midden usage - August 25th



(f) Workforce Cluster Noord usage - August 25th

Figure G.9: Workforce usage per cluster - August 25th

Results Scenario 1 - Graphs

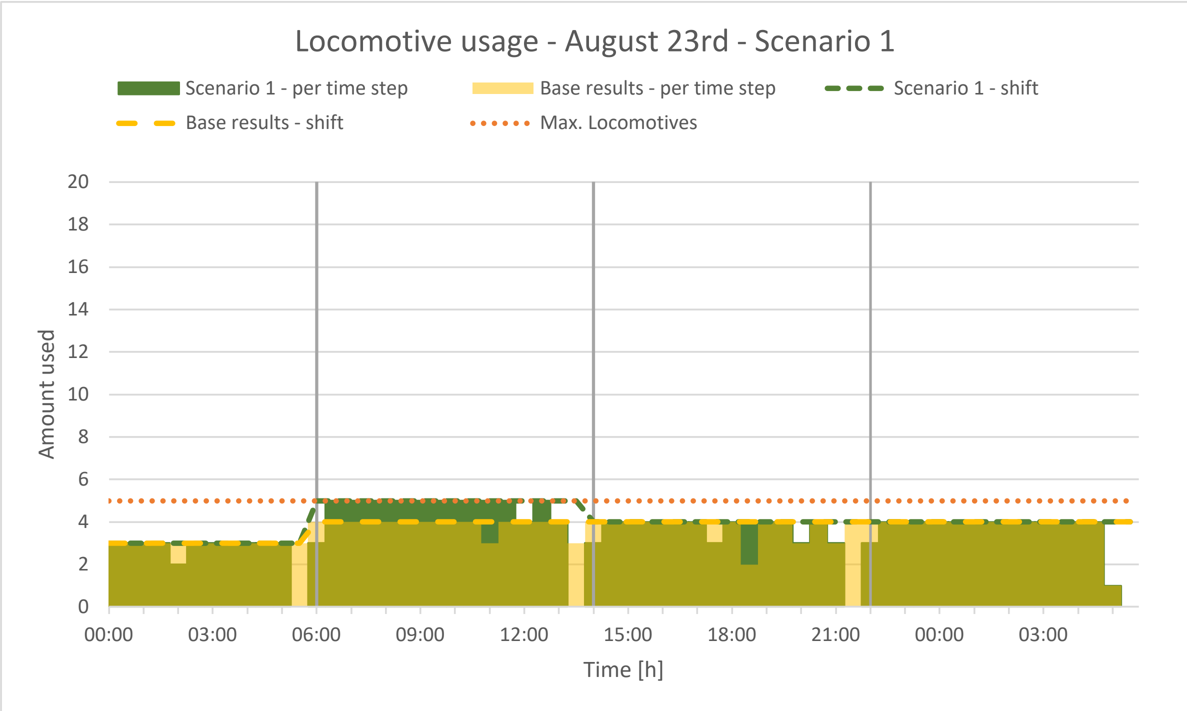
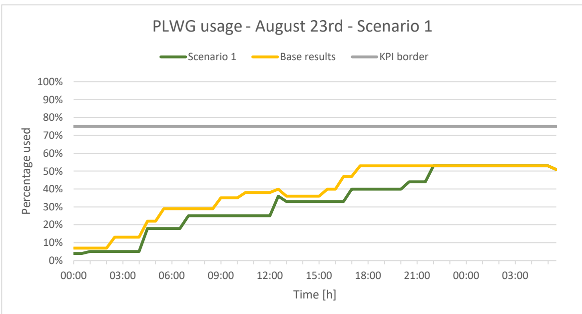
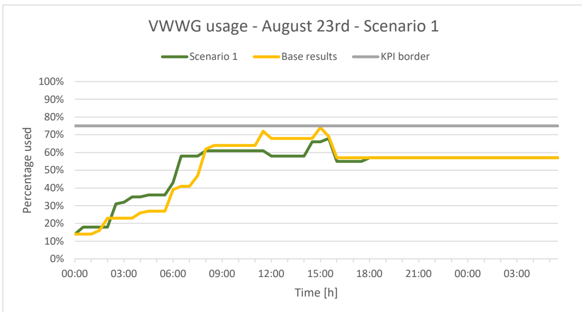


