Capacity optimization of industrial railway systems

A case study at Tata Steel IJmuiden

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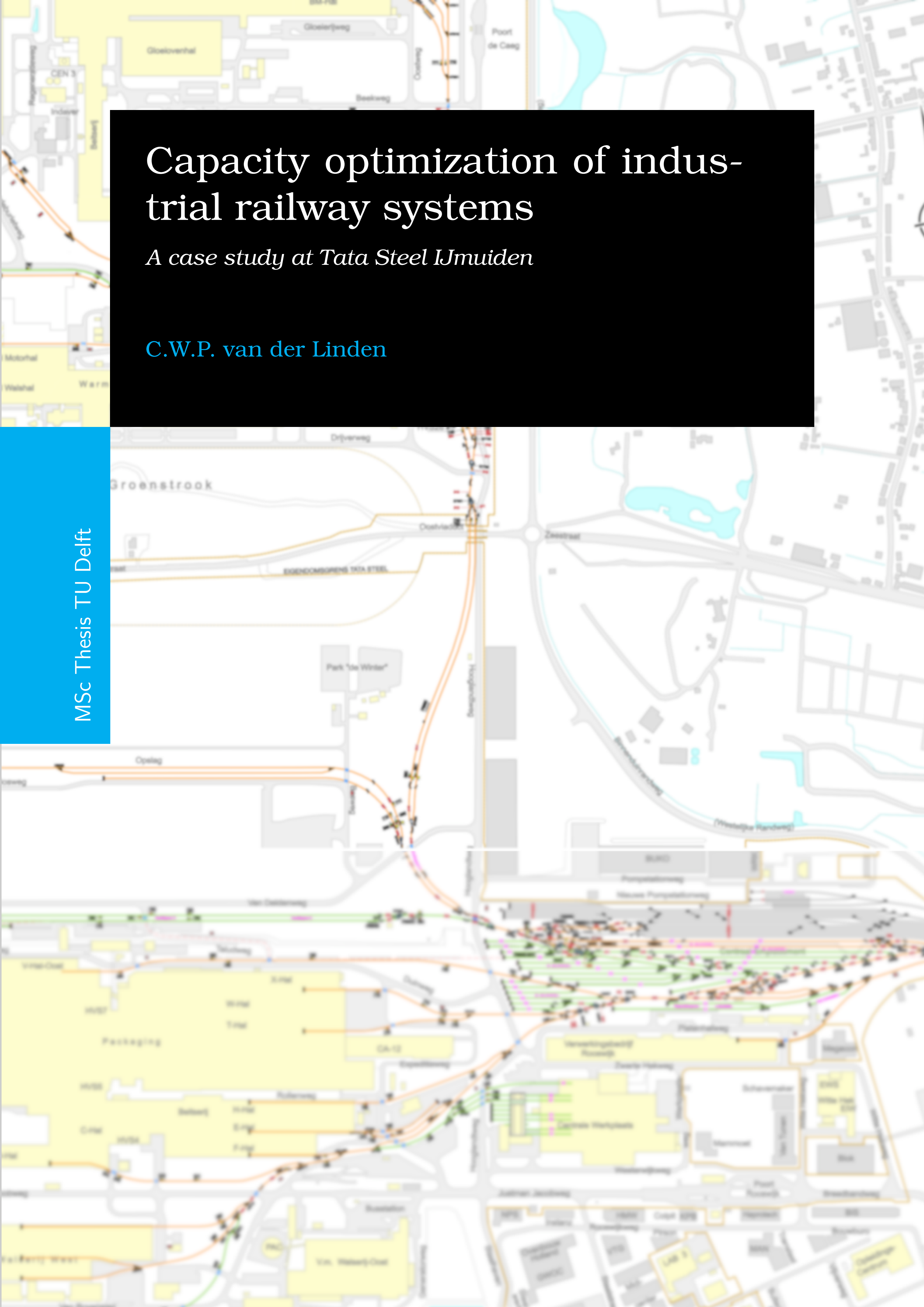
MSc Thesis TU Delft



Capacity optimization of an industrial site freight railway system

a case study at Tata Steel IJmuiden

by

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The private rail network of Tata Steel Ijmuiden consists of over 100 km of rail track. Multiple factories and storage facilities are connected to this network, and the main product that is transported over this network are rolls of plate steel. This transport is done by heavy-load locomotives with a varying number of wagons. Due to a growing demand of steel, multiple factories are going to have a planned expansion to increase the overall production capacity.

The rail network currently has a modest overcapacity, but it is expected that the capacity will not be sufficient with regards to the future expansion plans. The main goal is to find methods to increase this capacity in an efficient way, and to investigate if the proposed modifications are able to handle the expanded rail traffic demand.

Typical research questions could be:

1) **Rail network**: How can the capacity of a rail network be determined? Where are the future-bottle necks? What possible options are there to resolve these bottle necks?
2) **Coordinated control**: How is the current system controlled? Are there benefits of changing this control system? What control methods can help to increase automation and therefore the capacity?
3) **Trains and track characteristics**: How much is the fuel consumption for a train? How is the system currently maintained? What are the largest costs? How can the system as a whole benefit from certain modifications in terms fuel consumption, route times, amount of locomotives required, safety and reliability?
4) **Planning**: How can the planning of the individual factories be optimized for better flow?

The report should comply with the guidelines of the section. Details can be found on the website.

Summary

Industrial railway systems can be found within companies where the production and processing of goods require large quantities to be transported. These underdeveloped systems are often privately owned and are characterized by short to cover distances, many locations, inefficient layout due to historical expansion and bidirectional driving on the rail tracks. Examples of these systems can be found in mining operations, port operations in both container and bulk material, agriculture goods, lumber and other natural goods and steel manufacturing. Local optimization in such systems have been found to not directly lead to a global improvement of the system as a whole. This research suggest a new model to define and measure the performance of the system as a whole by using the creation of customer value, as known from the theory of lean thinking, combined with prioritization of transport tasks.

In order to test the model and to optimize the capacity of an industrial railway system a case study is performed at the railway system of Tata Steel IJmuiden, one of Europe's steel production giants located in the Netherlands. The industrial railway system found here transports the 7m ton of steel production to numerous production factories until the end product is send out for external transport. Here, the future performance of the railway system is under pressure since a growing production leads to an increase in rail transport demand. It is unknown if the capacity of the current railway system is sufficient to execute the increased future transport demand. The complexity of the system is caused by the historically expanded layout with over 30 connected factories, multiple wagon and locomotive types, high loads which cause track and wagons breakdowns and a diverse set of human decision making by experience and intuition. On top of that, the lack of transparency in the railway specific processes caused that the railway system and its performance as a whole is not well understandable. The following question is formed as a guideline for research:

> *What is the impact of an increasing future transport demand on the performance of an industrial railway system and in what way can this performance be improved?*

Transport capacity in general is known as the ability to transport a certain measurable quantity of goods in a specific time. The definition of the capacity of a rail network is less straightforward, since more variables play a role. The infrastructure, timetable and rolling stock all influence the capacity of a rail network. This complicates a formal definition. In literature, many different opinions on the definition of railway capacity exist. The by far most common railway operation is that of nation-wide passenger and occasional freight trains. It is therefore that most research on railway operations is focused on these networks rather than on industrial railway systems.

The research gap that is found is on the capacity optimization of industrial railway system. Since logistics performance of an industrial railway system is generated throughout the complete company site, the only correct approach is to define a global performance evaluation model. This model can then be applied in a case study to evaluate the future performance of the railway system at Tata Steel IJmuiden. Furthermore, the model can be used to evaluate the improvement of system modifications not on a local scale but on the system as a whole.

By analyzing the system is it found that the the main function of the railway system is not to transport a certain load, rather to perform the requested transport tasks provided by another department. These transport tasks only have a origin, destination and load specification. The transparency in the railway specific processes is truly low. In order to evaluate any global improvement the movement of trains, the driving times and stopping locations must be known. For this purpose a model in MATLAB is developed which analyses historical GPS location of sensors equipped on locomotives. By doing so a first step is made in order to identify waste in the process. Waste identification, known from the theory of lean thinking, helps to separate value adding time in a process from waste. Value adding time can be seen as time on processes where a customer is willing to pay for. Seven fields of waste are identified, being overproduction, waiting, incorrect processing, unnecessary movement, defects, resource utilization and uncovered assignments.

If the waste in a system is known, the way lies clear to design improvements which have the goal to reduce this waste. In order to evaluate these system modifications, a model is developed which can assess the global performance of an industrial railway system. From the theory of lean thinking subscribes that the focus in any process must be to create customer value. More customer value means a higher performance. The customer in the case of an industrial railway system is the department which provides the transport tasks. These tasks must be performed within a set time. Customer value in a transport system is known by 3 fields, reliability, punctuality and cost. A higher reliability or punctuality or a lower cost results in more customer value, and so a higher performance of the system. It is therefore that these three fields are expressed in measurable metrics.

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1 Introduction

1.1. Industrial railway systems

Railway systems are found in many forms and types. One of these types are industrial railway systems, which can be found at large industrial sites where the request for transporting is in extensive quantities. The benefits of the rail modality is that high quantities and substantial weight can be transported. It is therefore that at Tata Steel IJmuiden a railway system is used to transport heavy-load steel products between production factories, export facilities and storages. Before more information is provided on industrial railway system, the company of Tata Steel Europe and the production site at IJmuiden are discussed.

1.2. Tata Steel

The production site Tata Steel IJmuiden is part of the Tata Steel Europe group. This group is on itself a subsidiary of the Tata group. The organogram is displayed in Figure 1.1. The Tata group is an Indian company with over 100 operating companies. The steel making operations is part of the material branch. More business branches are Communications & IT, Engineering, Services, Energy, Consumer products and Chemicals.

The Material branch is the name for all steel making activities of the Tata Group company. The steel making activities consist of 4 companies, being Tata Steel India, which was the first Tata Steel company, Tata Steel Thailand, Tata Steel Europe and NatSteel Asia. Tata Steel Europe consist of 3 branches itself. Strip Products UK, Strip Products Mainland Europe and Long Products Europe. Strip Products UK are the facilities in Port Talbot and Llanwern in South Wales which produce hot rolled, cold rolled and hot dip coated steel. The Strip Products Mainland Europe is mainly formed by Tata Steel in IJmuiden. Other businesses in mainland Europe are factories for the production of steel products such as tubes.

1.3. Tata Steel IJmuiden

Tata Steel consist of two blast-furnace based steel production sites in Europe, one in IJmuiden, the Netherlands and one in Port Talbot, Wales. At the site in IJmuiden, a variety of steel types are produced for the industries of automotive, construction, consumer products, energy & power, general industry/strip, lifting & excavating, and packaging [10]. With over a hundred different types of steel produced here and with the development of many new types each year the steel production site of Tata Steel in IJmuiden belongs to the top world players.

The steel company located in IJmuiden was originally established in 1918 as the Koninklijke Nederlandse Hoogovens en Staalfabriek. Starting with a single blast furnace, the strategic location of the steel production site connected to the open North sea and the North Sea canal has been an advantage for nearly 100 years. The inland ship connection to the German Ruhr Metropolis and further on has enabled the transport of steel by inland ship, which is far more cost efficient than road transport. A merger with British Steel in 1999 was the initiation for a name change, being Corus. Only 8 years later in 2007, Corus was bought by the Indian company Tata and Tata Steel IJmuiden was formed.

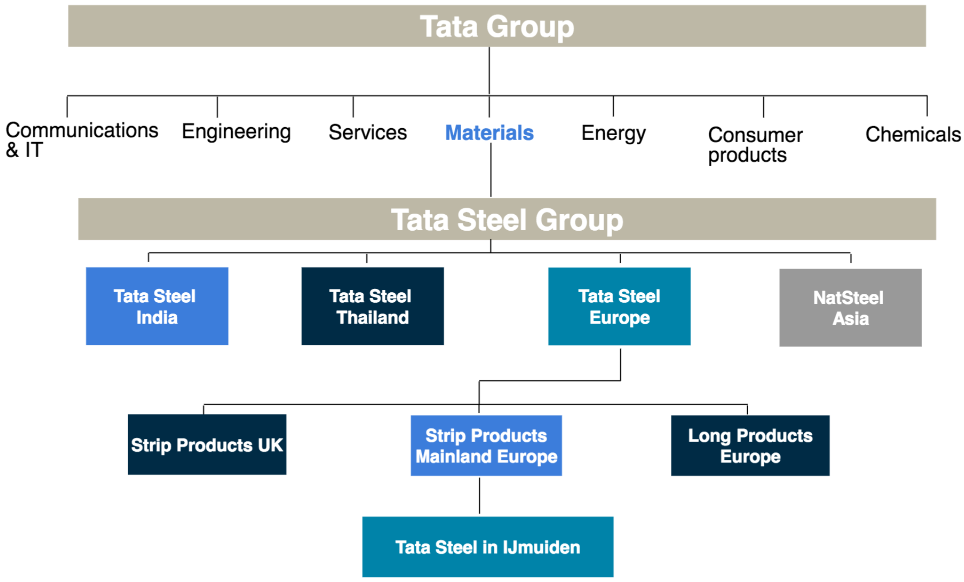


Figure 1.1: Tata Group organogram

At Tata Steel IJmuiden, an approximate 9000 people work to deliver an annual 7 million tons of high-end steel [10]. The steel market volumes is expected to be consistent for the upcoming decennia, but a shift is seen towards more high-end steel types instead of the lower quality. Customers are more demanding, as evidenced by the amount of requests for better moldable steels for car exterior manufacturing, more even top layer finished products and higher strength steels to improve crash and structural improvements [11].

1.4. Railway network at Tata Steel

At Tata Steel IJmuiden, a railway network is used to transport liquid iron and steel in the form of slabs, unprocessed coils, cold rolled rolls, plates, and coated products internally. Furthermore, slag and other side produce are transported in large pans. Besides this internal transport, the external lime trains and the trains with finished products are as well transported over this network. In total, the internal network consists of around 95 km of railway track. The complexity of the network is great, due to the widely branched tracks, many stations and extensive variety in rail transport equipment. Two different types of locomotives are used, 12 types of wagons and 5 types of railway switches. The historical expansion of the sites' facilities has left its mark on the current spread of locations of the factories. The current number of blast The rail track therefore is often positioned at slightly illogical locations due to the historical change in facilities. The rail network at Tata Steel IJmuiden is displayed in Figure 1.2.

A non-physical separation in the network is indicated by the red line. The part of the network to the left of the red line is is known as West, and the right part of as Central. This separation is due to the different goods that are transported. On the network West the main goods that are transported are liquid iron from the blast furnaces to the oxy-steel plant, and hot slabs from the oxy-steel plant to the hot rolling plant or an in between storage.

The rail section Central transports mainly unprocessed rolls, processed rolls and plate steel from the hot and cold rolling plants to the various storages around the factory's terrain. Furthermore, the steel products destined for export are transported on the Central network. The export modalities are ship (65 %), rail (25 %) and road (10 %). The facilities where the transshipment is done for export are the indoor port, the two outdoor ports, the export rail facilities and the truck loading facilities.

1.4.1. Railway network functions

The main function of the railway network at Tata Steel IJmuiden is the transport of steel, import and export products. The logistics of the complete production site in IJmuiden is operated by the On Site Logistics (OSL)

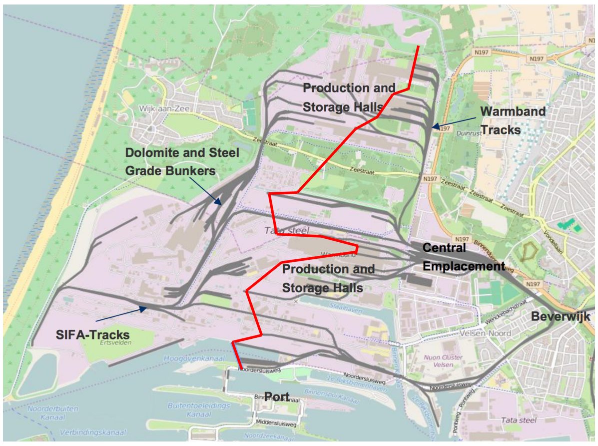


Figure 1.2: Rail network at Tata Steel IJmuiden. The red line indicates the non-physical separation between the network West (left) and the Central (right).

department. The OSL department is responsible for all on-site logistics, which consists of all import and export of materials and products, planning of transports and storage facilities and crane operations. The rail department, OSL Rail, is one of the branches of the governing OSL department.

While for outsiders it may seem like Tata Steel IJmuiden acts as one company, for insiders the different Tata Steel departments often act as single entities with a different interest. Every department has to deliver a certain performance, but between the departments the delivered performance indicators can be conflicting. As an example, the general performance of the OSL department can be the total throughput per year versus the costs. However, one of the functions of the department is to maintain sufficient storage capacity inside production halls. If for instance the hot-rolling mills department would need to shut down their operations because there in not enough storage capacity at the end of the line, the costs of this downtime will be around 250.000 Euro per hour. So the OSL department's first task is to maintain sufficient storage capacity and secondly to transport the maximum of materials with the minimum amount of costs.

The main function of the railway department is to perform the supplied transport tasks of the planning department of OSL. The tasks are transporting full wagons from the requested location in a requested time frame to the desired location and in a certain time frame. Furthermore, supplying the halls of empty wagons is a task. Maintaining the operationality of transport capacity is another function of the railway department. This is done by maintenance on the railway equipment, which are the railway tracks, switches, signalling systems, locomotives, wagons and more railway control equipment such as powerhouses and controllers. Providing and scheduling of personnel such as drivers, route and task schedulers, transport coordinators and directors is another task.

However, a secondary function of the railway department that is often forgotten is the function of buffer in the system. As stated before, if due to a build-up somewhere in a storage facility a large-scale production facility could not continue its production, the consequential costs are far more substantial than any rail specific breakdown. If certain production halls are working towards the maximum of their storage capacity, the rail department will provide empty wagons to the facility on which a substantial amount of rolls can be placed. This set of wagons can then be placed on a dedicated waiting track on the central railway network, or it can be transported towards a storage facility which has enough capacity available.

1.5. Problem description

The production forecast for the site in IJmuiden shows an increase of 1 to 1.5 million tons on top of the current annual 7 million tons for the upcoming 5 to 10 years. The transport of steel rolls on the site is predominantly done by the Central rail network. The question rises if the current rail way system is able to handle this annual 8 to 8.5 million tons of steel of the future with the current infrastructure, rail equipment and planning. An improvement in the rail network seems evident for this future state.

For a near future, an annual production of 8 million tons of steel is seen as a threshold, due to large the carbon dioxide production in the steel making process. This gas is a byproduct in the blast furnaces, oxy-steel factory and indirectly in every step where electricity is used. In the book year FY15/16 6.9 million ton of steel was produced, with a total carbon dioxide emission of 12.0 million ton [3]. The national government has limited the amount of carbon dioxide emission that Tata Steel can emit. Experts from Tata Steel predict that for the near future the threshold of 8 million tons of steel will produce the maximum currently allowable amount of carbon dioxide emissions.

The specific problem is that there is no understanding if the current railway infrastructure is able to perform the future increased transportation tasks. Furthermore, the maximum operational railway capacity is unknown. Since all of the rail network's factors have influence on each other, the overall effect of changing one specific part of the network has an unknown effect on the overall performance. For instance, if the operating locomotives will grow from 5 to 6, more transport tasks could be completed. However, more locomotives driving at the same network will result in a more dense occupation of the railway tracks. In this way the time that one locomotives has to wait for another locomotive to pass will increase. This will negatively effect the performance, but this effect can not be determined analytically. Furthermore, the costs of improving the railway network in anyway is the far most important factor to take into account.

