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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

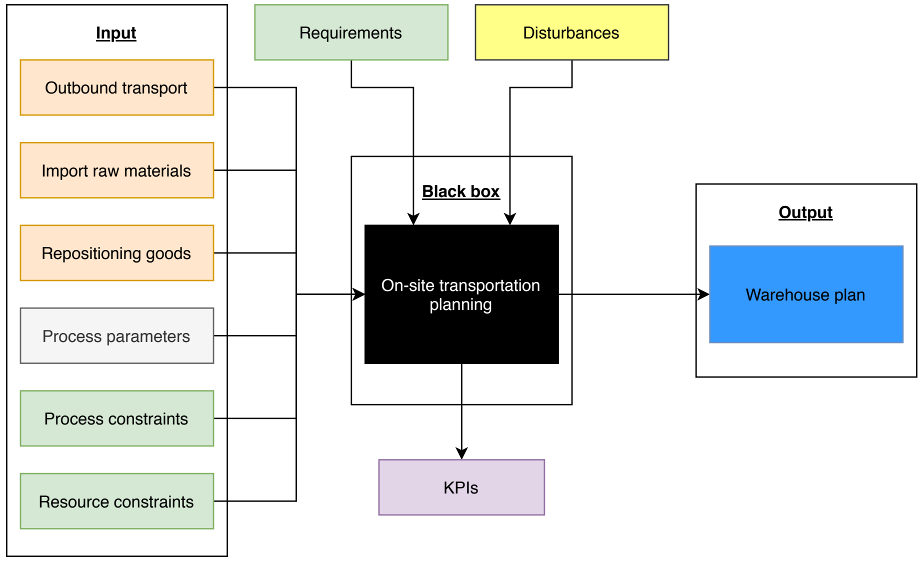


FIGURE 1: Black box representation of the on-site transportation planning of Tata Steel IJmuiden, resulting in the warehouse plan

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.

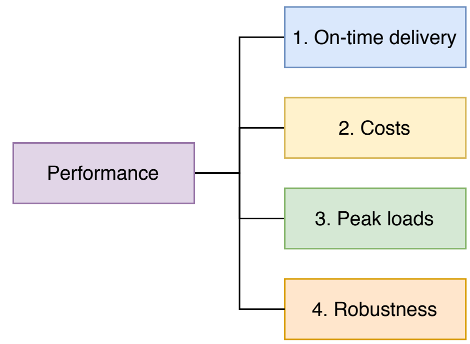


FIGURE 2: Key performance indicators, describing the performance of the warehouse plan.

$$\text{Performance} = \text{Weight}_1 \cdot \text{KPI}_1 + \text{Weight}_2 \cdot \text{KPI}_2 \ldots \quad (2)$$

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).

$$y_{0_{it}} = \begin{cases} 1, & \text{if at } t \; y_0 \text{ is between job } j = 0 \text{ and } j = 1 \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

$$\forall i \in I, \forall t \in T$$

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.

$$\text{MIN } Z_{tot} \tag{4}$$

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

$$Z_{loc} = \sum_{s \in S} C_s(U_{loc_s}) \tag{5}$$

$$\text{with} \quad U_{loc_s} = \max_{t \in s}(U_{loc_t}) \tag{6}$$

$$Z_{workforce} = \sum_{hs \in HS} C_{hs}(U_{workforce_{hs}}) \tag{7}$$

$$\text{with} \quad U_{workforce_{hs}} = \max_{t \in hs}(U_{workforce_t}) \tag{8}$$

$$Z_{wagons} = \sum_{t \in T} C(U_{frac-wagon_t}) \tag{9}$$

$$\text{with} \quad U_{frac-wagon_t} = \frac{U_{wagon_t}}{R_t} \tag{10}$$

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.

$$\sum_{i \in I} \sum_{j \in J} \sum_{u=\max(0,t+1-p_{ij})}^{t} r_{ijk} \cdot x_{iju} + \sum_{i \in I} r_{0ik} \cdot y_{0_{it}} + \sum_{i \in I} r_{1ik} \cdot y_{1_{it}} + \sum_{i \in I} r_{2ik} \cdot y_{2_{it}} \leq R_{kt} \tag{11}$$

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

Dummy tracker constraints

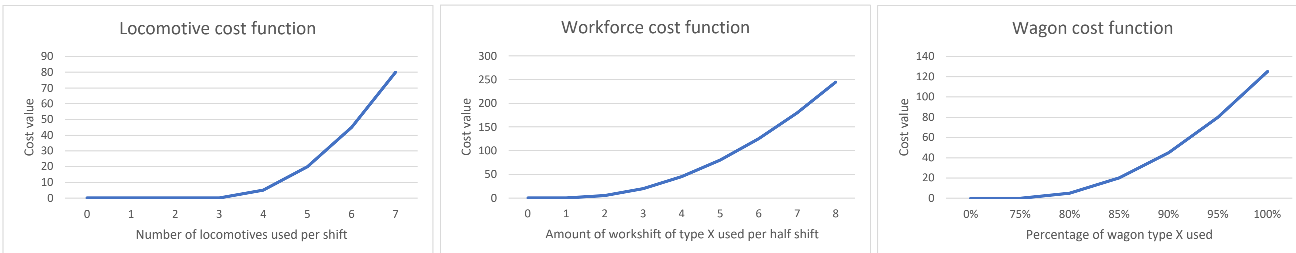
For the dummy trackers y_0, y_1 and y_2 three sets of constraints are added. Firstly the lower bound of the interval of t, based on the start time and processing time of the prior job of each task, for which the values of the dummy trackers are allowed

[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.

$$\sum_{t\in T} t \cdot x_{i0t} + p_{i0} \quad \leq \quad t \cdot y_{0_{it}} + M \cdot (1 - y_{0_{it}}) \qquad \forall i \in I, \ \forall t \in T \tag{12}$$

$$t \cdot y_{0_{it}} + 1 \quad \leq \quad \sum_{t\in T} t \cdot x_{i1t} \qquad \forall i \in I, \ \forall t \in T \tag{13}$$

$$\sum_{t\in T} t \cdot x_{i0t} + p_{i0} + \sum_{t\in T} y_{0_{it}} - \sum_{t\in T} t \cdot x_{i1t} = 0 \qquad \forall i \in I \tag{14}$$

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.