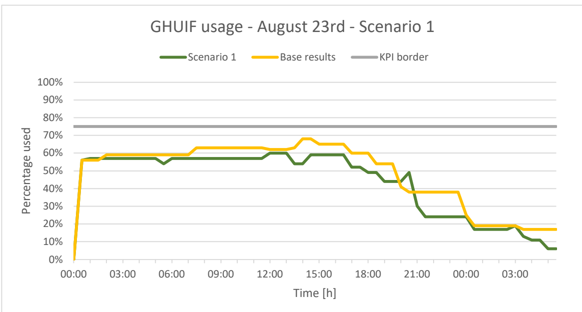
Figure G.10: Locomotive usage - Scenario 1 - August 25th



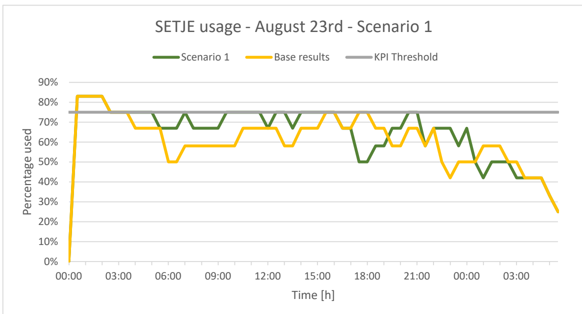
(a) PLWG usage - Scenario 1 - August 23rd