1.6. Research goal and scope

The goal of the research is to find improvements on how the capacity of the rail network can be improved in a cost-efficient way to ensure that the future demand of railway capacity can be met. From interviews with different employees at Tata Steel IJmuiden, it has come forward that there is no general understanding on which elements will have the largest effect on the global transportation capacity. So while many actors all try to locally optimize the process, this does not necessarily improve the global operational performance.

The capacity of a rail network is a vague concept. This matter is over viewed in the next chapter. For this concept of capacity, a more narrow scope is needed.

For this research the scope lies on the rail infrastructure with its rolling equipment. The total realized throughput of transported tonnage of steel is in the end the main function of the rail department. However, this throughput depends on many factors. Variations in the steel market will influence the customer demand, which result in a higher or lower production of steel. This variation works it way to a higher or lower demand for rail transport, and therefor the total realized throughput depends greatly on this customer demand. The realized throughput is therefore important, but it is less suited for a key performance indicator (KPI) for measuring the railway performance. As an example, the transport of a large load of rolls for only a short, non-preferred distance would let this KPI rise substantial, but does not have a substantial boots in the performance. This throughput does influence the capacity. In general, more tonnes of steel transported would mean a better performance. However, this greatly depends on the planning.

The planning of the rail shipments tasks is done by the planning department. This is a crucial step in the performance of the overall rail transport. However, the primal task of the rail department is to perform the transport tasks requested by the planning department. Although large optimization can be achieved in the planning of rail shipments tasks, the focus of this research lies on the performance of the rail transport itself. The planning of the locomotives itself, so which locomotives drives on which track on which time, is part of the OSL Rail department. So this planning does lies in the scope of this research.

For the planning of the locomotives the planned transport tasks are the input. It does not matter if the transport contains 1 coil of steel or 20. From the scope of the rail infrastructure, there is no distinction between them. They are both a transport task, and they are both a 100 % usage of the rail infrastructure and equipment.

So for this research, every transport task is set as equal. There is no difference in capacity usage for one task over another. However, the routes that need to be driven differ substantially. To take this variation into account, the assumption is made that there is little difference in driving speed between the drivers. This results in that the effective locomotive driving times are the value to be optimized. This means that is the locomotives drives with either a single wagon with a single roll, or 12 wagons with maximum loading capacity, the transport tasks are both seen as a 100 % use of capacity.

The next possible KPI that arises is the total amount of realized transport tasks, since the primary function of the rail department is to perform the requested amount of transport jobs in a certain time frame. Since the flow of products transported by train has a far higher export than import, imbalance in the rail system is inevitable. The driving back empty of locomotives is a causality of that. This occurs often since a rail transport to an export port will nearly always result in either a transport back to the northern part of the terrain empty, or with empty wagons without any load. In the scope of this research, this transport is inevitable and therefore it is seen as a full usage of the rail capacity.

Since this driving back is inevitable and since certain routes takes more time than other routes, the KPI of the amount of realized transport tasks in not sufficient to represent the performance of the rail department. If the assumptions are made that the driving of a certain route takes more or less the same time, and that the drivers of the locomotives have the same handling speed, the same route will take more or less the same amount of time each time it is driven. Adding this feature to the amount of transport tasks, and the KPI that follows is the amount of locomotive effective driving time.

So to conclude in short, the scope of this research lies on the infrastructure and rolling equipment improvement. The way of measuring this is to define the effective locomotives driving times. Effective in this description means the driving times conducted during the transport of goods or during the inevitable driving back empty from a transport job. Ineffective driving times are waiting times due to traffic on the way, turning rail switches, detours due to a variety of causes and more. With this scope known, the research goal can now be further defined as to improve the effective locomotive driving times.

1.7. Research questions

In order to structure the research, a set of research questions is set up. The main research question is used as a guideline to focus the research and to structure a final conclusion. It is formulated as the following:

> **Main RQ:** *What is the impact of an increasing future transport demand on the performance of an industrial railway system and in what way can this performance be improved?*

This research question makes way for a set of sub-research questions that require an answer in order for the main question to have a solid conclusion. This set of questions is the following:

> **Sub RQ 1:** *How can the performance of an industrial railway system be defined and how can such a system be modelled?*

> **Sub RQ 2:** *How does an industrial railway system work, what is the current and future demand for railway transport for a specific industrial railway system and where can inefficiencies be found?*

> **Sub RQ 3:** *In what way can design alternatives be found which potentially improve the operation of an industrial railway system?*

> **Sub RQ 4:** *In what way can modelling the railway system and discrete event simulation be used to experiment and evaluate the performance of design alternatives for a future demand of railway transport?*

> **Sub RQ 5:** *What is a proper executable experimental plan in order to find the best performing designs and what is the performance of these design alternatives*

To assess the performance of the Central railway network at Tata Steel IJmuiden, a measurable KPI is needed. The task of the network is to perform the demand of transport tasks in the correct time frame. More on this matter is discusses in the system analysis of Chapter 3. Performing the tasks takes time, and every transport has a certain time window that is set where either the load has to be picked-up or dropped off. Any delay in either the picking-up or delivery of the goods is unwanted. For a certain period of time, the total delay can be summed. Furthermore, from a cost point of view, the amount of locomotive driving needs to be minimized.

Both the delays and the locomotives driving times will initiate costs, but these are different. Therefore, a pricing mechanism is applied in order to valuate the two.
This objective is further worked out in Chapter 4.

1.8. Thesis outline

This thesis starts with the introduction as provided above. In the introduction, the

2

Literature Review

In this chapter relevant literature is studied regarding networks, network logic, railway operation, railway capacity and deadlocks in automated systems. The question to which an answer is sought-after is:

> *How can the performance of an industrial railway system be defined and how can such a system be modelled?*

2.1. Characteristics of industrial railway systems

Industrial railway systems can be found within companies where the production and processing of goods require large quantities to be transported. Rail transport is the most efficient means of transport for these companies [22]. Most industrial railway systems are privately owned, and are characterized by short to cover distances and many locations. Examples of these systems can be found in mining operations, port operations in both container and bulk material, agriculture goods, lumber and other natural goods, [6], natural goods such as lumber [1] and steel manufacturing. The grain handling facility at Penny Newmain[6], the bulk commodity handling at Milpitas [8], the Salinas lumber site [1] and the Alberta Midland Railway Terminal [5] are just a handful of examples of these industrial railway systems.

What characterizes industrial railway systems beside the fact that most are privately owned and that the covered distances are short, is that heavy-loaded wagons and thus heavy-load railway track is in place. On public national-wide railway track stricter rules are applied and the axle and track load is more limited. Furthermore, the tracks in an industrial railway system are commonly used in bidirectional way, and a large number of locations can be visited with only a small number of tracks.

What complicated industrial railway systems is that it is generally a system which has been present for a long time, and have historically grown into the present layout. Facilities that are added over the course of the history of the production site result in a far from optimal layout of the network. Furthermore, most of these railway systems lack transparency in the essential railway processes [22]. The real-time location is not known and little information regarding the service and processing time is known. Planning of transport is limited when little information of the current operation is known. This can be caused by the large variations in the processes, which results in low reliability and punctuality.

According to Schonnemann [78], complex freight hubs consist of two organizational parts: a logistic department for cargo handling and an associated rail yard. Rail yards are the main cause for inefficiencies due to their complex structure, many handling processes and little coordinated interrelations between the actors from different hubs. This is common for industrial railway systems .

Schonnemann showed that for many European freight hubs which had a rail network, the processes between the transport chains are poorly adjusted. The railway-specific processes are practised on a improvised policy rather than a scheduled one. This way of handling is known as undisciplined or timetable free dispatching policy.

Schonemann furthermore states 3 findings on rail networks at large industrial sites:

Finding 1: Each actor in the rail transport process plans its own work flow only. There is no general coordination of the train processes.

Finding 2: The railway-specific and logistic processes such as pick-up times, wagon set lengths, wagon requests and loading times are poorly coordinated. Local optimization do not lead to global optimal solutions.

Finding 3: A medium term capacity planning in complex freight handling terminals is not considered in real-time operation. The movement of trains is not scheduled, but carried out on operational basis. This leads to large proportion of unproductive processes and waiting times.

The UIC 2004 method of compressing the timetable to determine the capacity of the network will not hold if no timetable is used.

Studying the operation performance through assessing the operational performance with Key Performance Indicators (KPIs) would be useful. Parameters which can be used to determine the performance of the network are:

- **Locomotive driving hours**. If the assumption is made that every route taken is a useful one, the amount of actual value adding driving hours of a locomotive can be an indicator of the performance.
- **Amount of load transported**. The load that is transported between the locations at an industrial railway system can be seen as an indicator of the performance.
- **Amount of wagons transported**. With this KPI, the performance of the transshipment halls which plan and load the wagons is left out of context. This is not part of the rail department. In the end, the rail department's task is to transport certain wagons from one place to another.
- **Amount of kilometer routes driven**. This KPI is related to the locomotive driving hours. However, the total distance covered is a more clear indication of what the total effectiveness is.
- **Idle times locomotives**. More idle time would mean that there is more leftover transportation capacity. While the idle time can never be zero, since then there will be a build-up somewhere in the network, the idle time could be an indicator of how much the current demand for transportation capacity can still grow.

2.2. Railway capacity

This section provides two subsection. In the first section the literature is studies regarding the capacity of rail networks in general. In the second subsection the relevant literature found for the capacity and performance of complete industrial railway systems is studied.

2.2.1. General railway capacity

In the rising rail traffic the demand for objective quality measuring of rail systems is rising as well. Railways operators are searching for the most effective measures to increase their operations. Therefore, the International Union of Railways (UIC) redefined the capacity of railway infrastructure capacity in 2004 and provided a method for Infrastructure Managers (IMs) to perform capacity calculations.

A general definition for the capacity of a railway network cannot be given. The UIC provides their standing point as the following [92] :

Capacity as such does not exist. Railway infrastructure capacity depends on the way it is utilized.

The UIC describes that the basic parameters that underpin this capacity are the characteristics of these railway infrastructures themselves. These characteristics include the signaling system, the transport schedule and the imposed punctuality level [92].

A series of four parameters, which are shown in Figure 2.1, are identified on which the capacity of a certain infrastructure of a railway network depends:

- **Number of trains**: the train intensity is the most obvious parameter for the capacity of a railway network. An increase in the amount of trains per time interval, e.g. trains per hour, can enable a higher capacity. But according to the UIC less capacity is left for quality, as described in the next parameters.

- **Average speed**: The speed at which the trains drive will influence the capacity. A higher speed will in general enable a shorter travelling time, but the braking distance will increase with a larger proportion.

- **Stability**: This network wide parameter is the embodiment of the margins and buffers that are applied all over the network. These can be in the field of travelling time, train paths, planning and amount of freight loaded. A more stable system will ensure that stochastic delays are suppressed. A less stable system will respond in an amplification of these delays, and so will result in longer delays further up the network. The stability parameter could also be seen as the degree of margin between the scheduling and the performance. These timings will never be exactly the same, and so discrepancies between the scheduling and performance will in a stable network be suppressed.

- **Heterogeneity**: If the composition of the trains in a railway network have considerable varying operational speeds, the network capacity consumption of the train composition will increase. For example, if a fast-moving train has to wait on a slow-moving train driving in in a certain section, this effects the capacity negatively.

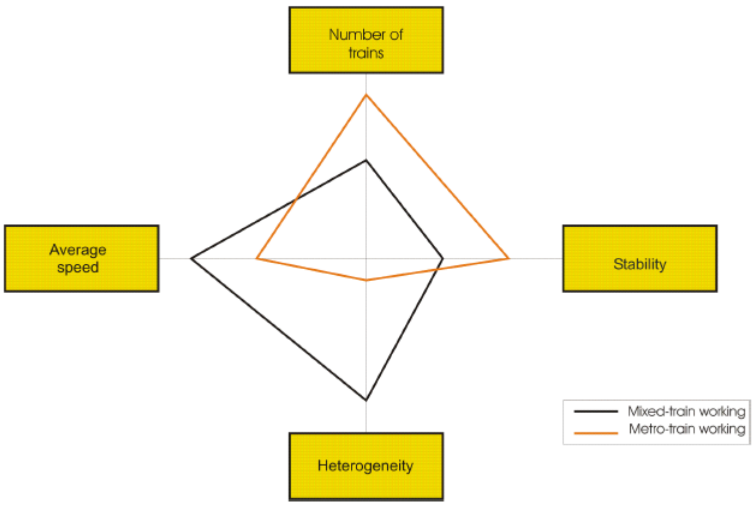


Figure 2.1: UIC 2004 capacity balance source: UIC 2004

Besides the UIC, various definitions of the capacity of a railway network can be found in literature. In transport systems the general definition of capacity would be the amount of goods transported per time frame. As an example, a conveyor belt that transports coal has a capacity in kg coal per minute and the capacity of a road can be in vehicles per hour. The determination of the capacity of a rail network is less straightforward, since more variables play a role. The infrastructure, timetable and rolling stock all influence the capacity of a rail network [55]. This complicates a formal definition.

In literature, many different definitions of the capacity of a railway network are given. Most railway operation is in a nation-wide network where passenger and freight trains drive among each other. So most research on railway operations is focused on such a network. An overview of possibles definitions is formed in the research of Landex [53]. Definitions found in literature on the capacity of a railway network are:

- Railway capacity is the ability of the carrier to supply as required the the necessary services within acceptable service levels and costs so as to meet the present and projected demand [48].

- The theoretical capacity is defined to be the maximal number of trains that can be operated on a railway link [75].

- The capacity of an infrastructure facility is the ability to operate the trains with an acceptable punctuality [47].
- Capacity is a measure of the ability to move a specific amount of traffic over a defined rail line with a given set of resources under a specific service plan [50].
- The only true measure of capacity therefore is the range of timetables that the network could support, tested against future demand scenarios and expected operational performance [96].
- Capacity can be defined as the capability of the infrastructure to handle one or several timetables [38].
- Capacity is defined as the maximum number of trains which can pass a given point on a railway line in a given time interval [88].
- Capacity may be defined as the ratio between the chosen time window and the sum of average minimum headway time and required buffer time [68].
- The capacity of the infrastructure is room on the track that can be used to operate trains [45]
- The number of trains that can be incorporated into a timetable that is conflict free, commercially attractive, compliant with regulatory requirements, and can be operated in the face of anticipated levels of primary delay whilst meeting agreed performance targets [15].

These definitions of the capacity of a railway network are mostly focused on passenger transport combined with freight on a large or national scaled network. In the next section, the topic of an industrial railway network is discussed, which is operated differently than the standard passenger railway network.

The UIC describes a method to assess the capacity usage of a railway network. The method, shown in Figure 2.2

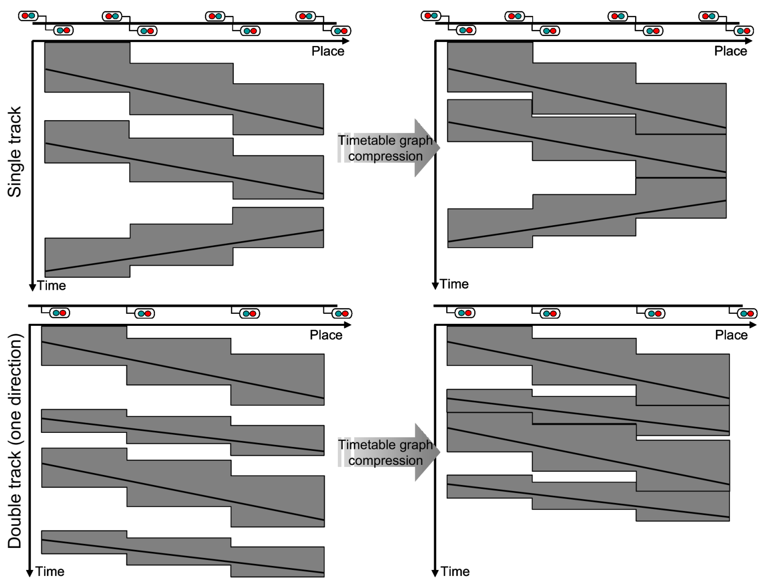


Figure 2.2: UIC 2004 capacity assessment source: UIC 2004

2.2.2. Industrial railway system capacity

Very little research has been done on industrial railway systems. Clausen [22] has performed an analysis on the performance of industrial railway systems. Industrial railway networks differ greatly from larger national passenger railway networks. In industrial railway networks, most of the time a transport modality change is made. In a container terminal, containers arrive through large container vessels and are transported through road, rail or inland ships further downstream. This transshipment implied large variations in the process, and so the reliability and punctuality of such a network becomes less. Furthermore, the level of complexity is high due to the widely branched connection to different factories.

In literature, the subject of industrial railway system and performance measurement systems for this system has not been studied in detail. Clausen [22] has provided an overview of the literature regarding the subject in 2014, but has came to the conclusion that the level of research on general railway systems is far more advanced. This is due to the fact that in industrial railway systems little optimization can be performed since most processes cannot be seen separate of the system. Even more, Clausen concludes that industrial railway systems lack the needed basic information flow such as real-time location, accurate transport and processing times and scheduling or slot allocation on the network in order to perform intelligent optimization. In other words, in order for performance measuring an industrial railway must have a flow of operational data. Clausen [22] noted 4 problems for service providers in this field:

- Any service provider has more difficulty to measure their service compared to the production of goods. In industrial railway systems this is no different.
- An industrial railway systems provides service in logistics, which does not generate any performance within an open market. Therefore, no market conform payment is done, from which a monetary performance can be extracted such as an return-on-investment (ROI).
- Logistics performance of an industrial railway system is generated throughout the complete company site. Measuring the performance cannot be done at a single point, but requires a system of observation points.
- The flow-orientated perception of logistics in order to control and manage processes requires unusual information.

Impacts on the railway system are the most influential factor for the performance. Since an industrial railway systems works as one single operation process, impacting factors are present in many forms. Clausen [22] has detailed on the possible influences, as shown in Table 2.1.