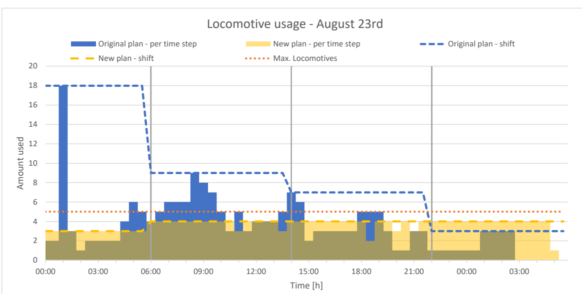


FIGURE 4: Locomotive usage - August 23rd

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.

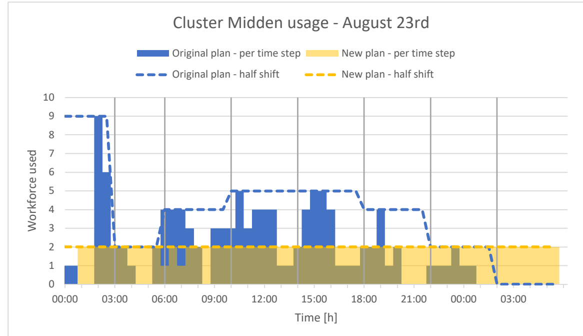
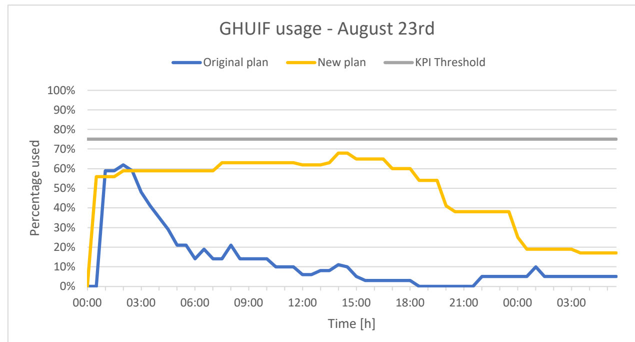
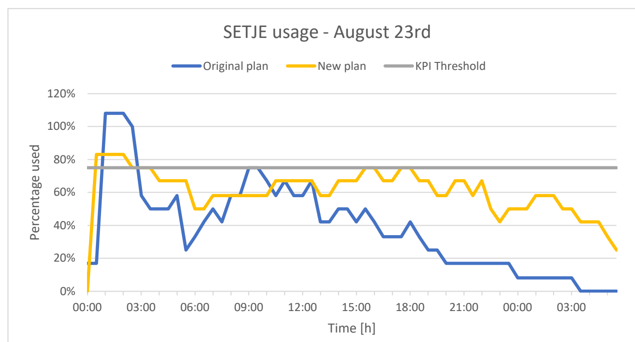


FIGURE 5: Workforce Cluster Midden usage - August 23rd



(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.

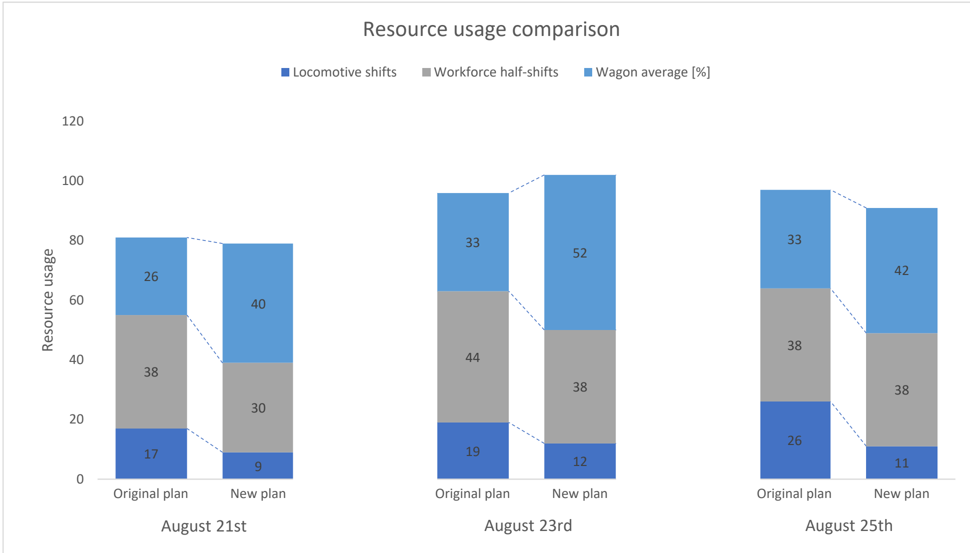


FIGURE 7: Graphical representation of the resource usage results per data set, comparing original plans to optimized plans by the planning model

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.

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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: $t = \{1, ..., T_{end}\}$	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	
$y_{0_{it}}$	Tracker dummy job 0: time between wagon-supply and loading
$y_{1_{it}}$	Tracker dummy job 1: time between loading and transit
$y_{2_{it}}$	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%