(b) VWWG usage - Scenario 1 - August 23rd

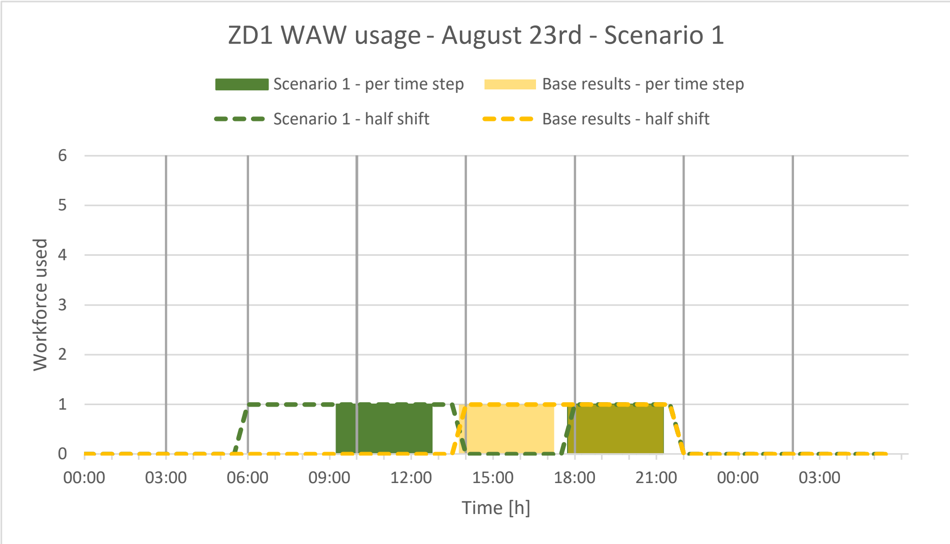


(c) GHUIF usage - Scenario 1 - August 23rd

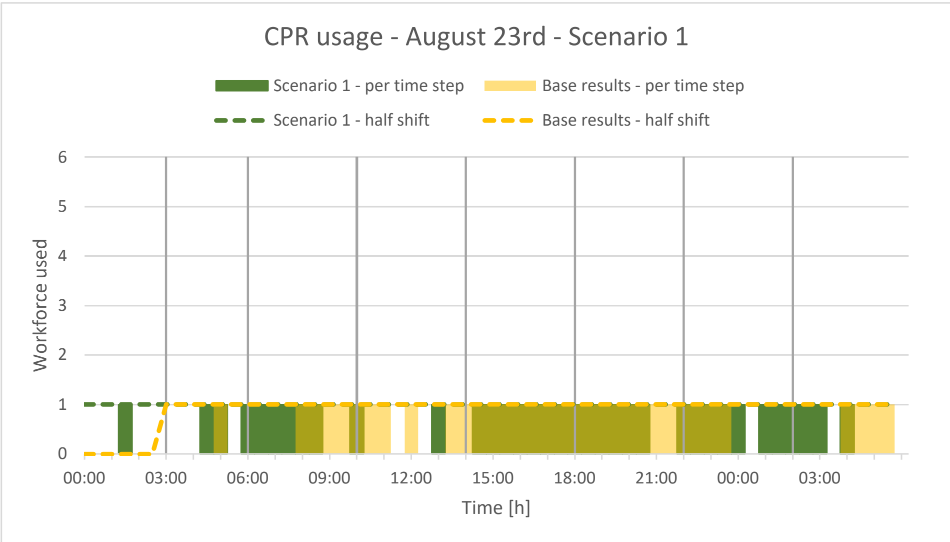


(d) SETJE usage - Scenario 1 - August 23rd

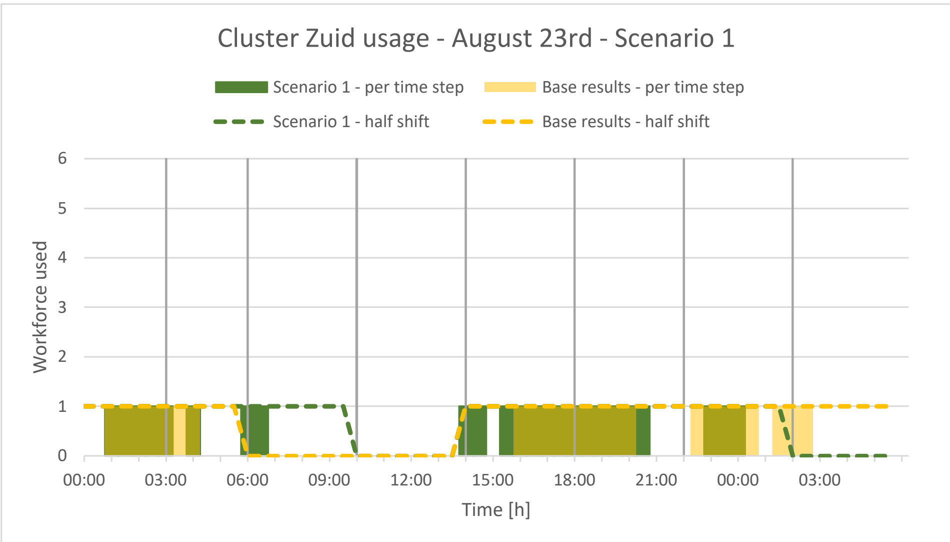
Figure G.11: Wagon usage per type - Scenario 1 - August 23rd



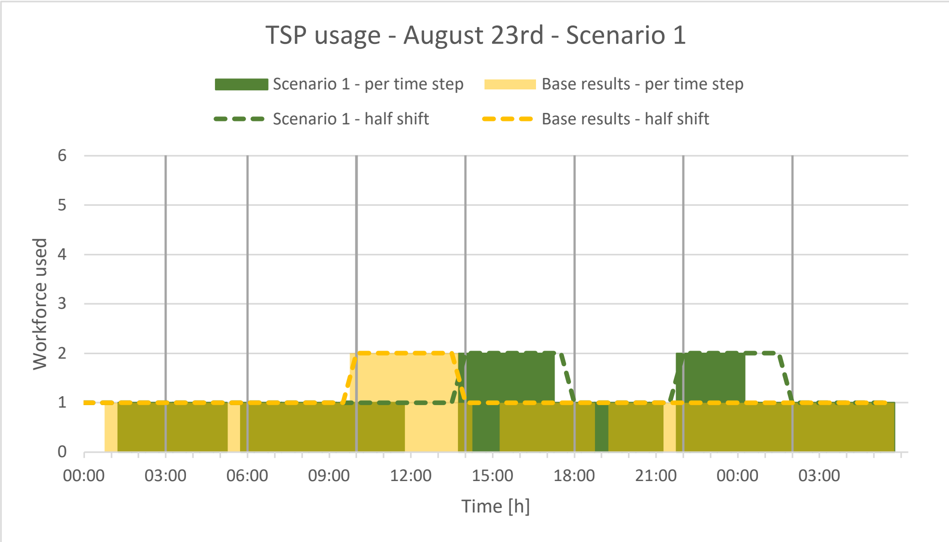
(a) Workforce WAW cluster usage - Scenario 1 - August 23rd