Table 2.1: Influence of figures on the order characteristics in a industrial freight railway system :source: Clausen

Category	**Influencing figure**	**Description**	**Time interval of measurement**
Order characteristics	Amount of recipients per order	An order can consist of one or several recipients. The higher the amount is, the higher is the shunting effort	Continuously
	Sequence of loaded cars	If an order consists of several recipients (e.g. A and B) there is an optimal sequence of cars. In case of 4 loaded cars the sequence would be AABB or BBAA, deviances cause shunting effort	Continuously
	Amount of orders (absolute)	The degree of capacity use of traction unit is decisively influenced by the absolute amount of orders	Per shift
	Amount of orders per hour	The complexity of scheduling increases if the demand does not occur evenly spread	Hourly
	Utilization of load line	Every load line has a predefined length that can be used for every load. In case of underachievement of capacity and constant amount of freight the shunting effort increases	Continuous
Environment	Limitations due to weather	Snow, ice or heat do have a high influence on the infrastructure and can thus restrict railroad operations	In case of occurrence
Operating resources	Inventory of cars	The amount of cars on factory premises influences strongly the possibility of shunting. Inventory has to be measured per type of car	Per shift
	Amount of car types	The higher the amount of different types of cars, the higher is the car inventory and the shunting effort. Car types can also be defined via transport relations	Nonrecurring, else in case of change
	Availability of traction units	Traction units can be unavailable for normal operating schedule for different reasons: dysfunctions, illness of employees or unscheduled demands of the production	Per Shift
Infrastructure	Limitations due to maintenance or dysfunction	Railway services can be limited by maintenance or unscheduled dysfunctions which have to be measured concerning duration and effect	In case of occurrence
Human resources	Available length of sidings	The length of sidings influences the variance of shunting possibilities and the maximum amount of cars on factory premises	Nonrecurring, else in case of changes
Production	Sickness figures	It is necessary to measure these figures, if a task cannot be executed due to an employees' sickness	Per shift
Freight	Accident frequency rate	The accident frequency rate stands for the relation of accidents to working hours	Per shift
	Limitations of qualifications	Not every employee possesses the required qualifications to handle every traction unit in every area of factory premises	Nonrecurring, else in case of changes
	Amount of failures in loading process	If a car has not been loaded according to safety regulations it has to been conveyed back to the loading point and unloaded or corrected. Every failure causes additional shunting effort	Per shift
	Inventory of loading points	The inventory of loading points is directly linked to the loading itself and has to be measured per loading point	Per shift
	Time- criticality of freight	Due to their physical characteristics and to production requirements a classification per freight concerning time-criticality is necessary	Nonrecurring, else in case of changes
	Amount of heterogeneous freights	Different freights may require different car types	Nonrecurring, else in case of changes

2.3. Network Design

A network is defined by the Oxford Dictionary [70] as *A group or system of interconnected people or things.* Networks can be found everywhere, such as in the field of transportation, electrics, relations, information and communication. A network representation displays the existing links between the location entities. This representation provides a powerful visual aid in the understanding of the complexity of a network. since it can be a complex matter. By visualizing a network, the existing links between the entities are manifested.

Network models consists of nodes *N*, which can represent cities, stations, terminals, bus stops, internet servers or any other connection point. The links (arcs) between these nodes is denoted as *(i,j)* for the arc between node *i* and *j*. Examples for the arcs are roads, rails, ship connection, bus lines or internet connections. The existing relations between the nodes and the arcs is best displayed in a nodal network graph, as shown in the example network in Figure 2.3.

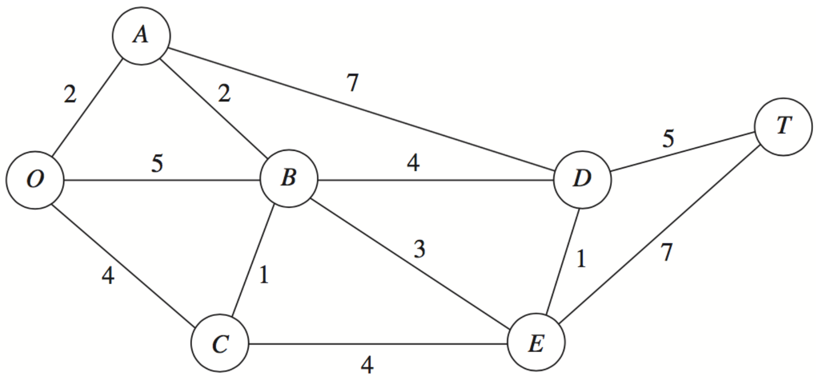


Figure 2.3: Example of a network model source: Hillier and Liebermann

The example of Figure 2.3 shows locations, indicated by the nodes *O, A, B, C, D, E* and *T* and connections between the nodes, called arcs. Furthermore, these arcs can have extensive properties such as capacity, flow, length, time, sequence or content which can be displayed in the graph. In this case the provides number on the arcs represents the capacity of that certain arc.

2.4. Network Design Problems

Network design problems can have many forms. To classify any network design problem, Zhu [101] describes a basic distinction is as followed.

2.4.1. Commodity and Demand

If the product that needs to be moved in a network is a commodity, which insists that no product differentiation is present, the network design problem can be set in the commodity and demand class. Grain, water, gold, oil and natural gas are examples of commodities. An original origin and destination pair (O-D) needs to be present, but several origins or destination can be added. However, if several origin and destination pairs are added, product differentiation can be present. For instance, grain is a commodity, but if a certain supplier has a slightly different type of grain, or if the shipping conditions alter the grain's content, the grain will not be interchangeable with other types of grain without mixing the content. An option is to set up another O-D pair for every commodity in the network.

The notation for the commodity is denoted as *p*. The flow of this specific commodity is then *m(p)* and the volume *w(p)*. This flow of product *p* has it's origin in $o(p) \in N$ and destination $d(p) \in N$. In the case that multiple commodities are transported in the network, the collection of individual products *p* is found in the set *P*. This specific network design problem is known as the multicommodity problem.

2.4.2. Minimum Cost

A large portion of the network design problems have the objective to deliver a certain performance in terms of throughput versus a minimum amount of cost. The costs can be split up into two groups, flow costs and design costs.

A flow of a commodity or product p on an arc *i,j* can generate a specific cost for that product on that arc of $c^p_{i,j}$. Depending on the system, the costs induced by the arc can be linear or non-linear. As an example, in a oil pipe line the costs will likely have a linear pattern. In the case of transporting washing machines by a truck on a road, a non-linear discrete pattern is present. If 5 washing machines can be transported by a truck, the costs of the first machine will need to cover the complete overall costs of the truck. With two or more, the costs are divided among these machines.

The cost of the design is the associated costs that comes from constructing arc *(i,j)*. When a network is already in place, the cost of design can be neglected. However, the costs of adding another specific arc could be taken into the model.

2.4.3. Capacity

In a capacity network design problem, a certain amount of resources is used. The amount of this specific resource can only be limited while being present on the arcs. The arc *(i,j)* has a certain (limited) capacity, noted by $u_{i,j}$. The difference between capacity and flow is that the capacity can see to a non-linear discrete flow. Once the capacity on a certain node is reached, no more of product p can be transported on this arc until capacity is made available again.

Different resources $r \in R$ can have specific capacities for every arc, as $u^1_{i,j}$, $u^2_{i,j}$, ..., $u^R_{i,j}$. When the capacity on an arc is more than the maximum possible flow on a arc, the arc is called uncapacitated since the capacity does not play a role.

2.4.4. Static versus Dynamic

The set of demands need to be met if the network design problem is to be solved. However, in many cases these demands can vary time. When these demands change in time, the network design problem is no longer static, but now dynamic. If the flows in the system are not simultaneous or constant, the aspect of times plays a crucial role as well. This also changes the network design problem from static to dynamic.

In dynamic network design problems, every aspect of the design can be time dependent. Furthermore, associated time constrains or parameters such as delay costs can be implemented.

Since the current state of the network changes in time, normally a time-space network shape is used track the network's state. This time-space network adds a layer at every chosen time step next to the previous one. This is a duplication of the network, but with the possibility of altered values for flow, capacity, node occupation or other aspects.

2.5. Network Design Models

To model a network, an interplay between the design decisions and the operating decisions needs to be included. In general, the design costs are fixed while the operating costs are variable. In order to model the relations of a network, two groups of variables are needed [57]: design variables and flow or operating variables. The design variables display the discrete choices that are made in order to give the networks its shape. On the other hand, the flow variables note the continuous changing choices that make up the transport of the resources from one node to another.
The design variables $y_{i,j}$ note the decision that resource p makes on that arc. The complete set of all arcs combined form A. The design variable $y_{i,j}$ can either be closed or open. When closed, the value is 0, and when open, the value is 1 or a higher integer. In mathematical form, this results in:

$$y_{i,j} \geq 0, integer \quad (i,j) \in A. \tag{2.1}$$

Flow variables are notes by $x^p_{i,j}$, where p resembles the specific resource that flows on arc (i,j). The total flow of a product is $w(p)$, which leads to $0 \leq x^p_{i,j} \leq w(p)$. For uncapacitated flows a different approach for $x^p_{i,j}$ is used where $x^p_{i,j}$ expresses a percentage of the total flow $w(p)$ on arc (i,j) by the expression $0 \leq x^p_{i,j} \leq 1$. If the network used discrete resources, the flow variable $x^p_{i,j}$ can best be expressed by integers $x^p_{i,j} \in \{0,1\}$.

Instead of defining flow on arcs, flow on paths can also be expressed. If L^p is the set of paths for resource p from the origin $o(p)$ to its destination $d(p)$, the flow on path l can then be defined as h^p_l, where $l \in L^p$. Finally, to set out the path l, the parameter $\delta^{l,p}_{i,j} \in \{0,1\}$ describes if the arc (i,j) is in path l. If $\delta^{l,p}_{i,j}$ is 1, it does belong to the path. When $\delta^{l,p}_{i,j}$ is 0, it does not.

2.5.1. Arc-based Model Formulation

When the flow is defined on the individual arcs, the Fixed-charge Multicommodity Capacitated Network Design (FM-CND) as described by Zhu [101] with continuous flow variables and flow volume has the following outline.

$$
\begin{aligned}
& min \sum_{(i,j)\in A} f_{i,j} y_{i,j} + \sum_{(i,j)\in A} \sum_{p\in P} c^p_{i,j} x^p_{i,j}; && && (2.2)\\
& s.t. \quad \sum_{j\in N} x^p_{i,j} - \sum_{j\in N} x^p_{j,i} = w^p_i && i \in N, p \in P; && (2.3)\\
& \sum_{p\in P} x^p_{i,j} \leq u_{i,j} y_{i,j} && (i,j) \in A; && (2.4)\\
& (y,x) \in \phi && (i,j) \in A, p \in P; && (2.5)\\
& y_{i,j} \in \{0,1\} && (i,j) \in A; && (2.6)\\
& x^p_{i,j} \geq 0 && (i,j) \in A, p \in P. && (2.7)
\end{aligned}
$$

In the following model, the objective is to minimize the sum of the fixed design costs and the variable flow cost, as seen in 2.2. To meet the demand, the constraint as in 2.3 expresses that the flow over every must be equal to the demand.

$$
w^p_i = \begin{cases} w(p) & \text{if } i = o(p) \\ -w(p) & \text{if } i = d(p) \\ 0 & \text{otherwise.} \end{cases}
$$

Constraint 2.4 ensures that the flow on arc (i,j) will always be smaller than the capacity. Here, $y_{i,j}$ is the notation to see if the arc is present, means that when $(y = 0)$ the arc is closed and with $(y = 1)$ the arc is open for flow. The formulation for constraint 2.4 is for a directed arc. If however an undirected arc is to be used, the constraint needs to be replaced by the following:

$$
\sum_{p\in P} (x^p_{i,j} + x^p_{j,i}) \leq u_{i,j} u_{j,i} \qquad (i,j) \in A. \tag{2.8}
$$

The flow can only be in one direction. If this direction in not known, both flow direction are taken into account as constraint 2.8 illustrates by both $x^p_{i,j}$ and $x^p_{j,i}$.

Since the objective is a cost minimization, another constraint can be added which takes the maximum amount of expenditures, the budget B, into account, as such:

$$
\sum_{(i,j)\in A} f_{i,j} y_{i,j} \leq B. \tag{2.9}
$$

2.5.2. Path-based Model Formulation

The previous model has an arc based formulation. The origin node o(p) can be connected to its destination node d(p) by a series of arcs. The set of all these arcs forms the path, noted as $l \in L^p$. The flow on this path is then h^p_l. The Path-based Fixed-charge Multicommodity Capacitated Network Design (P-FMCND) suggested by Zhu [101] formulation of the model is therefore slightly different then the arc-based version.

$$min \sum_{(i,j)\in A} f_{i,j} y_{i,j} + \sum_{p\in P} \sum_{l\in L^p} k_l^p h_l^p; \tag{2.10}$$

$$s.t. \quad \sum_{l\in L^p} h_l^p = 1 \qquad p \in P; \tag{2.11}$$

$$\sum_{p\in P} \sum_{l\in L^p} h_l^p \delta_{i,j}^{l,p} w(p) \leq u_{i,j} y_{i,j} \qquad (i,j) \in A; \tag{2.12}$$

$$y_{i,j} \in \{0,1\} \qquad (i,j) \in A; \tag{2.13}$$

$$0 \leq h_l^p \leq 1 \qquad l \in L^p, p \in P. \tag{2.14}$$

$$\tag{2.15}$$

Constraint 2.10 is to conserve the flow. Constraint 2.12 ensures that the demand of resource flow is met. The variable cost k_l^p found in the objective function can be expressed as:

$$k_l^p = \sum_{(i,j)\in A} c_{i,j}^p \delta_{i,j}^{l,p} w(p). \tag{2.16}$$

2.5.3. Intersection control

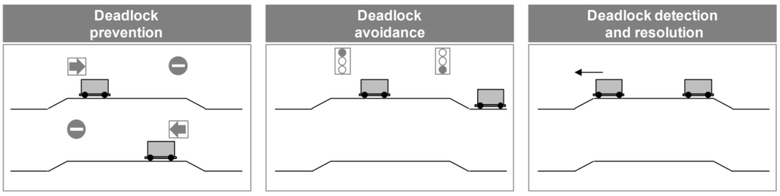


Figure 2.4: Multiple types of deadlock control source: N. Klein

2.5.4. Solution Methods

Network design models

2.6. Train rescheduling

Most large railway systems such as the public transport systems have an arrival schedule.
MAKE SECTION ON RESCHEDULING B. FAN

2.7. Locomotive Assignment Problem

The locomotive assignment problem (LAP) cannot be seen as a single problem, but as a class of multiple problems. The objective of the LAP is commonly to optimize the costs, profit, fleet size or level of service [71]. The LAP can be split into three individual sub-problems:

1. Locomotive planning problem (LPP);
2. Locomotive scheduling problem (LSP);
3. Locomotive routing problem (LRP);

2.8. Deadlock

2.9. Discrete event simulation

With the help of a discrete event simulation, the possible improvements of the previous chapter can be simulated to test their influence on the operational performance in a simplification of the real situation. The KPIs will be the criteria on which can be determined if the possible improvement has a true positive effect in the simulated environment.
Programming Environments

- Rockwell Arena
- Symio
- Simflex
- MATLAB Simulink
- Delphi
- AnyLogic

2.10. Lean thinking in transport operations

The application of lean thinking in production systems has been known since the era of Henry Ford and the mass production systems build for Ford automotive [17]. However, the true adaptation of lean manufacturing was started by the Toyota automotive production system. Toyota has been famous for its system in continuously identifying wastes in their production system and resolving these types of waists. The Toyota way of thinking has been described extensively in literature [30, 69, 76]. Waste elimination is of extreme importance for customer value. Customers are not paying for the wastes in the production process, but rather on the value adding processes. By separating waste and value-adding processes, and by categorizing waste types.

2.10.1. Waste identification in transport operations

The application of lean thinking in transport systems has only seen a few studies so far. Sternberg was one of the first who applied the waste identification of the lean manufacturing to road transport [87]. Sternberg concluded that only 5 of the original 7 types of waste are applicable to a road transport system. The waste of excess inventory was not applicable in a transport system, as well as excess conveyance. Sternbern identified two new waste types for a road transport system, being resource utilization and uncovered assignments. An overview of the waste types are shown in Table 2.2, which is an adaption of Sternberg [87] by Villareal [95]. Guan [91] added a 5 waste type system for road transport specific being driver breaks, excess load time, fill losses, speed losses and quality delays.

2.10.2. Kaizen: continuous improvement

The theory of lean explains the identification of waste in a process. The focus lies on the customer, and how value for the customer can be created. Processes that do not create value for the customer and are not essential are noted as waste. Kaizen is a step further [**?**]. Kaizen is the continuous identifying of waste in a process and trying to resolve this waste. The identification step is important, since the awareness of waste will only rise if people know where to look for. If people can identify waste, they could also find a proper solution to resolve the waste. Not using the skill of people is a waste type of its own.

2.10.3. Lean-based performance measures in transport operations

The types of wastes found in Table 2.2 are different than the original waste types for lean manufacturing. A transport process does not have the goal to produce any type of product. The goal in a transport process is to move a certain entity from one location to a desired next location in an (cost) efficient way. Therefore, the performance of a transport system from a lean perspective must also be adapted.

In the original field from lean manufacturing, the overall equipment efficiency (OEE) is a way to review and improve equipment use. A view on this matter for a general truck transport system is given by Simmons [84] by the use of an overall vehicle effectiveness (OVE). This metric uses the available time, and assesses the losses that occur during this available time. It defines 3 categories, the availability, performance and quality. A multiplication of these 3 forms the OVE value, as such:

$$\text{OVE} = (\text{Availability}) \times (\text{Performance}) \times (\text{Quality}) \tag{2.17}$$

The blocks of equation 2.17 are shown in part (A) of Figure 2.5. An alternative view on the OVE is started by Guan [91] and Villareal [95]. They suggest not to use the available time, but the total time. So no distinction between useful and not-useful time is made. The total overall vehicle effectiveness (TOVE) as suggested by Guan and later by Villareal. It splits the vehicle efficiency and the operational availability and makes the

Table 2.2: Lean thinking within a road transport system source: Villareal 2016 [95]

Waste Type	Description
(1) Overproduction	Producing reports no one reads or needs, making extra copies, e-mailing/faxing the same document/information multiple times, entering repetitive information on multiple documents and ineffective meetings
(2) Waiting	Employees having to stand around waiting for the next process step, such as loading and unloading, or just having no work because of lack of orders, processing delays, equipment downtime and capacity bottlenecks
(3) Incorrect processing	Consuming more resources for moving the goods than necessary due to inefficient routing or driving
(4) Unnecessary movement	Any wasted motion employees have to perform during the course of their work, such as looking for information, reaching for, or stacking goods, equipment, papers, etc. Also, walking and extra movement created by sequencing errors is waste. This was found to be synonymous with conveyance
(5) Defects	Waste caused by repairs, redelivery, scrapping, etc., due to damages on the transported goods or the equipment
(6) Resource utilization (new)	Waste due to excessive equipment and bad resource planning
(7) Uncovered assignments (new)	Carrying out unprofitable transport work due lack of information or planning

components mutually exclusive. The vehicle efficiency is defined by the administrative availability and the operational availability. The operational availability is set by the performance and the quality.

$$\text{TOVE} = (\text{Adm. Availability} + \text{Op. Availability}) \times (\text{Performance}) \times (\text{Quality}) \tag{2.18}$$

2.11. Lean thinking in rail transport

Lean production (LP) methods from the Toyota production system (TPS) have not yet been applied to rail transport by many researchers. Hong-Chang [40] addresses the value chain engineering way of thinking from the TPS into railway transportation. The crux that is noted is the question whether lean production theory, used for manufacturing processes, can be applied to a service industry. Hong-Chang shows several cases where this has been done, and therefore states that service industries such as railway transportation can be improved by lean thinking.

While the most common known tool in lean production is the elimination of wastes in the system, more tools such as Kanban, JIT, inventory management and organizational improvements are also part of the TSP. Hong-Chang notes that the most important objective of lean thinking in railway operations is to improve punctuality. To be on time is important since the planning of processes after transport rely on the rail transport. Uncertainty in this transport implies that people or businesses must keep a buffer time, which by the definitions of LP is a waste.

Jianjuan has reviewed the objective of lean thinking in rail transport as firstly to eliminate as much possible waste in the links and processes and secondly to create as much value for the customer [46]. This second objective can be seen as performing the required transport request in time, with the least amount of cost.

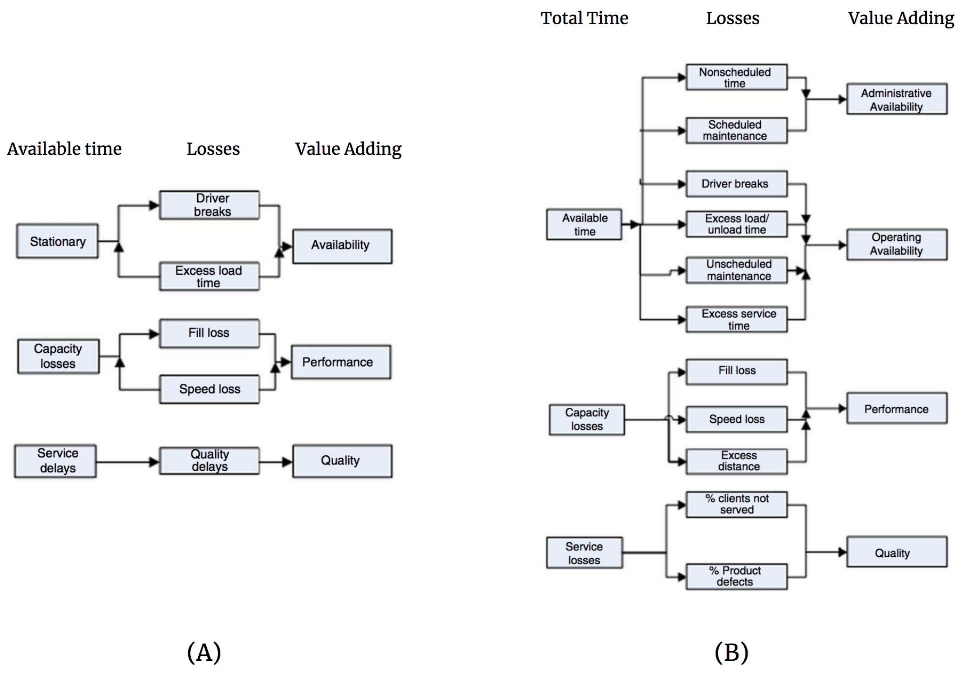


Figure 2.5: Definition of efficiency of performance through lean thinking. (A) is the overall vehicle effectiveness defined by Simmons [84], and (B) the total-time overall vehicle effectiveness defined by Guan [91] and improved by Villareal [95] source: Sternberg [**?**]

Sekulova shows a case study at several national railway systems where lean thinking is implemented [83]. The main attribution is that regulation can help to increase the reliability and therefore can create value for customers. Customer focus is the most promoted focus, which resulted in the monitoring of the punctuality of the German and Swedish national railway system.

2.12. Conclusion

From the many different definitions found for the capacity of a railway network, it can be concluded that the demand of transport tasks, in any form, cannot be separated from the demand and infrastructure if the performance is to be measured. The capacity of a railway system is therefore inherent of the demand input. This demand can have different forms; the amount of load, wagons or units transported, the transport tasks performed, the locomotive distance driven or the locomotive driving hours. Since many components make up a complete railway system, the measurement of the performance is bound to the way the network is utilized. No general performance measurement for all railway systems can be defined, since the processes within a railway systems cannot be seen as individual processes but are better represented as a single complex coherent process.

The literature regarding industrial railway systems is highly limited. These systems are mostly private owned and found in companies where the demand for internal transport of goods is high. Industrial railway systems are the most cost effective mode of transport. Most systems have little to no information present regarding the real-time location of trains, transfer and processing times. So smart solutions are minimal in these systems. Most research on railway systems is focuses on large national-wide systems where freight transport can occur, but passenger transport is dominant. Industrial railway systems are different due to the relative many destinations per area, low speeds and bidirectional rail tracks.

Lean thinking is a useful tool to assess the current state of a transport process and to evaluate improvements on complex systems. The classic lean manufacturing do need an alteration step in order to be applied to a transport system, since in a transport system value for customers is created by being (1) reliable, (2) punctual and (3) at a low costs. These 3 aspects can be formed into metric by frameworks where the waste and valuable time are separated.

Lean thinking in the field of rail transport is new. Since most lean manufacturing ideas can be applied reasonable simply to any manufacturing process, lean thinking within railway operations is not. It requires a bespoke approach, and therefore the only true aspects that is found in literature is to focus on customer value.

2.13. Research relevance

Industrial railway networks have not been studied extensively. This research contributes in in the process defining and optimization of industrial railway systems by interpreting the system as a single process. The effects of local optimization of railway processes to the system as a whole are unknown unless the scope is to contain the complete railway system. Optimization of these systems is complex, since the movement of trains is not scheduled but carried out on operational basis. This research aims to provide insights in the effects of (local) optimizations on the global performance of an industrial railway system, which has not been done before.

Since it is concluded that the capacity of a railway network cannot be identified without its demand, the necessity of a bespoke approach rises. Each railway system is different, and therefore the performance is measured differently. Even more, the way the performance of a complete railway system is influence is system dependent. This research provides a view on how this can be done for a real-life case.

Furthermore, lean thinking in freight rail networks has not been performed before. This is a new field of study, and this research aims to provide knowledge for this research gap.

3
System analysis

Currently the railway operations at Tata Steel provides sufficient transport capacity. There is no structural shortage of railway capacity. However, a variety of processes have inefficiencies. These inefficiencies result in unnecessary costs, delays, system unreliability, less punctuality and loss of rail transport capacity. As describes in the Introduction 1, the main problem is that it is unknown if the current railway network with its infrastructure can meet the transport demand of the future.

In the introduction, a general understanding on the term of railway capacity is given. In this chapter, an in depth analysis of the railway system at Tata Steel is given. Question to which an answer is sought is:

> *How does an industrial railway system work, what is the current and future demand for railway transport for a specific industrial railway system and where can inefficiencies be found?*

3.1. Understanding and defining the system

In this section, the processes that make up the railway system are detailed. Furthermore, the processes and characteristics are defined. Values essential to the system are obtained through analysis.

3.1.1. Steel making process at Tata Steel IJmuiden

The steel making process starts with The influences on the movements done by the rail department start as early as when the sales department have their initial talks with customers. If this is successful, in the next step an order can be made. In this order, the specific quality, quantity and form of steel is fixed. Hereafter, the planning department starts by making the planning for the individual factories. To make a certain degree of steel, the raw material of iron ore and coal has to be of the correct composition. The procurement department is responsible for obtaining the correct quality of raw materials.

DESCRIBE STEELMAKING PROCESS

3.1.2. Future steel production

The vision on the future steel production of Tata Steel IJmuiden is not fully developed. With a changing market, and with an upcoming merger with ThyssenKrupp, the demand for steel and steel types changes year after year. A fact is that a higher steel production in general leads to a more cost efficient one, and so the goal is to upscale the production over the upcoming years. From insiders at Tata Steel is is expected that the current production of 6.9 million tons of steel is going to be scaled up to 8 million tons in 5 to 10 years. The limitation of around 8 million tons of steel is caused by the total carbon dioxide emission that is accompanied with this production. The steel making process is highly carbon intensive.

A new development in the steelmaking process is the HIsarna. This new method of producing steel is still in development, but the goal is to make the steelmaking process 50 percent more efficient in terms of carbon emissions [7]. The process is based on batch smelting. According to M2i [7], HIsarna combines the heating and partial pyrolysis of coal in advance. Hereafter the two are in a cyclone, were the ore melts. Since this process is substantially less carbon dioxide intensive, the limitation of 8 million tons of steel production with the normal process could be scaled up even further by the use of the HIsarna method. However, it is yet unclear if the HIsarna method is able to produce large quantities of steel, and if it would, it would still require further development before implementation. For this research a possible future production of 9 million tons is taken as a maximum.

3.1.3. System boundary

While every step from the steel making process will influence the transport needs over the rail network, not all details can be taken into account for this research. The system boundary for this research lie at the end of the rail network in every factory of the Central network. This implies that the planning of the goods that need to be transported is not taken into account. So every shipment is seen as equal, no matter the size. It is the task of the rail department to perform the requested amount of transport movements, and therefore the system boundaries lie here. Improvements can certainly be made in the planning of the transport of steel goods, but these lie outside of the system boundary. In Figure 3.1 the described system boundary is displayed.

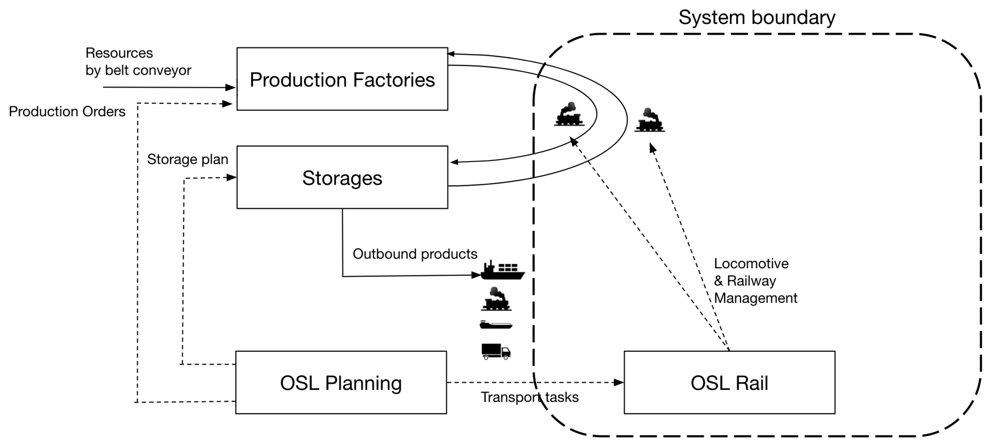


Figure 3.1: Defined system boundary of this research

This boundary is furthermore chosen due to the fact that the rail department performs more function than transporting wagons, loaded or empty, from one location to another. The rail network together with its rolling equipment acts as a buffer. An example of this function is the following. Large transport vessels heading towards Canada are loaded at one of the outdoor quays, for instance BUKA 1. The loading of this ship takes around 8 hours. If a certain storage location has a substantial amount of steel coils destined for this ship, multiple rail shipments are needed to transport these coils to the BUKA 1 crane facility and storage. However, in the origin storage, only a single track exists where 4 wagons can be loaded with steel coils. So only one transport of coils can be loaded in here. Before the ship arrives ate the port, a rail shipment of 4 wagons has already been taken by a certain locomotives and positioned somewhere on the rail infrastructure. Now 4 empty wagons can be placed inside the storage facility, and the loading of these new wagons can already take place. In such a way, by storing coils of steel on wagons, the buffer function of the rail department is exposed.

Now that the system scope is defined, the next step is to define the used definition for railway capacity. The large variations in the definitions of the railway capacity found in literature show that a bespoke definition will always need to be made depending on the specific system. In the Tata Steel IJmuiden case, a timetable free dispatching policy is present. This means that for the capacity there is no reference schedule which can be used to assess the current capacity usage. Furthermore, the system scope does not include the planning of steel coils, and so every request for transport is equal, no matter the size or amount of coils transported. Every transport request can be seen as a 100 % use of capacity. The amount of wagons or the load does not influence this effective capacity.

The Central rail network at Tata Steel IJmuiden is predominantly an export terminal. The incoming trains transport lime and sporadically equipment to the site. These transportation tasks form only a minor part (<3%). This means that the locomotives will drive with steel coils to the export terminals, and drive empty back. This empty back driving is therefore inevitable. It is for that reason seen as an utilization of the transport capacity.

3.1.4. Demand for transport

The steel products that are produced at Tata Steel IJmuiden have to be transported several times to different facilities such as a hot rolling mill, cold rolling mill, the galvanizing plants and to export locations. The On-Site Logistics (OSL) department constructs a plan to transport these steel products, and initiates a transport schedule consisting of transport tasks. Planners from OSL transform the orders of the clients into a planned production.

The main task of the rail department is to perform the requested transport tasks. Whenever transport is needed, the planner make a transport task in Planwise, as shown in Figure 3.2. This can be as early as a week in advance, but most of the transport tasks are formed in the 24-48 hours in advance. So the birth of a transport task takes place here. Every transport task has a time window for picking up the load from the origin and a time window for the delivery at the destination. Furthermore, every task has information regarding the amount of wagons, amount of steel coils and weights of the coils. Below, this information regarding a transport task is clarified:

$$\text{Transport task} = \begin{cases} \text{Origin}, & [t_{o,1},\ t_{o,2}] \\ \text{Destination}, & [t_{d,1},\ t_{d,2}] \\ \text{Load}, & [\#\,\text{Wagons},\ \#\,\text{Coils},\ \text{Weight}] \end{cases}$$

The value for $t_{o,1}$ is the earliest allowed pick-up time for this transport, and the latest time the task needs to be picked-up is $t_{o,2}$. The same holds for delivery at the destination location, $t_{d,1}$ and $t_{d,2}$.

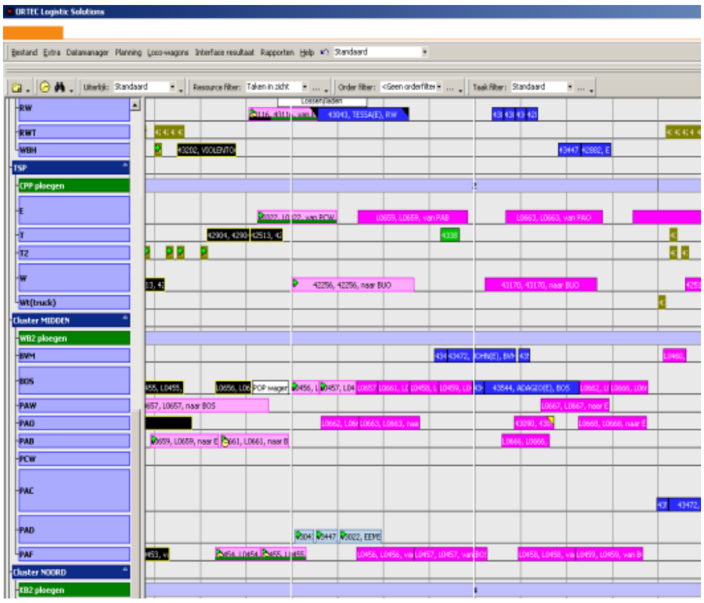


Figure 3.2: Planwise: rail transport planning tool

The information availability at Tata Steel regarding the realized train movements is minimal. The individual rides of locomotives are not tracked, nor are the amount of transport tasks tracked. This complicated further optimization research, since the start of any optimization starts with identifying the current state.

In Planwise, every task has a departing and arriving time slot. Most time slots are 30-60 minutes minimum for departure, and up-to 8 hours for arriving when large vessels need to be loaded. Both these slots are changed by a controller for optimization purposes when the time until execution becomes smaller. For instance, the departing time can be postponed when another task with more priority has got delayed. The arriving time for large vessels heading towards far destinations such as the United States have a long loading time. So these transport tasks are planned the furthest in advance, and have a large buffer in their arriving time to ensure that the ship can depart at the correct time. If for instance the weather turns from a sunny day into rain, the ship cannot be loaded, since water can build up near the steel coils. The loading process has to be postponed until the rain has gone by.

The Planwise transport tasks consist of wagons, amount of rolls and the weight of the rolls. The weight and amount of rolls are logged by another IT system, but unfortunately here the individual tasks disappear and only the sum of the tons is logged. The finance department keeps track of the transported tons of steel between the different facilities in order for the internal billing. In Figure 3.3 the month total of May 2016, which has a slightly above average amount of tons moved, is shown.

	Destination															
Origin	BOSWEG	HAL BVM	HAL CPP	HAL CPR	HAL KB1	HAL KB2	HAL PAF	HAL WAW	HAL WB2	HAL WBH	KADE	NS	TRH	WEEGBRUG	HAL CPRCH	Grand Total
BOSWEG	1922	52			2469		146267		9635		44719	1140				206203
HAL BVM					1418		994	634	2494		42285	822	1403			50051
HAL CPP			592					11403			44776	2473				59245
HAL CPR				1484		2913					22012	22698	1887	541	1146	52681
HAL KB1									631							631
HAL KB2				20534		512		11	12702		105168	42294	20026			201247
HAL PAF	250								2171							2421
HAL WAW			184								4798					4981
HAL WB2	108122	33978		6082	87898	17750	11556		1091	11619	38041	1929	10483			328549
HAL WBH				154					363		5416	326	679	52		6990
KADE			57	3022		3520			526		3791		14623			25539
TRH				273		1495					5207					6975
WEEGBRUG				76												76
HAL CPRCH				39443		58943					683			1020		100089
Grand Total	110293	34030	833	71070	91785	85133	158817	12048	29612	11619	316896	71683	49100	1613	1146	1045679

Figure 3.3: Tons moved on the Central railway network in May 2016

3.1.5. Future demand of transport

From section 3.1.2 is is noted that the steel production could in the near future of 5 to 10 years be increased from 6.9 to 8 millions tons of steel. When the horizon is set further, a maximum of 8.5 million tons is taken.

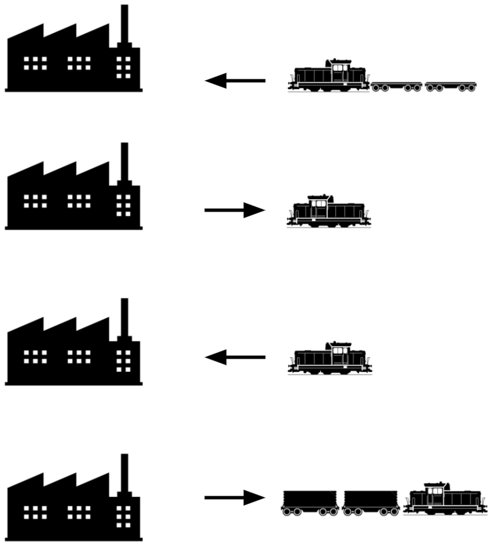
The number of train rides will likely not increase linear with the increase in production. Since currently now all wagons are filled up to the maximum number of steel coils, and since not all rides contain a maximum or near maximum number of wagons, efficiency in loading the sets of wagons will rise with an increase in demand. It is assumed that 10 percent of the newly added transport request can be filled by effectively management of current requests. The future percentage increase of transport rides for different production scenarios is displayed in Appendix A, in section A.2.

3.1.6. Empty wagon management

The data of total weight transported and the way the transport tasks are defined may at first seem as if only full wagons with steel products are transported. As logic implies, at every location where steel products are loaded onto empty wagons, empty wagons will need to be present there beforehand. These wagons are available in a limited amount, and so the management of these wagons plays an important role. To complicate the system further, wagons are used to store steel products on the railway track.

From a general point of view, the pickup and delivery process of steel products goes according to Figure 3.4. First (1) empty wagons are transported to the facility. The locomotive leaves the wagons and goes on for another task (2). Thirdly, the locomotive arrives to pick up the filled wagons at a later time (3). Last, the locomotive drives away with wagons filled with steel products (4).

As can be seen, in general the locomotive will visit a facility twice in a single repetition cycle. This can be more if only a limited amount of wagons are picked up for transport, but this is exceptional. Empty wagons are often transported to the central station where a buffer of wagons of several types is held. Combining loads from different facilities with full, empty or a combination of the both is not uncommon. Local optimization of load picking has been done for several decades, and so the current system can get complex.



(1)

(2)

(3)

(4)

Figure 3.4: Delivery and pickup process of wagons

3.1.7. Indication of the number or locomotive rides

The number of train rides is not tracked, but from the total tons moved and from an average steel coil weight, an indication on the number of locomotive rides can be made. This indication must consist of full wagon rides, empty wagon rides and empty rides.

Every facility handles different coils. The coil weight can differ significantly between the facilities. In Appendix A, Figure A.0.1 the average coil weight of the transported steel coils is shown for the period of Q4 2016 and Q1 2017. When this average coil weight is multiplied with an estimation of the amount of transport wagons per ride, the transported tons of Figure 3.3 can be transposed into an estimated number of transport tasks, as shown in Figure 3.5.