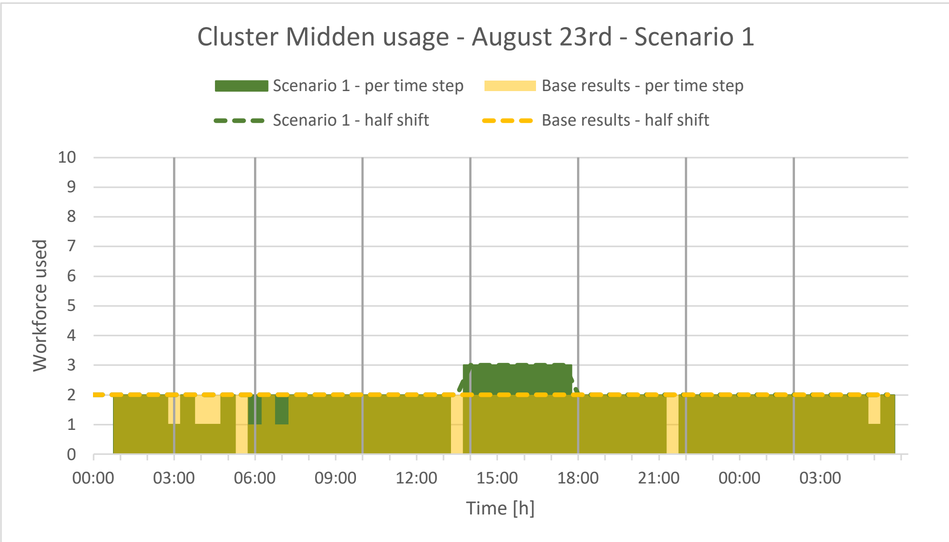
(b) Workforce CPR cluster usage - Scenario 1 - August 23rd



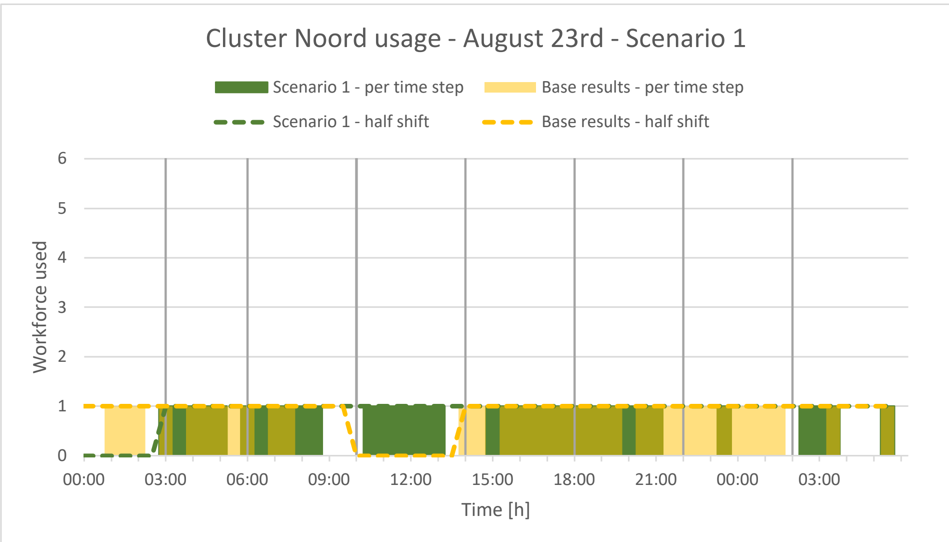
(c) Workforce Cluster Zuid usage - Scenario 1 - August 23rd



(d) Workforce TSP cluster usage - Scenario 1 - August 23rd



(e) Workforce Cluster Midden usage - Scenario 1 - August 23rd



(f) Workforce Cluster Noord usage - Scenario 1 - August 23rd

Figure G.12: Workforce usage per cluster - Scenario 1 - August 23rd

Results Scenario 2 - Graphs

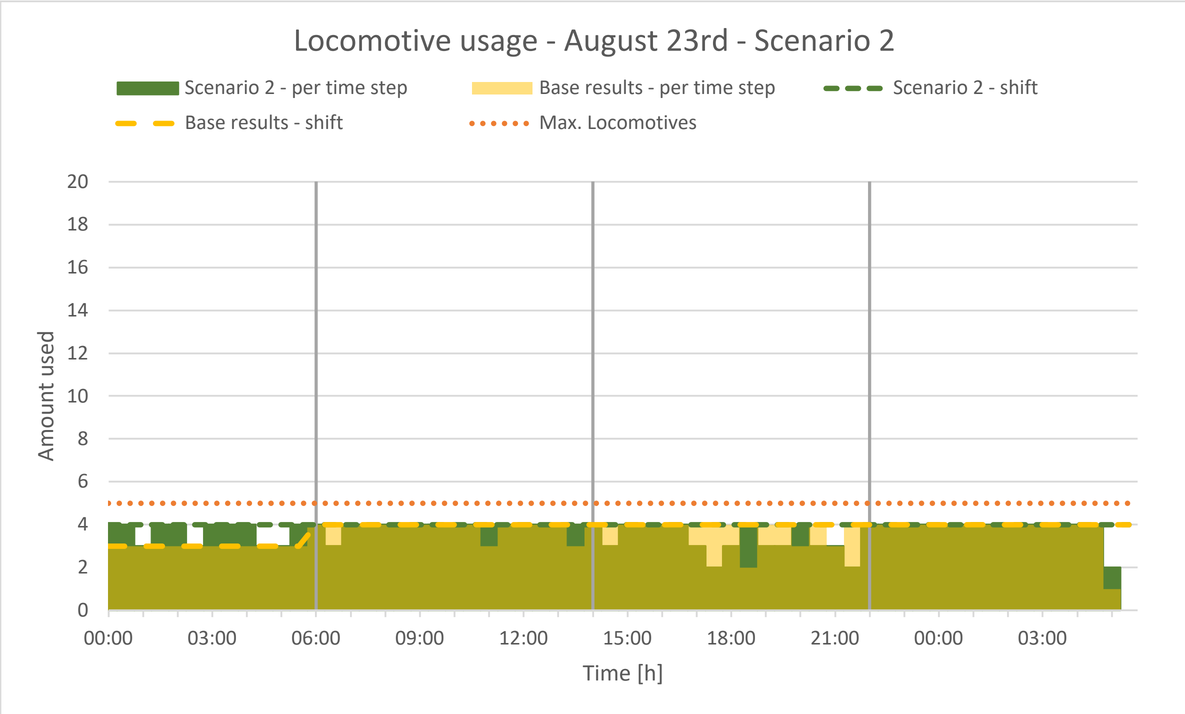
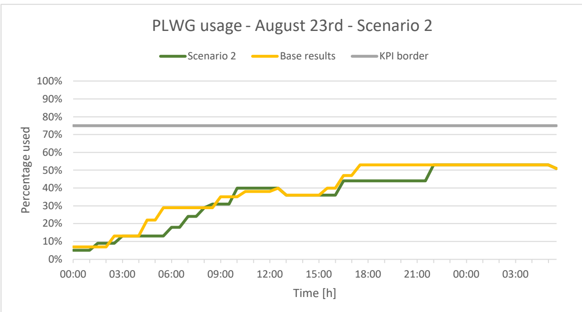
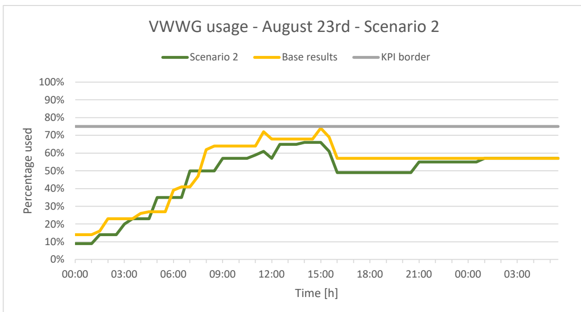


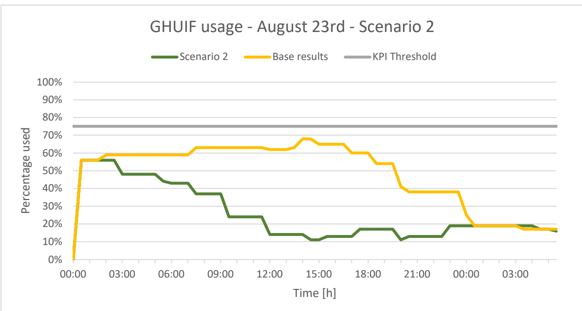
Figure G.13: Locomotive usage - Scenario 2 - August 23rd