	Destination															
Origin	BOSWEG	HAL BVM	HAL CPP	HAL CPR	HAL KB1	HAL KB2	HAL PAF	HAL WAW	HAL WB2	HAL WBH	KADE	NS	TRH	WEEGBRUG	HAL CPRCH	Grand Total
BOSWEG	10	0	-	-	13	-	758	-	50	-	232	6	-	-	-	1069
HAL BVM	-	-	-	-	7	-	5	3	13	-	219	4	7	-	-	260
HAL CPP	-	-	3	-	-	-	-	59	-	-	232	13	-	-	-	307
HAL CPR	-	-	-	8	-	15	-	-	-	-	114	118	10	3	6	273
HAL KB1	-	-	-	-	-	-	-	-	3	-	-	-	-	-	-	3
HAL KB2	-	-	-	106	-	3	-	0	66	-	545	219	104	-	-	1044
HAL PAF	1	-	-	-	-	-	-	-	11	-	-	-	-	-	-	13
HAL WAW	-	-	1	-	-	-	-	-	-	-	25	-	-	-	-	26
HAL WB2	561	176	-	32	456	92	60	-	6	60	197	10	54	-	-	1704
HAL WBH	-	-	-	1	-	-	-	-	2	-	28	2	4	0	-	36
KADE	-	-	0	16	-	18	-	-	3	-	20	-	76	-	-	132
TRH	-	-	-	1	-	8	-	-	-	-	27	-	-	-	-	36
WEEGBRUG	-	-	-	0	-	-	-	-	-	-	-	-	-	-	-	0
HAL CPRCH	-	-	-	205	-	306	-	-	-	-	4	-	-	5	-	519
Grand Total	572	176	4	369	476	441	823	62	154	60	1643	372	255	8	6	5422

Figure 3.5: Estimated number of transports jobs including empty routes and wagon delivery in May 2017

Since the information from Figure 3.5 only contains an estimation, the actual data containing the total amount of full wagon transport tasks is unknown. Another method to assess the amount if train rides is discussed hereafter, by means of GPS analysis. The average number of rides for this method lies at 175. Since in real life loads of different wagons for different factories are combined and at certain locations the locomotive can pickup wagons after it has dropped of its initial wagons, this estimation will only work as a ball figure.

3.1.8. GPS analysis for the number of rides

The locomotives are equipped with GPS trackers. For a time period of several months in 2017, the GPS locations of the locomotives was obtained. This raw data contains information of the latitude and longitude of the locomotive at a sampling time of more or less 5 seconds. The GPS data is used to identify the number of rides from one location to another through another method besides the estimation made in the previous section.

The raw GPS data only provides the coordinated, speed, date, time and locomotive number. To identify if the locomotive is at a specific known facility, the spread of GPS coordinates of the individual facilities are determined. As an example, Figure 3.6 A shows a series of coordinates where the black dots fall into the facility and the red ones outside of the facility. If a computer model needs to identify if the coordinates fall into the facility, the minimum and maximum latitude and longitude of a box can be taken at which most of the coordinates that are inside the facility as shown in Figure 3.6 B.

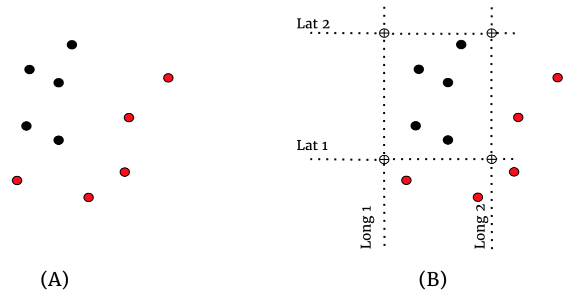


Figure 3.6: Location identification through GPS analysis

Since only the rectangle shape of a box is taken, it could be that some GPS data points will fall just outside or inside the box which should not be there. Logic in the data analysis is implemented to prevent unwanted behaviour with the help of a MATLAB script, which can be found in Appendix C. The image of Figure 3.7 shows the plotted GPS data of Locomotive 824 for a period of 18 days in May 2017. The image is zoomed in on a specific part of the network, and the purple boxes show the used coordinates for these three facilities as described. A red line indicated that the train has stopped or has a very low speed and dark blue indicates that the locomotive runs at full speed.

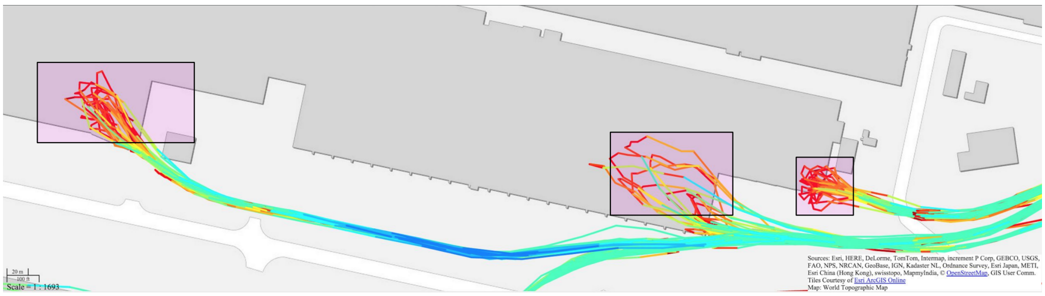


Figure 3.7: Applied GPS localization

Since buildings and other obstacles can interfere with receiving GPS signals, the accuracy drops when a locomotive encloses onto a facility. If for instance a look is taken at the far left box in Figure 3.7, the spread of GPS signals lies around 60 meters wide, while the track is only around 2 meters wide. So therefore, a large margin and some data logic is used in order to prevent incorrect allocation of GPS signals to facilities.

By applying these boxes for every facility entrance a train can go, an identification of when a locomotive is at a location is done. Even more, the time it takes to drive from one location to another can now also be obtained, as well as the waiting time at a location. For now, the most interesting part is the number of rides from one location to another. In Figure 3.8 the summation of these rides per day is given.
The average number of rides from one location to another lies at 202. This is higher then the 175 of the estimation through transported weight. The number of rides found with GPS signal is taken as the most accurate one.

3.1.9. Route times

The times it takes for the locomotive to drive from one location on the track to another is an important factor. While some transport tasks take 3 minutes to complete, other can go up to 40 minutes. A transport task from

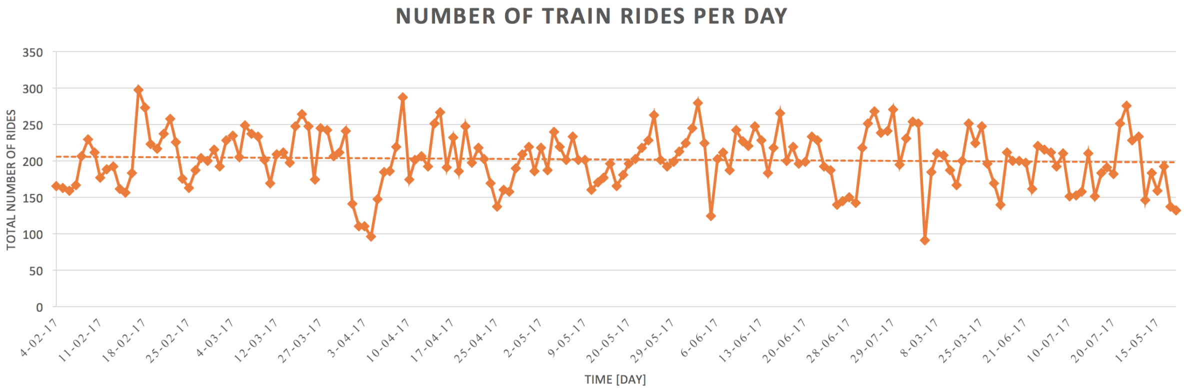


Figure 3.8: Number of locomotive rides per day

a origin to a destination will have to be completed by driving on many different parts of the network. The Central rail network at Tata Steel IJmuiden is split up into sections. The sections are defined by a begin and end by either a facility location or a railway switch. On each section between two switches, only a single train can drive, except for double track parts in the network. For simplicity reasons, some parts of the network with multiple switches are taken as one single section.

3.1.10. Real-life time measurements

By measuring the clock times while driving along with the locomotives, several section driving times are obtained. These initial timing formed the base to make a proper estimation on the driving times of missing parts of the network. The created timings include the stopping of the locomotive to change the direction of an occasional railway switch. The same holds for stopping due to the traffic of other locomotives.

Figure 3.9: Google Maps image source: Google Maps

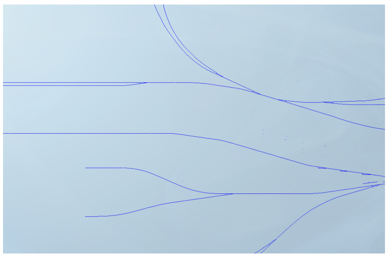


Figure 3.10: Filtered map on rail specifics

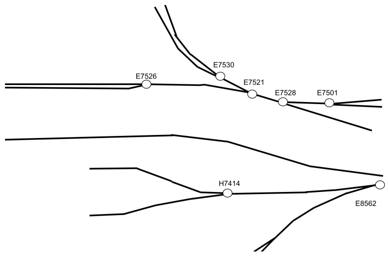


Figure 3.11: Nodal rail network

When the measurements are combined with the estimations of the remaining sections, the determined route times are as shown in Figure 3.12.

3.1.11. Using GPS data for route times

The locomotives are equipped with GPS sensors. When the locomotive heads to the maintenance department, this data from this tracker is stored. In Figure 3.7 an image of the plotted GPS data is shown. This plot is made from the data provided by a single locomotive on a single day, on a section of the network. The red lines are the slowest steps, meaning the train has made a stop there or drives at a speed below 1 km/hr. The more blue the line is, the higher the speed. Normally, the trains drive at a maximum of 15 km/hr. The diesel engine of the locomotives is controlled in a way that at this speed the engine will not provide more power. In some cases however, the large gravitational pull on the train lets it drive faster than this 15 km/hr maximum driving speed.

The advantage of GPS analysis is that it holds unbiased information. Firstly, when measuring route timings by hand, it could be that driving along with the locomotive operating staff could influence their normal driving behaviour. Since for most locomotive only a single operator drives the locomotive, this could be an

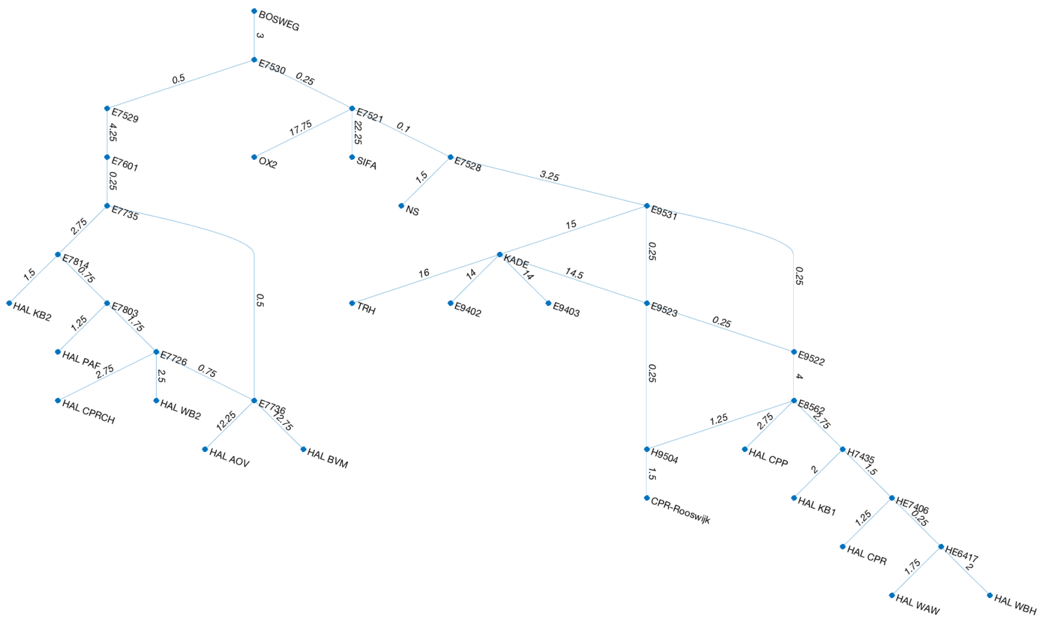


Figure 3.12: Nodal model of the Central railway network. The arcs in the network represent the driving times in minutes between the sections

issue. Secondly, the difference in driving behaviour between the operating staff can bias the measurement results as well. One operator could work substantially faster or slower than another. By so, the assessment of the route times could be influenced.

The GPS localization of the locomotives is used to determine the route times as well. The moment the locomotive departures from one location until it is within the GPS zone of another location is set as a single route. The locomotive driving personnel now (un)couples the load, and then continues to the next location. From this process, the individual routes and route times are assessed.

As an example, the route times from the BM hall to the Central location from 4 February to 12 July are displayed in a histogram in Figure 3.13. A log-normal distribution is fitted, since the histogram shows a short left-tail and a very long right-tail. For future simulation purposes, it is useful to simplify the route time to a mean average. To do so, the largest 5 percent of the data is left out of context, and a mean average of the 95 percent of data points is taken. This is done for every possible route, and the results are displayed in Appendix D.

3.1.12. Locomotive turnaround time

The turn around time of locomotives is mainly influenced by the coupling and decoupling of wagons, the inspection of the load, walking to and from the beginning of the set of wagons and waiting for instructions by the local controller. Furthermore, it happens occasionally that loads on the wagons are misplaced, and so a delay occurs since a crane operator has to move the load. A histogram of the turnaround time is placed in Figure 3.14. Values found below 1 minutes and above 45 minutes are removed from the data set due to likely other explanations for their quick or slow turnaround time.

3.1.13. Shunting and wagon management

Locomotives themselves do not carry a load of steel coils, but the wagons that they either push or pull do. 7 types of wagons are used, which complicated the management of wagons. Factories require a specific type of wagon to load their steel coils on. When a locomotive picks up a few wagons of type on, and then picks up more wagons of another type, the wagons must be resorted near the Central location. This sorting is called shunting. It takes the drivers of the locomotive substantial time.

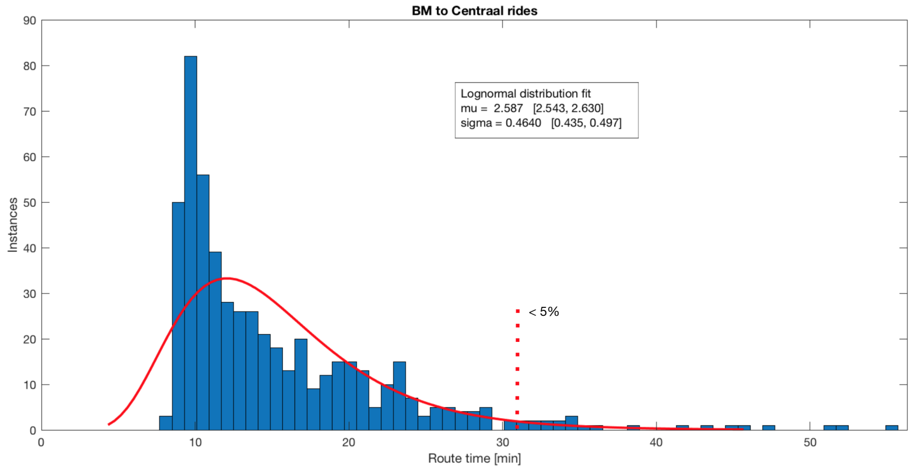


Figure 3.13: A histogram of the time it took a locomotive to drive the BM-Central route. The GPS data used is from from April to July 2017. A log-normal distribution is fitted.

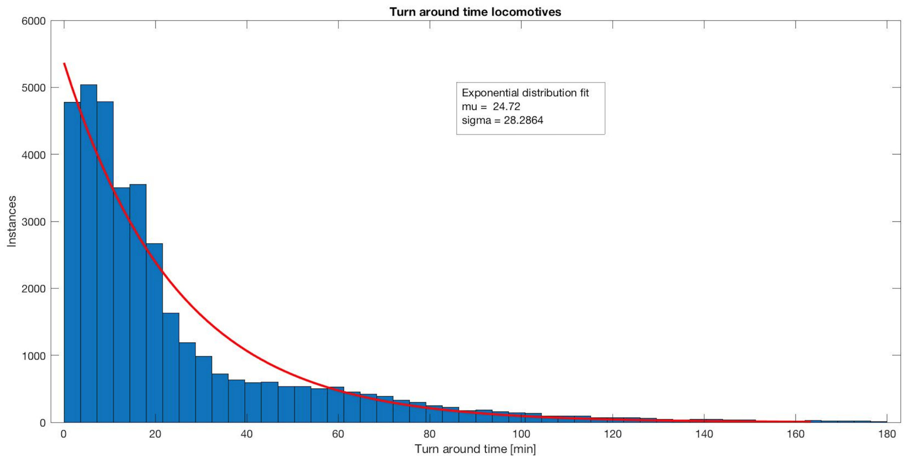


Figure 3.14: A histogram of the turnaround time of locomotives. The GPS data used is from from April to July 2017. An exponential distribution is fitted.

3.1.14. Realized throughput

To start, a period of one month is taken. To define an average throughput of tons, a view is given on the yearly results. These are shown in Figure 3.15. From this figure, the month of October 2016 is just above average. This month is picked due to the little peaks in the transported goods.

The next step is to identify the traffic on the sections. Is it not the amount of train movements that are leading, but the occupational time a train is situated on that specific part of the track. In this way, the used capacity of that specific part of the railway track can be identified.

3.1.15. Nodal network model Tata Steel site

To represent the Central rail network between the different locations at Tata Steel IJmuiden, a adjacency matrix is made. In this matrix, the links between different transport location are represented in the table. This is represented in Figure 3.16.

This adjacency matrix can be used to build a nodal network model for the network. The transport locations are represented by nodes, and the existing links between the locations are represented by the arcs. This network can be used to identify optimal routes. With the help of MATLAB, the shortest path problem can be solved.