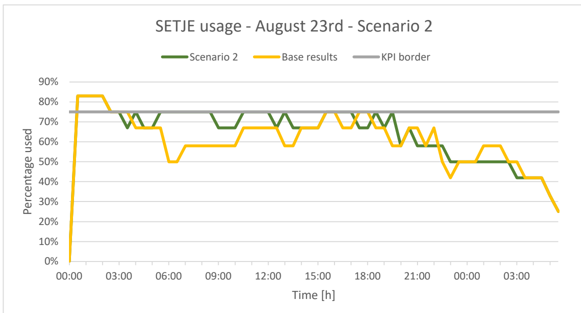
(a) PLWG usage - Scenario 2 - August 23rd



(b) VWWG usage - Scenario 2 - August 23rd

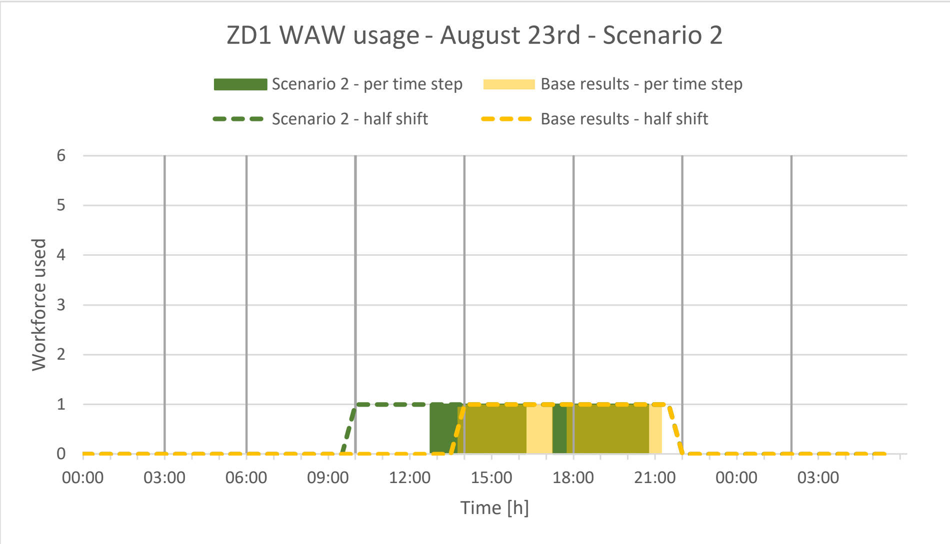


(c) GHUIF usage - Scenario 2 - August 23rd

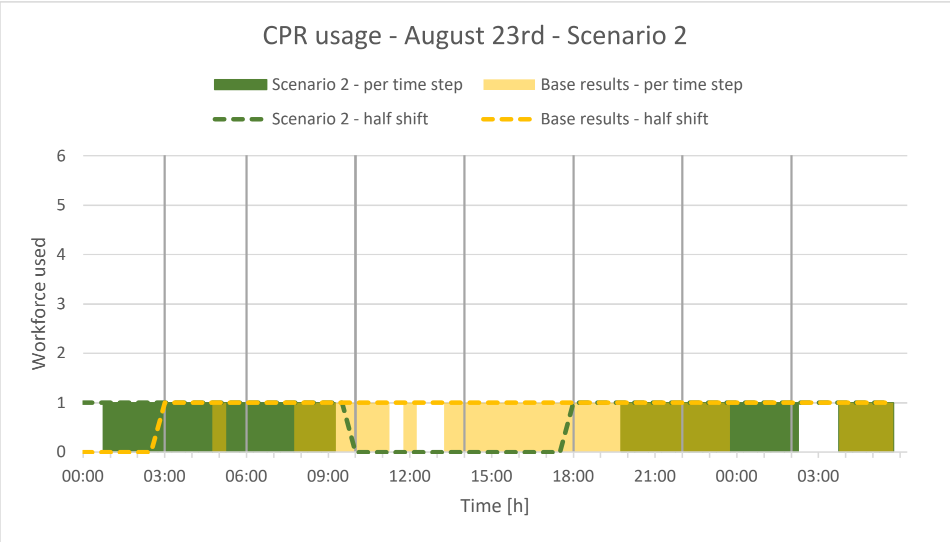


(d) SETJE usage - Scenario 2 - August 23rd

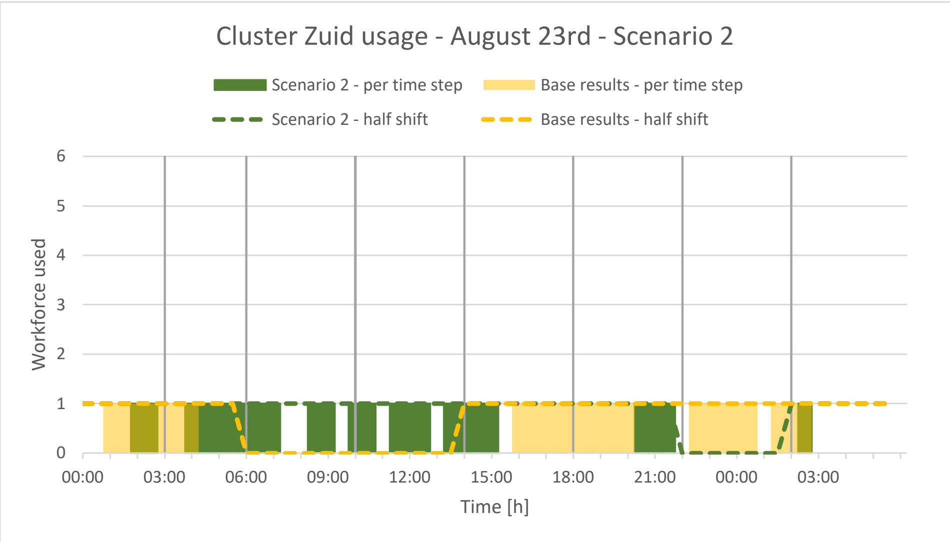
Figure G.14: Wagon usage per type - Scenario 2 - August 23rd



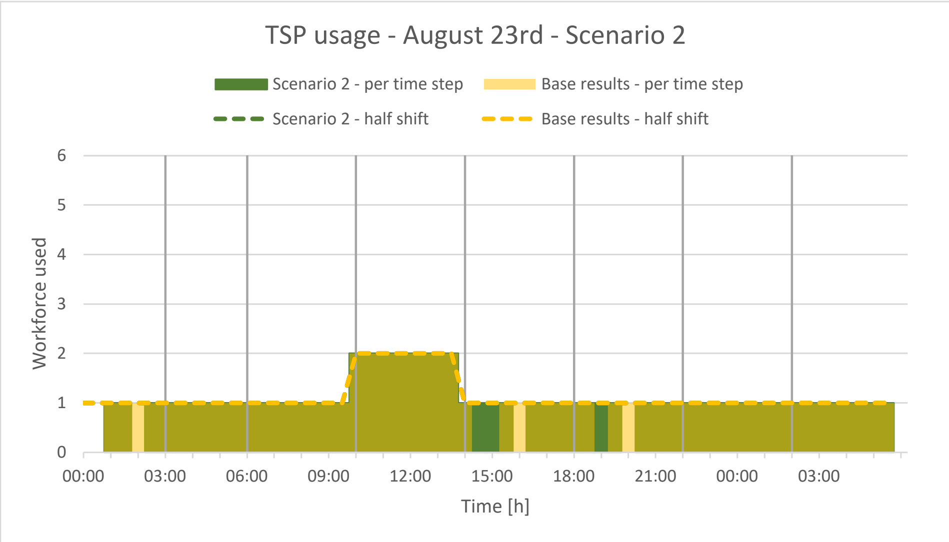
(a) Workforce WAW cluster usage - Scenario 2 - August 23rd