Rail Transport (Ton)	2016	2016	2016	2016	2016	2016	2016	2016	2016	2017	2017	2017	Bookyear	
Origin	4	5	6	7	8	9	10	11	12	1	2	3	Total	Average
AF-HAV	-	-	-	-	-	-	-	-	-	-	-	-		
BOSWEG	203 813	206 203	189 039	193 328	160 927	183 705	185 592	211 805	196 584	212 236	172 920	199 440	2 315 592	192 966
HAL AOV	-	-	-	807	-	-	-	-	5 748	14 912	25 080	56 804	103 351	8 613
HAL BVM	50 037	50 051	72 189	54 549	82 846	61 997	59 281	62 932	1 990	31 765	52 224	59 143	639 004	53 250
HAL CPP	36 621	59 245	60 399	57 729	53 199	51 162	48 988	45 346	48 466	47 711	42 756	47 708	599 330	49 944
HAL CPR	21 231	52 681	62 512	64 121	59 082	62 233	52 576	61 261	55 079	46 277	47 063	50 678	634 794	52 899
HAL CPRCH	80 635	100 089	91 154	90 246	90 012	87 450	95 111	96 271	84 070	92 868	85 673	89 138	1 082 717	90 226
HAL FS	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HAL KB1	837	631	1 278	1 451	832	1 402	1 527	1 817	1 185	1 156	2 325	2 200	16 640	1 387
HAL KB2	222 100	201 247	196 093	204 683	197 573	193 115	210 435	181 650	131 789	167 749	159 199	190 006	2 255 639	187 970
HAL PAF	3 297	2 421	2 414	3 129	5 064	5 108	4 975	2 209	3 799	2 838	1 615	3 481	40 350	3 363
HAL WAW	2 179	4 981	9 430	3 945	1 750	7 918	1 862	7 476	4 080	2 318	2 824	3 511	52 274	4 356
HAL WB2	305 348	328 549	327 007	322 382	299 201	329 428	345 632	276 812	245 345	341 836	306 113	359 353	3 787 005	315 584
HAL WBH	16 588	6 990	13 760	9 446	18 397	15 749	17 375	13 389	17 860	25 581	12 367	8 638	176 138	14 678
KADE	17 590	25 539	32 399	68 127	18 786	22 909	25 082	35 366	21 427	23 289	20 250	27 415	338 180	28 182
NR-HAV	-	-	-	-	-	-	-	-	-	-	4 321	13 231	17 552	1 463
NS	57 225	48 572	57 425	51 500	54 290	55 176	55 336	51 558	39 130	34 092	37 384	46 780	588 469	49 039
OPSL. AOV	-	-	-	448	20 594	7 021	106	-	12 147	7 640	9 485	43 534	100 975	8 415
OX2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SIFA	-	-	-	-	-	-	-	-	-	128	-	-	128	11
TRH	9 003	6 975	4 229	7 010	9 376	9 378	6 846	8 146	10 785	6 382	11 969	7 562	97 661	8 138
WEEGBRUG	366	76	-	-	-	-	-	44	-	-	103	-	589	49
Total	1 026 869	1 094 251	1 119 329	1 132 900	1 071 928	1 093 751	1 110 724	1 056 081	879 484	1 058 777	993 670	1 208 625	12 846 389	1 070 532
vs annual average	-4%	2%	5%	6%	0%	2%	4%	-1%	-18%	-1%	-7%	13%		
Destination														
AF-HAV	-	-	-	-	-	-	-	-	-	-	240	68	308	26
BOSWEG	97 403	110 293	100 793	133 380	93 289	100 743	154 549	109 663	76 216	113 917	96 242	120 808	1 307 294	108 941
HAL AOV	-	-	11 255	3 910	1 592	-	-	-	-	-	628	1 381	18 766	1 564
HAL BVM	31 326	34 030	36 617	16 218	37 111	41 496	27 075	19 851	-	27 551	24 608	27 360	323 243	26 937
HAL CPP	166	833	436	583	288	931	285	492	351	157	154	247	4 922	410
HAL CPR	25 021	71 070	55 290	61 604	64 612	53 910	58 757	71 664	57 213	46 513	49 308	55 926	670 888	55 907
HAL CPRCH	284	1 146	294	673	711	878	930	544	350	173	283	522	6 788	566
HAL FS	-	-	-	-	-	-	-	-	-	-	-	50	50	4
HAL KB1	68 614	91 785	86 908	81 848	79 739	70 549	82 856	59 713	85 208	75 536	88 227	87 364	958 346	79 862
HAL KB2	99 434	85 133	78 624	83 510	80 953	75 385	81 571	82 791	65 765	78 822	74 869	82 393	969 251	80 771
HAL PAF	133 454	158 817	147 152	151 405	121 624	131 984	132 316	156 050	158 457	112 422	114 531	165 662	1 683 874	140 323
HAL WAW	8 327	12 048	7 256	8 389	10 760	4 311	7 023	6 478	8 983	11 234	12 831	11 368	109 007	9 084
HAL WB2	41 833	29 612	27 004	33 328	90 820	49 320	36 170	35 920	34 253	62 623	42 765	21 197	504 844	42 070
HAL WBH	13 061	11 619	14 797	13 590	13 825	24 530	10 471	21 810	10 294	27 651	10 370	9 326	181 345	15 112
KADE	307 812	316 896	357 847	325 086	266 441	329 325	307 602	308 066	211 455	307 218	279 246	389 825	3 706 820	308 902
NR-HAV	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NS	88 998	71 683	85 968	88 143	84 222	98 372	87 890	91 210	92 077	118 243	123 941	147 319	1 178 065	98 172
OPSL. AOV	2 000	-	-	29 344	19 198	238	212	2 474	200	-	-	176	53 842	4 487
OX2	20 880	20 220	21 660	18 000	22 800	20 940	20 177	20 160	14 340	19 620	17 640	17 160	233 597	19 466
SIFA	36 345	28 352	35 711	33 500	31 490	34 170	35 159	31 289	24 790	14 600	19 694	29 279	354 380	29 532
TRH	51 657	49 100	50 896	49 859	52 020	56 100	66 169	37 260	38 830	42 139	37 636	40 946	572 612	47 718
WEEGBRUG	253	1 613	821	531	432	569	1 515	647	704	357	457	249	8 147	679
Total	1 026 869	1 094 251	1 119 329	1 132 900	1 071 928	1 093 751	1 110 724	1 056 081	879 484	1 058 777	993 430	1 208 557	12 846 081	1 070 507
vs annual average	-4%	2%	5%	6%	0%	2%	4%	-1%	-18%	-1%	-7%	13%		

Figure 3.15: Finding an average month

	BOSWE	HAL AO	HAL BV	HAL CP	HAL CP	CPR-Ro	HAL CP	HAL KB	HAL KB	HAL PA	HAL WA	HAL WB	HAL WB	KADE	NS	OX2	SIFA	TRH	E7814	E7803	E7729	E7726	E7736	E7735	E7601	E7529	E7530	E7521	E7528	E9531	E9523	H9504	E8562	H7435	HE7406	HE6417	E9402	E9403
BOSWEG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
HAL AOV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HAL BVM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HAL CPP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
HAL CPR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
CPR-Rooswij	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
HAL CPRCH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HAL KB1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
HAL KB2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HAL PAF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HAL WAW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
HAL WB2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HAL WBH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
KADE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1
NS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
OX2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
SIFA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
TRH	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E7814	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E7803	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E7729	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E7726	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E7736	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E7735	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
E7601	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
E7529	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
E7530	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
E7521	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
E7528	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
E9531	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
E9523	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
H9504	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0
E8562	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
H7435	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
HE7406	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0
HE6417	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
E9402	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E9403	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 3.16: adjacency matrix

3.2. Identifying waste

In order to improve the system, lean thinking shows that the way to do so is to identify waste in the process. Improvements in the process can help to reduce this waste. The waste types for transport systems are defined in Table 2.2. It is noted in Chapter 2 that value stream mapping (VSM) cannot be applied to a railway system since the processes that make the railway system cannot be singled out. However, the waste identification can be done for a railway system. In this section, this is done for the railway system at Tata Steel IJmuiden.

The analysis follows the waste types defined for transport systems by Villareal [95] in Table 2.2; (1) overproduction, (2) waiting, (3) incorrect processing, (4) unnecessary movement, (5) defects, (6) resource utilization and (7) uncovered assignments.

3.2.1. Overproduction

Waste of overproduction in a transport system is less straightforward than it is in a manufacturing environment. Villareal [95] defines overproduction mostly in processes regarding the management of the system; in production of reports that no one reads, entering repetitive information in multiple documents and ineffective meetings. It can be subjective if some reports that are created at Tata Steel IJmuiden are unnecessary because they are not read. However, the repetitive entering of information is certainly a waste type that can be found at Tata Steel.

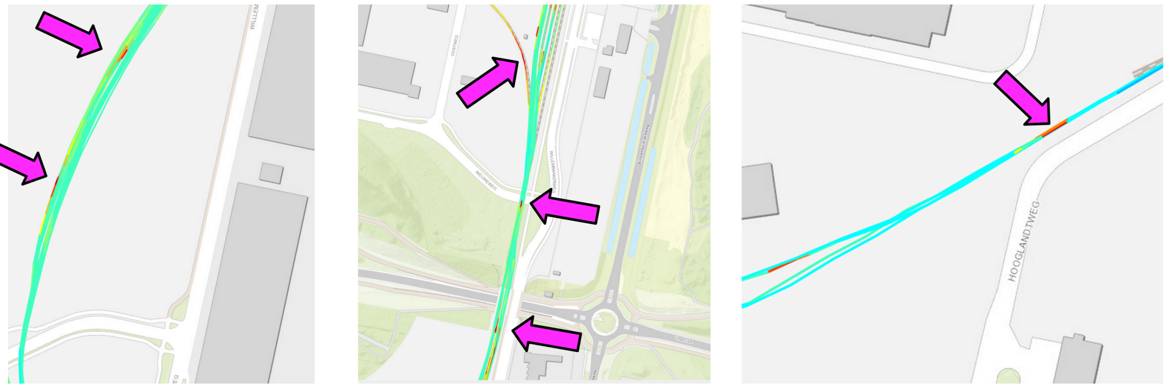
In section 2.10.2 the theory of Kaizen is explained. Continuously looking for waste and figuring a way to resolve this waste is what Kaizen is about. Overproduction is a waste type that can be resolved with Kaizen. People need to find out if their reports are essential, if they are entering repetitive information in systems or if meetings are ineffective. The awareness on these matters is little. Most people at OSL-Rail have worked here or at Tata Steel for a long time. Continuous improvement is certainly not happening. For example, the locomotive driving hours are entered by hand into an excel sheet multiple times are various locations.

3.2.2. Waiting

Waiting is the most recognizable noticeable waste type, but the cause why someone or some process is in hold can be less straightforward for a railway system. The most noticeable waiting time are the moments that the locomotives are not moving. From a customer point of view, value is created in a transport system when the locomotives make a useful movement. Unnecessary movement is another waste type, discussed later. When the movement of a locomotive stops, waiting occurs. Locomotive stops at the pickup and drop off locations are necessary in order to couple or decouple the load of wagons. In Figure 3.14 the turnaround time of the locomotives over a period of time is presented. The coupling and decoupling of wagons takes time, and this time can be seen as value adding. However, a large variation in time can be seen in Figure 3.14. This means that most transport tasks take much longer than the average. All excessive time here can be seen as waste. The process of arriving and departing at a location has multiple components. In short, the locomotive arrives near a destination. The driver stops the locomotive, and signs up through an intercom to the responsible person of that location to communicate that he is arriving. While it has some safety and mostly a regulatory function, this process can be identified fully as waste.

When the driver has announced its presence, it must accelerate the train and enter the facility. Here, the driver inspects the load and couples the primary wagon to the locomotive. While being necessary, the coupling and decoupling could be automated. The customer is not paying for the coupling or decoupling time. When there is something wrong in the process, the transport gets delayed. This can be seen from the turnaround time. It happens often that the locomotive stops for a certain amount of time due to mishandled loading, waiting for the local responsible person, bad coupling or other factors.

So far only waiting in or close to the facilities is discussed. Stopping of locomotives occurs along the track as well. From the GPS analysis stopping locations are identified. The movement of the locomotive is plotted, and with a color index the speed is given. Cyan means that the locomotive drives at full speed, and red indicates that it has made a full stop. In Figure 3.17 several stops are located. Stops in part (A) are due to traffic ahead. The locomotive has to wait for another train to pass. In part (B) the locomotive stops for both traffic or because the locomotive driver has to change a railway switch. The time it takes to change a switch is a waste in the category of waiting. The last image (C) shows a locomotive stopping in order for flipping the switch. All these stops from Figure 3.17 can be identified as a waste. The customer is not paying for these stops, and so it is not value adding.



(A) (B) (C)

Figure 3.17: Three examples of stops at locations other than factories. Figure (A) shows stops made at the Bosweg due to traffic, Figure (B) shows a variation of stops, which can be caused by traffic or by necessary switch stops, Figure (C) shows a stop due to a switch

3.2.3. Incorrect processing

The waste type of incorrect processing is identified with inefficient routing or driving, or with consuming more resources for moving an entity than is needed [95]. This type of waste is less seen in an industrial railway system. The inefficient routing can hardly be done, since nearly always only one single route lies between the origin and the destination. A fully automated ideal system could help in inefficient driving by adapting its speed to traffic, in a way so that it would not have to brake and accelerate.

The major waste in the type of incorrect processing is the driving of all locomotives to the central location at every driver break and at the end of a shift. Here again, the customer is not paying for the drivers to go here. So this can be seen as incorrect processing.

3.2.4. Unnecessary movement

Unnecessary movement of employees is the next waste type. Unnecessary movement of a locomotive is of the type of waste of incorrect processing. The current handling and safety checking of the locomotive driving employees now lead to movement back and forth from the cabin to the front wagon. This movement is unnecessary because the primal task is to inspect of couple the wagon, not to walk there. With a proper camera system, the walking would become unnecessary. Therefore, most of this movement can be seen as a waste.

In an ideal future state, no movement occurs. Everything is monitored either locally or externally with sensors and cameras. Only in case of a problem a visual checkup will need to be made.

3.2.5. Defects

In an industrial environment with human operated cranes loading and unloading wagons inevitable defects occur due to human misjudgment or inattentiveness. A slight touch of a crane will damage a wagon in such a way that it has to be send in for repair. These human inflicted defects will cause delay, but random material failure will happen as well. Railway track cracks, excessive locomotion wear or other driving essential material will break down. While being inevitable, the effects in terms of delays and costs caused by these failures of material can be reduced by proper management and maintenance. Currently the experts at Tata Steel IJmuiden maintaining the equipment do their job well. The rail tracks are check by human visual inspection. Still it occurs that the track breaks down. Robotic sensing could aid in maintenance in a future design.

Locomotive breakdowns form in the current state little delays since a larger fleet of locomotives are maintained. So a replacement locomotive is present.

3.2.6. Resource utilization

The largest resource utilization that can be identified as a waste type and being unclear is the use of wagons. Around 250 wagons are used and maintained at the site of Tata Steel IJmuiden. Many of them have only a slightly different coil holding feature. Exchangeable between holding features does not occur. In the central part of the railway system around 7 wagon types are used for internal and external transport. The system would benefit from a reduction of wagon types, even if it would mean that for some wagons the capacity will drop slightly. Not being able to perform a transport task because no wagons are available will in the future occur more often.

3.2.7. Uncovered assignments

Villareal shows a final waste type for the carrying out of unprofitable transport work due to lack of information or planning [95]. From a global perspective the loading of wagons with sufficient steel coils and a large set of wagons per train highly effects the performance. From a local perspective, the task of the OSL-Rail department is to perform the requested transport tasks. From this scope it does not matter what the load is. A certain capacity is requested, not a value in tons or number of coils delivered.

From the global perspective the lack of information will lead to this type of waste. There is no precise understanding on what the capacity of the railway system is, neither are the effects of their planning back tested. The information flow is missing. Measuring the system is the first essential step in identifying the effects of a certain planning. Driving times, number of performed tasks and locomotive movements are missing. Literature dictates a clear message on that the performance of a railway sytem cannot be separated from the demand that is put onto it. The demand input starts at the planning of tasks. So the performance of the system at a certain demand planning must be measured in order to predict what the influence of planning alterations will be. Since this is not done, it is currently noted as a waste.

3.3. Conclusion

Looking back at the research problem, being that it is unknown whether the demand for transport tasks of the future can be met, the corresponding literature shows that the performance of a railway network cannot be separated from the demand. The performance of a railway network such as present at Tata Steel IJmuiden is not common. The distances between the locations are small, and so the transport times are small as well. It is stated that to measure the performance, the total costs of delays in both pickup and delivery plus the sum of the locomotive costs are to be minimized. The transport tasks function as an input. In this research, this is where the system boundary lies. No optimization in the planning of these tasks is going to be made. However, the locomotive assignment to the transport tasks is taken into account.

Scenarios for future demand of transport tasks are made in a following chapter. These scenarios resemble possible cases of the near future, varying from an overall growth in transport tasks to the building of a new factory, which involves a new stream of transport tasks.
In order to be able to measure the effects of the future demands, a model will be made in a discrete event simulation environment. At first, the transport are taken as an input in the model. These tasks are formed into a locomotive assignment schedule.

4
Improvement Design

The waste types found in the system analysis work as an input for the search for possible system improvement. In this chapter an ideal state is formed where these waste types are not present. The process of finding possible improvements is to find modifications for the system that eliminate a part of this waste so that the system can function more such as the ideal system works. So from the identified waste and the ideal state, a set of possible fields for improvements is derived. The question to which this chapter provides an answer is:

> *In what way can design alternatives be found which potentially improve the operation of an industrial railway system?*

Figure 4.1 visualizes the process. A step is made to an ideal state in a thought experiment. From there, steps back can be made to realistic implementations that could be applied to the Tata Steel railway network in order to improve the performance.

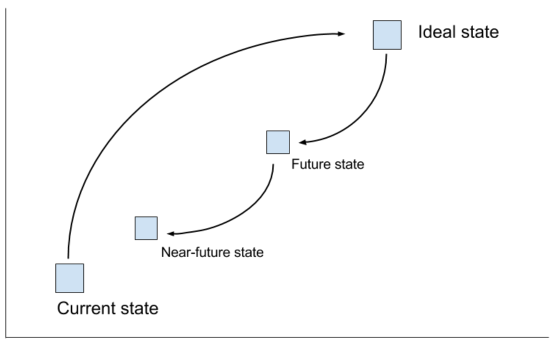


Figure 4.1: From the design of an ideal future state, to near future improvements.

4.1. Ideal state

Defining an ideal state is not trivial. It depends on the way that is looked at the system. Examples of questions that must be answered before the ideal state thought experiment can be performed are: *Is the current layout of tracks obligated to use? Are goods still transported by the modality of rail? Is transport between factories needed in an ideal state?*. For this research it is assumed that there will be a request for transport in an ideal state and that no futuristic transport modalities are developed which will be more efficient than rail transport. However, system modifications are within the scope, as well as all possible non-physical improvements.

The theory of lean thinking subscribes a value stream map as the approach to define and evaluate states. In the case of rail transport, value stream mapping is not fully applicable, since it requires repetitive processes which can be identified solely. In the case of rail transport every transport of an individual load is under the influence of a network of other locomotives, tracks, switches, locations and past and future tasks. Therefore, value stream mapping (VSM), or in terms of transport, transport value stream mapping (TVSM) is less applicable.

What can be used from lean thinking, as described in the conclusion of the literature review 2.12, is the approach to maximize customer value. Customer value in rail transport was defined in three fields:

1. **Reliability**: Multiple factories at Tata Steel IJmuiden rely on the railway system to deliver their requested orders and to send out specific products at specific times. This reliability is the most important factor. If the railway system would not work, storage buildups could lead to major problems further downstream. if a customer, being the factories, can rely more on a secure service from the rail department, the factories will likely be able to hold less inventory which is one of the lean thinking waste types.

2. **Punctuality**: If a time schedule is present, the punctuality of the arrival of a train can create customer value. Arriving at an accurate time will provide customer value since the customer can plan its own operations more precise towards this arrival. If for instance a loading/unloading crane needs to be present during the arrival and departure of a train, the more precise the train arrives, the more precise this resource, being the crane, can be reserved. More precise planning of this resource will in the end eliminate the waste in the form of waiting resources.

3. **Cost**: Like any customer in any system, customer value is created when the price is lowered and the service stays the same. Cost

From the literature review of industrial railway system in section 2.2.2, it is noted that an improvised policy regarding the task scheduling is often used. At Tata Steel, the policy regarding the planning of the rail transport tasks can be seen as improvised as well. A schedule is made, but not strictly executed and changed at several moments even until the final execution.