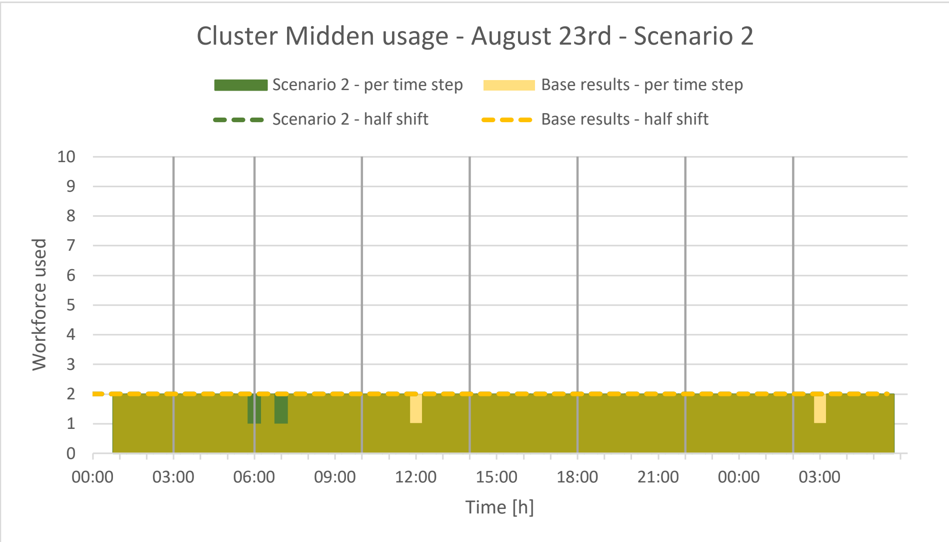
(b) Workforce CPR cluster usage - Scenario 2 - August 23rd



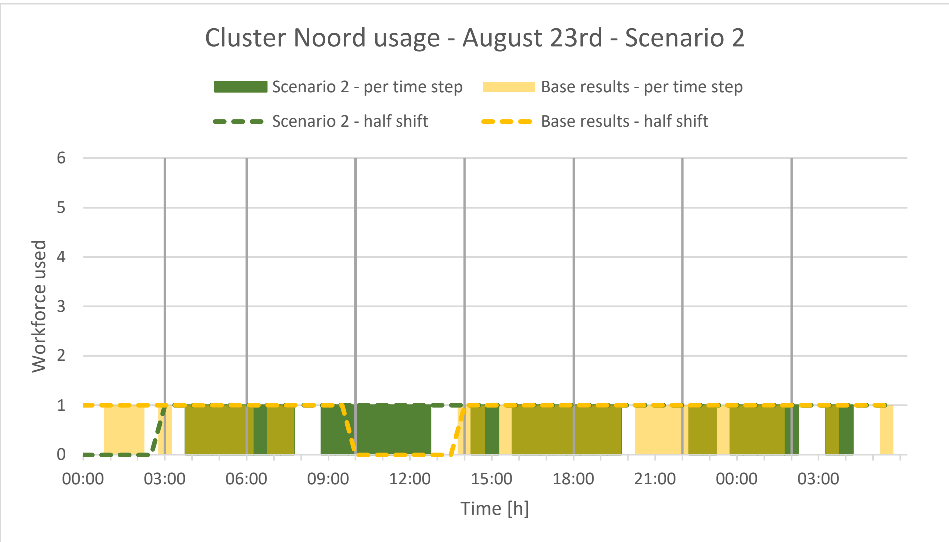
(c) Workforce Cluster Zuid usage - Scenario 2 - August 23rd



(d) Workforce TSP cluster usage - Scenario 2 - August 23rd



(e) Workforce Cluster Midden usage - Scenario 2 - August 23rd



(f) Workforce Cluster Noord usage - Scenario 2 - August 23rd

Figure G.15: Workforce usage per cluster - Scenario 2 - August 23rd

H
ORTEC Reference

This thesis project was commissioned by ORTEC B.V., supervised by L.A. van Vledder and J.J. Nieuwenhuis. Throughout the project, information was shared via email, MS Teams, internal documentation, interviews and calls. Additional information was provided by Stevo Akkerman (Tata Steel Data Analytics) and Piet Korf (Tata Steel Planner) from Tata Steel IJmuiden. All the information and data used in this thesis provided by these experts are cited as: *(L.A. van Vledder & J.J. Nieuwenhuis, personal communication, 2020).* They have been reviewed and approved by L.A. van Vledder and J.J. Nieuwenhuis.