Since customer value will be the way to evaluate the performance, metrics must be defined in order to do so. This is done by the defined metrics from Table 4.1, where the customer value types are formed into KPIs. For the reliability, the metrics of transported request and equipment utilization are used. Higher utilization of equipment means that the problem when equipment brakes down are higher. On the other hand, high utilization will likely mean a high use of resources and therefore a lower cost per ride. To measure the punctuality, the metric of pickup time and delivery time are noted. Since scheduling is improvised and not strictly executed, these metrics can provide a useful insight. The time it takes from the moment a transport request is created and ready to be picked up is created until it is. For the delivery time holds the time from pickup until it is delivered at the requested destination.

Table 4.1: Customer value metrics formed into KPIs

Customer value type	KPI	Unit
Reliability	Number of performed transport tasks	#
Punctuality	Pickup time	hr
	Delivery time	hr
Cost	Locomotive fuel	Euro/hr
	Personnel	Euro/hr
	Overhead	Euro/hr

In order to come to near future improvements, an ideology known in the field of lean manufacturing is to firstly define an ideal state. A railway operation has tangles processes that operate simultaneous. And in order to define an ideal state, the fields of control or in other words the aspects with can be altered must be defined in advance.

In the ideal case where the network structure can be changed the highest customer value can be created by laying direct double routing between all the individual locations. With infinite working locomotives and wagons, the reliability and punctuality can be at a maximum. From a costs perspective, the costs will be infinite large since infinite locomotives and wagons must be maintained and operated. So the relation between the defined reliability, punctuality and costs is important, and defining an ideal state cannot be done straightforward. However, every action that increases the reliability or punctuality, or that reduces the cost in any way is an improvement.

4.2. Evaluation model for design concepts

The customer in an industrial railway system is the planning department which sets out a required set of transport tasks. This customer values if these tasks are performed, and more performed transport tasks mean more value for the planning department. This is the upside side of the performance. The downside is that the operation of picking up, driving and delivering the loads come at a certain cost and require a certain time. These two are to be minimized.

In short, the performance of an industrial railway system is a coherent mix of the number of performed transport tasks, the time it takes to perform such these tasks and the costs that the railway department makes during the operation. A final important aspect in the value for the customer, being the planning department, is the fact that not all transport tasks are equally urgent. Some facilities will have a shorter storage capacity, and so require a more adequate discharging of their filled wagons in order to maintain continuity in production further up. Unplanned delays in a large operation such as found in industrial railway are common. This further causes the prioritization of tasks a necessity. So for the planning department the prioritization of tasks is another aspect for customer value.

In order to evaluate concepts, a model to asses the customer value, and so the performance of the system, is constructed. For this model the subjective delay of transport tasks must be made comparable with the other components, being the transport costs and the number of transport tasks. This is done by a pricing mechanism. The subjective cost of delay is expressed in an objective price. By doing so, the suggested model can compare multiple outcomes objectively. This newly developed method to evaluate the performance based upon pricing delay can be steered by the customer through prioritization. The customer must provide a priority number for a transport task. The cost of delay is then the multiplication of the total transport time times the priority times times the cost per priority time. The model is shown in equation 4.1 can be used.

$$\mathrm{CV} = \frac{\#\ \text{Transport tasks}}{\sum \text{Cost of delay} + \sum \text{Cost of transport}} \tag{4.1}$$

$$= \frac{q}{\sum c_p \Big(p_t (t_{\text{pick-up}} + t_{\text{delivery}}) \Big) + \sum \Big(c_{t,o}\, t_{loc,o} + c_{t,i}\, t_{loc,i} \Big)} \tag{4.2}$$

In this model, c_p [Euro/prio hr] is the cost per priority time, p_t [#] is the priority of a transport task, $t_{\text{pick-up}}$ [hr] is the time between the creation and the pickup by a locomotive of a transport tasks, and t_{delivery} [hr] is the time between the pickup and the delivery of a task. $c_{t,o}$ [Euro/hr] times $t_{loc,o}$ [hr] is the multiplication of the operational costs per hour for a locomotive times the operational hours of the locomotive. The operation hours are the hours when the locomotive is driving. The $c_{t,i}$ [Euro] times $t_{loc,i}$ [hr] part is cost per hour when the locomotive stands idle, so it does not consume fuel but personnel is being paid and stands ready for work. This results in the customer value to have the unit of [Tasks/Euro].

4.3. Near future improvements

First of all, to come to new concepts, an overview is given of the possible control types which could be altered. In Figure 4.2, the multilevel control structure is given. This structure is made out of 3 parts, the strategic, tactical and operational level. The distinction between the three levels can be made in several ways. Options are the scope of control, being for the strategic level the complete railway system, for the tactical level the locomotive control, and for the operational level a single locomotive. Another option, which is displayed on the left-hand side of Figure 4.2 is the time forward the control type takes. The strategic levels can control beyond the 24 hours limit. Choosing a set of traffic rules or changing the layout of the infrastructure takes far more than 24 hours in advance. The tactical level has control over operations that are done 5 minutes to

24 hours in advance. As an example, the assignment of the drivers to locomotives happens every 8 hours. Determining if a locomotive needs to refuel happens at the end of every shift, so 8 hours as well. At the operational level, all the quick and cognitive decisions are made. The decision to accelerate or brake takes only seconds, and a visual inspection of the locomotive before riding off 2 minutes.

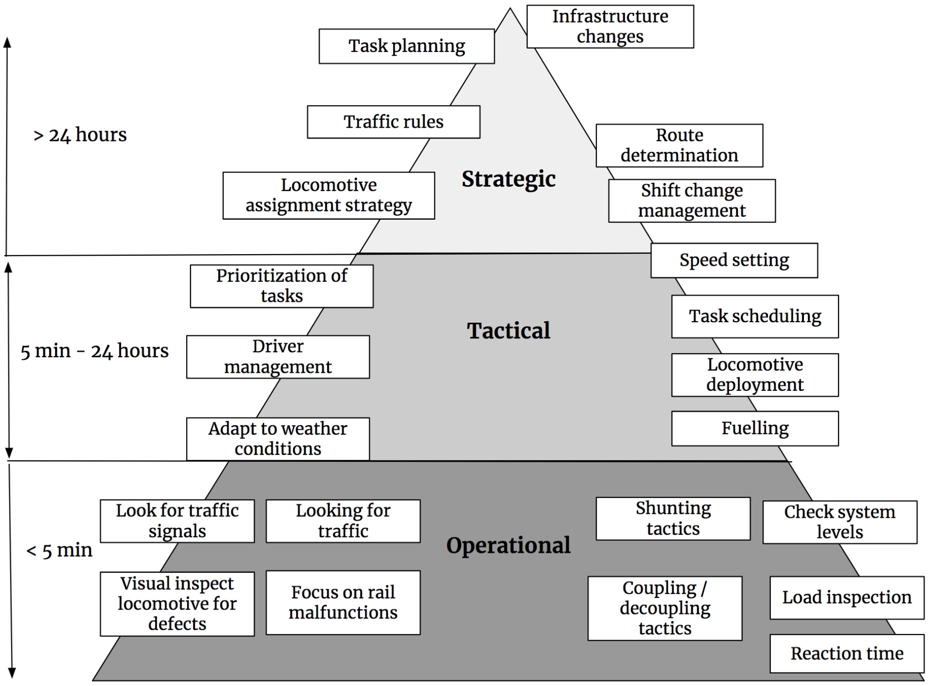


Figure 4.2: Control options on different levels: strategical for control with a time span until execution of more than 24 hours, tactical with a time span of 5 minutes to 24 hours, and operational with a time span of less than 5 minutes.

Figure 4.1 shows an image of how to come to near future improvements. The ideal state has the highest possible reliability and punctuality, while the cost is at its low. It is impossible to predict which measures will have the most impact.

The levels of control found in 4.2 are only the options where control can be exercised onto the system. These options are not yet applicable improvement. In the next section, multiple improvements are evaluated.

4.3.1. Selection fields for improvements

Since the time for this research is limited, a selection of improvement fields must be chosen for this research to investigate further. The goal of applying any improvement is resolve waste from the railway system process. In section 3.2 the waste identification is shown. In order to do reduce the waste, suggested applicable solutions are listed below. For each improvement the waste field is noted. The improvement all fall into the scope of this research. This means that the planning of transport tasks and is left out of context.

Smart fuelling: Waste: *Incorrect processing.* The locomotives are driven by a diesel combustion engine. Multiple times per week a locomotive needs to be refuelled. If the locomotives has a full tank, it required more fuel due to the higher weight. A smart fuelling model could be formed in order to find an optimal moment in time and location for refuelling.

Work schedule: Waste: *Unnecessary movement, incorrect processing.* In the current work schedule the team operates for 8 hours and the drivers have 3 breaks. During these breaks, the majority of driver drive back to the Central location, which result in congestion and unnecessary movement. At the end of a shift, the drivers drive to the same location and the new shift team arrives. They start from the next location. Alterations to the break and shift working process can help to resolve these dead moments of zero capacity. More information regarding the waste here can be found in 3.2. Newly developed schedules are able to improve the continuity and availability of railway transport capacity.

Prioritization Waste: *Resource utilization.* Prioritization of task is in fact present in the system, but only in a subjective matter. The transport coordinators have substantial knowledge on which transport task will need to have priority based on experience. The problem is that the prioritization of tasks is not made explicit. No priority is assigned to tasks, and so no clear privilege to a certain tasks can be done. Furthermore, from historical data the effects of giving a certain priority cannot be analyzed if it is not made explicit. A simple example is the transport to BUKA3. If a large vessel is planned for leaving in a short notice, the final transport tasks that will need to be loaded onto the ship will have the highest possible priority. If these steel products get delayed, either the ship leaves without them of the total ship gets delayed. So the effects will be more dramatic for one transport tasks than for another. In order to quantify these effects and to provide a transport privilege, prioritization of tasks needs to be an explicit property of the task.

Smart deployment Waste: *Resource utilization, uncovered assignments.* In the current system the locomotive deployment is done impulsively. Average 5 locomotives are in constant operation, and a 6th is often added to the fleet. The choice to use this 6th locomotive in high demand moments is done to complete transport tasks in time. However, the total effect on customer value where the costs are also present in is unforeseeable. So the use of this 6th locomotive could also lead to more traffic on the railway system and so more traffic delays, more costs and finally less choosing option for the current locomotives for their next assignment. Logically when a larger variety of transport tasks are ready to be performed, there is more choice in choosing the best suitable tasks. This effect disappears when a large number of locomotives are present. A smart deployment of locomotives where a single customer value is optimized can combine all parameters, so that the optimal fleet size can be determined.

Locomotive assignment strategy Waste: *Resource utilization.* If multiple transport tasks are present in either a schedule or a general queue, there is a choice to which transport task is assigned to the locomotive. From the possible set of transport tasks the assignment to a locomotive can be done by selection of a property of the transport task. This can be aspects such as its location, priority, scheduled departure time, load, total weight, wagon size, wagon type, or destination. The effects of different strategies can help to reduce inefficient driving.

Smart scheduling by slot allocation Waste: *Incorrect processing, resource utilization, uncovered assignments.* Slot allocation is an advanced method where the locomotive will reserve a specific part of the track at a specific moment in time. By doing so the amount of traffic stops can be reduced to a minimum. This method requires a highly reliable operation with little differentiation in processing times and driving times. A mathematically optimized time schedule can be constructed as shown in the literature review. However, is a certain train gets delayed during the loading or unloading process inside a facility, the schedule needs to be rerun with the newly estimated departure times. Such models take a serious amount of run time, and it must be done well in advance. So this method can only work is all processes are far more reliable than they are in the current system. The turnaround time as shown in the system analysis is far to variable to make precise scheduling possible. The mathematically optimized schedule can have the goal to maximize the total customer value.

Infrastructure changes Waste: *Waiting.* The infrastructure of industrial railway systems in general often have an inefficient layout. The construction of railway track is expensive. Experts provide an estimated price for the deployment of railway track of 1000 Euros per meter, excluding the switches. The layout has historically been developed with the growth of new factories at Tata Steel IJmuiden. New location needed to be attached to the rail network, and so a more distributed inefficient layout is present. Furthermore, the variety railway switches cause unnecessary waiting in the system. Automated railway switches have been around for many years, however the purchase, installation and maintenance of these switches can drive up the cost. A manual switch can take a total of 50 second to stop the train, flip the switch and accelerate the train again. This causes unwanted fuel cost and most of all a higher transport time. The average transport time of a transport task is between 8 and 12 minutes, so 50 second is a substantial part of that.

Automated coupling/decoupling Waste: *Unnecessary movement, waiting, defects.* The coupling and decoupling of wagons takes the drivers precious time. They need to walk to the coupling location to visually inspect the process. Either a camera system or a full automatic coupling system can reduce this waste. Another advantage of automated coupling is that it can happen in a more constant matter. Now the driver needs to drive the locomotive with a certain speed onto the wagon's coupling mechanism. The impact must not be to small because the coupling mechanism will not work. The human involvement in this matter results in overpowered coupling, which causes excessive wear and breakage of the systems. Furthermore, automated coupling could potentially be faster.

Automated speeding Waste: *Incorrect processing.* The acceleration and braking of the trains require fuel, and fuel is a main post of the costs. The more efficient the locomotive can maintain their speed, the less fuel they will consume. Automated speeding can reduce the fuel costs. Even better, automated speeding can be used combined with a locating system do adapt the speed to future traffic. Automated speeding will also lead to a more reliable driving time process. For automated systems, the reliability that the train takes a certain amount of time to cover a part of the network is more important than for the train to drive as fast as possible. Automated system can provide this reliability, since human operated locomotives will always experience differences in driving behaviour. Each driver has slightly different tactics, which results in unreliability and less punctuality. For the concept of slot allocation, the punctuality is the most important factor.

Automated maintenance sensing Waste: *Defects.* If defects of the railway system are found in an earlier stage before it leads to a sudden breakdown, the reliability of the system rises and so the overall performance could potentially increase. Currently, manual inspection is the main way to find little defects in the railway tracks. Every part of the track is visually inspected on average once every two weeks. An automated robotic maintenance sensing unit could drive along the track and visually inspect the train far more often and potentially more precise. The development and sensor technology of these systems is in development.

Fully automated driving, loading and unloading Waste: *Waiting, incorrect processing, resource utilization, uncovered assignments.* The ideal state goal is to have a fully automated railway system with as little human involvement as possible. Mathematically determined schedules could provide the optimal way to transport the wagons. Automated locomotives with automated coupling and decoupling would require far less turnaround time since the complete registration part would be skipped. Locomotives would not have any traffic stops along the way, and fully automated robotic maintenance sensing units could find defects in the track in a short time. The development of such a fully automated system can take a serious time, but in other AVG (automated guided vehicle) systems it has been a proven concept.

The above improvement all have different influence on waste reduction in the system. The effects will be correlated to the demand scenario. For example, the effects of reduced transport time will increase respectively with an increasing demand. Further more, the development and implementation effort of the individual improvement varies substantially. An improved work schedule could require a week to develop and implement, while a slot allocation system can take multiple years.

In Figure 4.3 the different improvements are set out in a graph. On the x-axis the expected cost of implementation is set out on a subjective basis. On the y-axis, the expected possible performance improvement is displayed, also on a subjective basis. Since the effects of the improvements can only be determined afterwards, the subjective placement of 4.3 is not on any scale. The size of the improvement shows the level of effort for developing a practical implementation of the method. The ultimate goal is a fully automated system, which is shown in the top right corner. Hereafter the improvement which individually has the most estimated impact on the performance is the slot allocation method. This method however requires far more development than other more simple improvements. The selected green fields are the improvement chosen for further experimentation. As can be seen from Figure 4.3 the combined development effort of the green improvement fields is less than the single slot allocation method, but the possible effects of the performance are estimated to outperform the slot allocation method. The selected improvements have the maximum possible performance gains for the limited time available in this research.

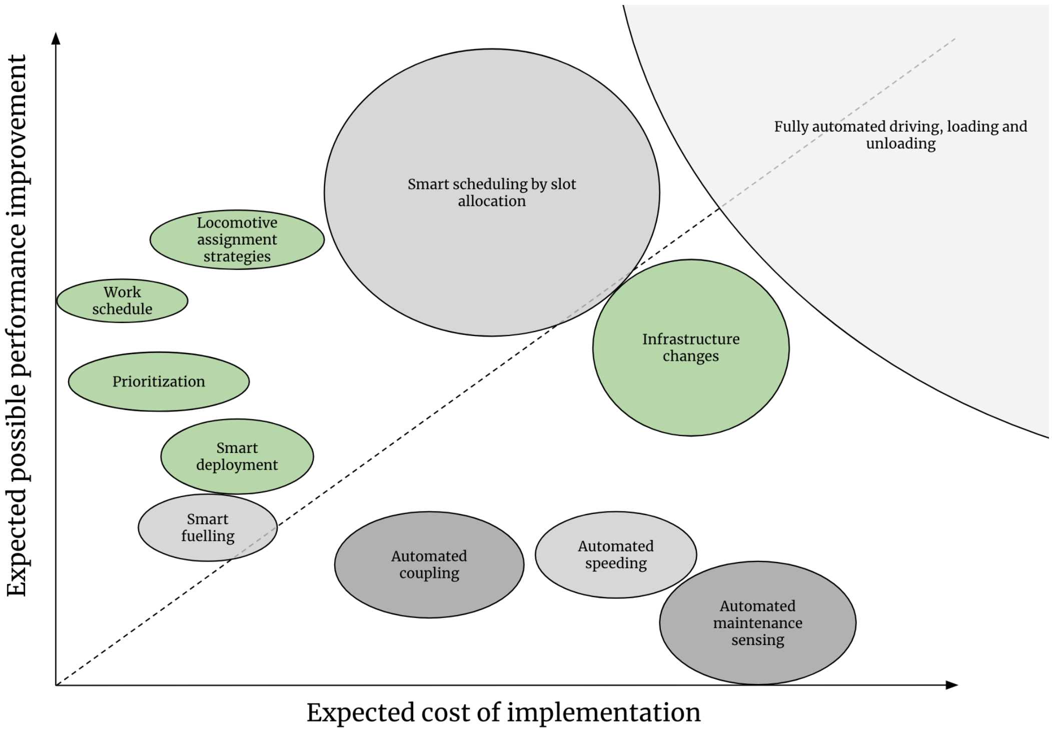


Figure 4.3: Selection the most promising improvements. The size of the fields indicates the time it would take to design and implement solutions.

4.3.2. Locomotive assignment strategy

To assign locomotives to transport tasks can play a crucial role. Therefore, these different assignment strategies are tested:

- **First-in-first-out**: The simplest form of assignment strategy. The chronologically order of creation of transport tasks is maintained in the assignment to locomotives. A hypothesis is that by using this strategy the pickup time will be low. However, more driving to and from locations will be done in comparison with more smart strategies.
- **Closest available**: Once a locomotives drops of a set of wagons at a location, it will look for a next assignment in its surroundings. It evaluates the possible assignments to which the locomotive has the least amount of travel time (without taking possible traffic into account). The hypothesis here is that with this strategy the average delivery time will be the lowest, and the utilization of the locomotives will be high.
- **Priority**: A priority is a required property of a transport task. Task with a higher priority will be picked up at first. Furthermore, the cost of delay for a transport task is determined by multiplication of the priority times the standard cost of delay. In this way, the subjective negative effect of delay can be quantified. The hypothesis is that by selection the next transport task on its priority the cost of delay can be reduced, which leads to a higher customer value.
- **Designated zones**: By using designated zones for locomotives, locomotive can only be assigned to transport tasks that lie withing their zone. For this strategy it is expected to have beneficial effects if the traffic on the rail becomes higher with a large demand. By using these zones, locomotives will not block one another, and so the delivery time can stay low.

4.3.3. Network configurations

Improvement to the layout of the network can be made to add an extra piece of rail track at specific locations. By adding track at some bottlenecks not only will it assist in the number of train passages over that section, but it can alter the local traffic rules. For instance, in Figure 4.4 and Figure 4.5 the added track can make a double one-direction section from a single bi-direction section. One directional tracks are useful in prevention traffic congestion, deadlock prevention and are far more easy in use.

Three different options of rail track addition are tested, which are shown in Figure 4.4, 4.5 and 4.6. These improvement come from the system analysis where unnecessary stops in the system are located. The positions of the improvement are placed at the top 3 bottlenecks in the system. The first two are discusses above. The final addition at the Bosweg, Figure 4.6, is expected to short cut the transport route from all location above the Bosweg. A small second piece of railway track is added so that the locomotive can drive a front into the Bosweg and is able to release its load and drive on to the parallel track to continue its course.

To identify the bottlenecks in the railway system, a first round of interviews with different persons at Tata Steel was performed. However, the nature of people is to give a biased answers to the questions. In order to have an unbiased view on the occupation of the individual railway tracks, transport data is analyzed.

Another change to the configuration is the change of railway switch types from basic hand switches to electronic, automatic or even smart switches. It is expected that this would benefit the driving time, and so could lead to a rise in capacity. In Figure 4.7 a set of railway switches is shown which are suitable for alteration to more smart switches. A list of suitable switches is made, and the effects of changing these switches can be tested.

4.3.4. Work schedules

A simple but high in potential improvement to the system is an altered drivers work schedule. The railway transport system goes on 24hr a day, 365 days a year. At every day, 3 teams work in shift of 8 hours. Such a shift of 8 hours consists on average of 3 breaks, where one break is a larger lunch session. These breaks happen at

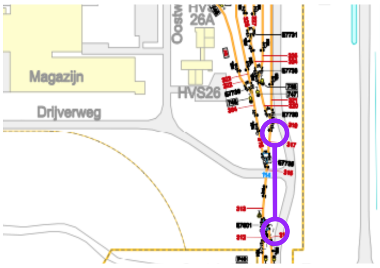


Figure 4.4: The end of the northern Bosweg route bypassing from switch E7601 to E7730

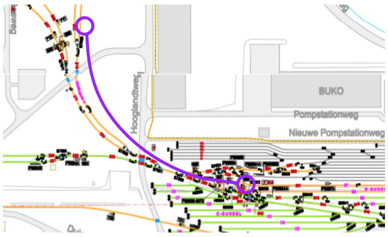


Figure 4.5: Bypassing the Konijnenberg for downstream traffic

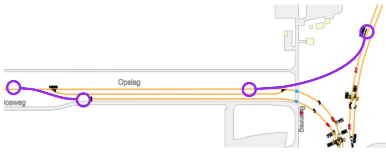


Figure 4.6: Addition to the Bosweg from the Northern part

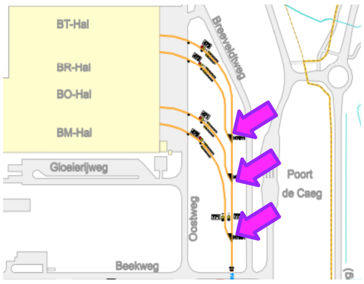


Figure 4.7

the Central location. This means that every driver drives his or hers locomotive to the Central location, and from there continues its route. While the planning of transport tasks does take this breaks into account, it is likely that most of the time unnecessary driving with the locomotives happens. Furthermore, during these breaks the capacity of rail transport drops to zero. And another problem is the congestion of traffic when all the locomotives are focused into one place.

In Appendix D Figure **??** shows the current work schedule. On an 8 hour shift 6 hours are schedule driving. With 5 locomotives, this means that there is 30 hours of driving the locomotives per shift. If a relief schedule would be in place, with the same amount of drivers 4 locomotives could be operated constantly. This would be a total of 32 hours of driving. If the two hours are subtracted for the shifting of driver for all locomotives, the same total 30 hours of driving as with the normal schedule would be available. The benefits could be numerous. Less congestion on the tracks is one, since only 4 locomotives are in movement in stead of 5. A car must be present for picking up and changing drivers. This can be taken into account in the costs.

4.3.5. Locomotive number

Not a true improvement of the system, but the effects of having more or less locomotives are tested. Less locomotives are expected to make the system less congested, but it depends on the demand if the locomotive number is still capable of performing the transport requests.

4.4. Conclusion

Lean thinking principles form a useful way of identifying ways to improve a railway system. However, the lean manufacturing methods cannot be adapted to transport systems and in specific railway operations to their full extend. Transport value stream mapping (TVSM) cannot be applied to the railway operations at industrial freight railway systems since the processes that make up the system cannot be separated into individual steps. It is not possible to identify the valuable and waste time in single processes.

The focus in lean thinking is to create customer value. Since the different factories and the export/import location at Tata Steel can be seen as the customers, value for these customers is created with reliability, punctuality and at a low cost.

5

Railway Model

In order to evaluate the effects of future demand scenarios, design alternatives or an improved planning on the railway system, the components of the railway system and their relations are formed into a model. The processes between the actors of such a model can be simulated over time. While it is impossible to simulate the exact real world, a reasonable approximation of this system can be made through detailing specific processes and making assumptions of unknown or non-determinable parameters or processes. The following questions to which this chapter must provide answers are:

> *In what way can modelling the railway system and discrete event simulation be used to experiment and evaluate the performance of design alternatives for a future demand of railway transport?*

5.1. Conceptual Model

The basis of a simulation model is best represented by the black box principle. The model has an input, which can anything physical such as trains, steel coils or people, or non-physical such as production schedules, stochastic breakdowns or product orders. Inside the black box, certain processes alter these inputs in a particular unknown way until it is send out of the scope of the black box as an output. The output can be of the same (non)physical form. In order to prevent build-up within the black box, the output of the black box must form a steady state with the input. Timing differences due to time consuming processes within the black box are allowed.

Simulation models are a powerful tool to test the effects of specific scenarios or cases on the systems performance. For a large variety of system real-life testing is not feasible due to a variety of reasons such as costs, practicality or safety.

The simulation model of the Tata Steel railway system has one main task; to carry out the requested transport tasks. These tasks consists of having to transport filled wagons with steel coils from one location to another within two time frames for both pick-up and delivery. In section 5.1.1 it is explained in more detail on how these tasks are used as an input of the model. In the same section, the output and system border are discussed. To evaluate how well the system is performing this task, a set of key performance indicators (KPIs) are denoted in section 5.5. These indicators are used to evaluate future demand scenarios, design alternatives or an altered planning strategy.

5.1.1. System border, input and output

From the black box. the first step into a system is to fill in the input, output and the system border. The system border has been described in section 3.1.3, and is visualized in Figure 3.1. The described railway network system of a limited amount of locomotives that can move on limited railway tracks to specific destinations is used. The input in the system, which is still displayed as a black box, are the transport tasks. The set of transport tasks in the real world have the following form:

$$\text{Transport task} = \begin{cases} \text{Origin,} & [t_{o,1},\ t_{o,2}] \\ \text{Destination,} & [t_{d,1},\ t_{d,2}] \\ \text{Load,} & [\#\,\text{Wagons},\ \#\,\text{Coils},\ \text{Weight}] \end{cases}$$

This notation of the real-world transport task form describes how a general transport tasks includes. However, since the scope of this research and the corresponding system border described in 3.1.3 contains only the movement of the locomotives, locomotive assignment to transport tasks, the management of locomotive and locomotive maintenance, the assignment of loads does not fall into this scope. By using this border, the effectiveness of the loading of locomotive rides does not influence the performance of the described system. Every transport task, whether the wagons are fully partial or non loaded, will not have an effect on productivity within this system border. Performing a single task, no matter the number of steel coils, weight or wagons, has the same impact on the applied performance.

Furthermore, since the planning and scheduling of transport tasks, while having a major influence on productivity, is left out of context for this research, the only relevant timings of a transport task are the two following: the time between the creation of the transport request and the moment the wagons are picked up. And secondly the time between the wagons are picked up and delivered at its destination.

So by defining a transport task from the scope of On Site Logistics and so this research, it is defined as:

$$\text{Transport task within scope} = \begin{cases} \text{Origin,} & [-] \\ \text{Destination,} & [-] \\ \text{Pickup time,} & [\mathrm{t_{pickup}} - \mathrm{t_{creation}}] \\ \text{Delivery time,} & [\mathrm{t_{delivery}} - \mathrm{t_{pickup}}] \\ \text{Priority,} & [1, 3, 10] \end{cases}$$

An overview of the simulation process is given in Figure 5.1. By starting off with a black box principle, the processes in the railway simulation itself are initially left out of context. The input of the simulation is on the left side of the figure, being the transport tasks. These tasks are the requested pickup of full wagons, empty wagons or a combination of both that need to be transported to another facility. The input flow of transport requests is present throughout the complete simulation time.

On the top side of Figure 5.1 is the initialization. In here, all initialization steps of the simulation model are present. Several groups of initialization steps are made. The first is the network configuration, which contains all the physical aspects of the railway system such as the network layout, existing tracks, switches, junctions, locomotives number. Secondly, the traffic control group contains all rules and logic such as the basic traffic rules, routing, traffic priority, allowed directions of driving, pickup times, locomotive speed. Thirdly, the locomotive assignment policy is the group where the strategy is placed on the determination of locomotives to assignment. Examples are First-In-First-Out (FIFO), highest priority first and local search. Finally, the group of deadlock avoidance. Literature dictates 3 types of deadlock control, as shown in Figure 2.4 from the literature review: (1) prevention, (2) avoidance, (3) detection and resolution. Deadlock prevention can be done by making a layout in which deadlocks cannot occur. Since in this research bidirectional paths are used, deadlock prevention can no longer be fully applied and step (2), deadlock avoidance, is needed. Deadlock detection and resolution (3) is not implemented into the simulation, since deadlocks do not occur when step (2) is properly applied.

With the input and initialization steps present, a simulation run can be performed.
The simulation's function is to generate output, and the goal is to obtain the performance of the described system.

5.1.2. Model assumptions

In this section a list of model assumptions is summarized.

1. **Transport tasks**

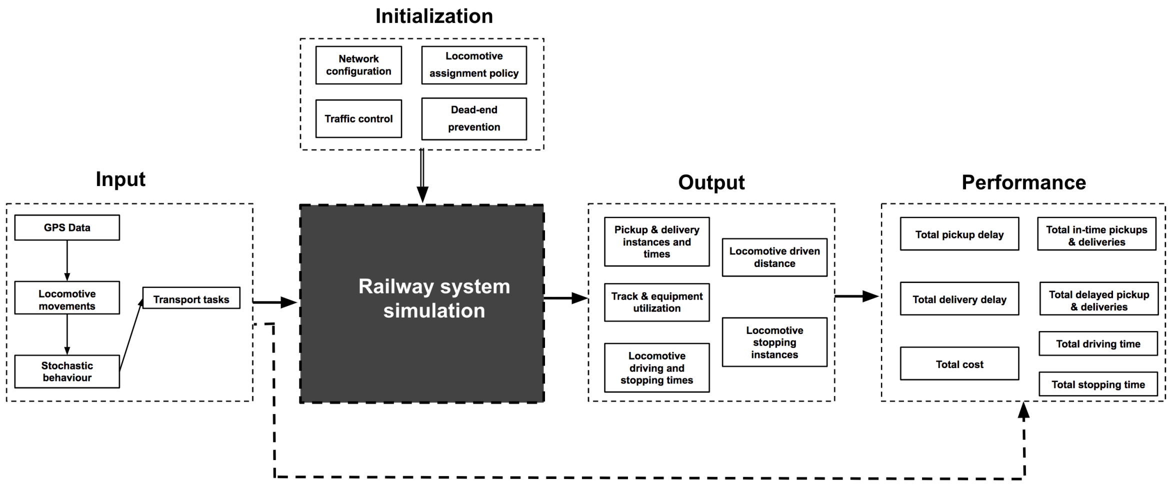


Figure 5.1: Black box figure of railway simulation system.

(a) **Known demand schedule**: The demand for transport tasks changes up until 4 hours prior to departure. In the simulation model, the demand pattern is set as known.

(b) **Timing and delays**: The timing of pick-up at the origin and drop-off of at the destination are given as a time window. For simulation purposed, the premature pick-up of a load is infeasible. Delays in the transport task can only be formed in the delay pick-up or delayed arrival at the destination.

2. **Train Characteristics**

(a) **Train speed**: The train speed is determined not on a uniform speed, but rather on the time it takes a train on average to cover that specific section of the network. These times are obtained from historical GPS sensor analysis. Train slowing aspects such as switches, geographical sloping and load inspections are included in this GPS analysis, and so will not be added.

(b) **Train type**: At Tata Steel IJmuiden two different types of locomotives are used. These locomotives will have a slightly different driving and stopping behaviour. Although the behaviour differences are small, the effects are assumed to be neglectable. For simplification purposes, only one type of locomotive is used in the simulation.

(c) **Breakdowns**:

3. **Load Characteristics**

(a) **Load content**: Load content is set at an average of the origin it is picked up. No specified varying loads for every transport tasks is used.

(b) **Load material**: It is assumed that only one single uniform load is transported.

4. **Origin and destination**

(a) **Basic assumptions**: All locations can function as both a origin as well as a destination. However, smart allocation of loads, load origins, bundling and on-track storage are left out of context.

5.1.3. Components of conceptual model

A network representing the Tata Steel IJmuiden network must be made. The network must consist of **nodes** (factory locations), and **arcs** (railway tracks). At positions where the railway tracks meet and a switch is in place, another node must be present. **Locomotives** must be represented by objects than can transport only on these railway tracks. A locomotive can contain either 1 set of wagons or nothing. The direction where the wagons are placed, in front or in the back, is left out of context for this research. Furthermore, the amount of wagons is also left out of context, since a transport task as defined does not contain a certain number of wagons. If railway locations, track, switches and locomotives are in placed, all the basis components are present.

The factory location must create transport request according to Table **??**. A stochastic process is used in order to create the request, with a random exponential distribution. The priority of transport tasks is randomly selected and can have a value of 1, 3 of 10, with a distribution of 20, 75 and 5 percent respectively.

5.1.4. Model logic

Locomotive assignment: Locomotives must be able to pick up a set of wagons according to a certain strategy. The locations of the factories can provide a transport request, and then the locomotive must decide whether it must assign itself to this transport request. When a locomotive is assigned to a task it can not look for another task, neither can another locomotive take the current assigned task over.

Locomotive driving and deadlock prevention: The locomotives will drive at a defined speed when no track cover time is present. When a specific cover time is present, defined in Table **??**, it must take the locomotive this specific time to cover the section of railway track. A set of traffic rules must be applied in order for the self driving locomotives to not crash into each other. First off, if a section of the network is blocked by one train, is must be made impossible for another train to enter this section. Blocking sections or individual tracks can be done by every locomotive, and the locomotive will need to release the section only when their trailing edge have left the section.

For deadlock prevention, the section blocking logic must apply a few steps ahead. The layout and logic of the network together must be sufficient to prevent deadlocks, as long as the number of locomotive stays limited.

Pickup and delivery: The pickup and delivery process must both take 5 minutes for coupling and decoupling the wagons.

5.2. Simulation Model

In this section, a list of the different components that form the simulation model is given.

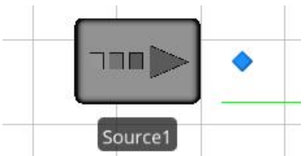


Figure 5.2: A source object

First off is the source object, shown in Figure 5.2. The source object is used to create entities. For every factory location in the Central rail network at Tata Steel IJmuiden, a source object is placed inside the simulation environment. The source objects are placed at the geographical location where the railway track ends. Every source produces entities, which in this case are transport requests. Since steel products of a particular factory will only have a set of specific possible destinations, these destinations are formed into a reference table. The number of transports from a single location to the potential locations is based upon the origin-destination table of all ridden routes from a period of 5 months. This table can be found in Appendix D. The process of creating a transport request goes as followed. The initial transport request by the source is created with a random distribution. This stochastic variable selects a certain time to create an entity by probability. More information on which distribution is used can be found in the Scenarios section. Since the average number of transport tasks for one day N is known, the mean inter-arrival time of transport requests is $1/N$. If an initial transport request is created, next its destination is assigned. This is done by another random distribution, but with a weight factor according to the provided number of historical transports. As an example, the WHB hall has an average of 6 transport requests per day. 5 of these are to Central, and 1 to factory KB1. So the inter-arrival time of transport requests is 1/6 per day, and secondly the stochastic process selects the destination of the request by an average of 5 to Central and 1 to KB1.

Every source has an ride station queue. Whenever an entity is created, it has to wait for a transporter to be picked up. Until this happens, it is positioned inside this queue.

The second type of object used is a sink object, shown in Figure 5.3. A sink object can destroy an entity, and so in the rail transport case a finished transport tasks ends at a sink object. Here, the entity is destroyed and the transport time is tallied. A final destination for the transport requests from the set of sources is added at the source object. This final destination is the sink. At Tata Steel IJmuiden, every factory location connected to the rail network has both an incoming as well as an outgoing demand. Therefore, in the simulation model a combination of both an source and a sink object is present to fulfill this aspects.

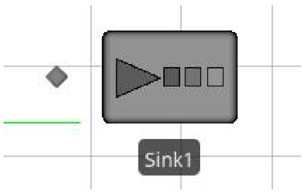


Figure 5.3: A sink object.

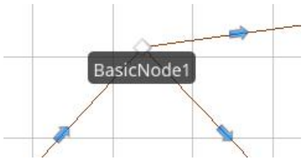


Figure 5.4: This is a figure caption.

Besides sources and sinks, another type of location are basic nodes. These nodes are only used on other to form connections. The basic nodes are places at railway switches. At such a switch, a split from one railway track into two others is made possible. Railway tracks at a switch will need to be positioned in either one of the two direction in order for the train to prevent derailing. This means that in some cases the switch will lay in the correct direction for the train to continue its path to its destination, while in other occasions the switch will need to be laid into the other direction. This ratio between correct versus non-correct laying switches differs substantially between the railway switches found at Tata Steel IJmuiden. From measurement in real life and from analysis of GPS data, an average switch delay time of 38 seconds it obtained. This delay is build into the simulation at the locations, but with different probabilities of occurrence for different locations. The largest probability is a 30 percent occurrence of a required change in direction, while for some switches there are no delays taken into account. The fact that in real life different types of switches are used, being from fully manual to automated electronic switches, enlarges this diversion.

The network nodes, being the sources, sinks and basic nodes, are connected to each other by path objects. The path object can only exist between two nodes. Two example of the path object is shown in Figure 5.5. A path object has several properties. First off, it has a capacity. For the purpose of railway modeling, the capacity of a path is always 1. If two trains would be present on a single track, the traffic signal system would fail. So in order to maintain traffic control, only one train can be present on one path. Secondly, the path can be unidirectional or bidirectional. In Figure 5.5 the path on the top is a unidirectional path. The bottom path is bidirectional.

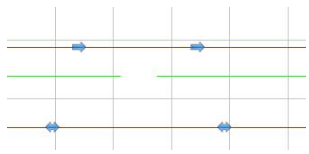


Figure 5.5: A path object

The largest advantage of unidirectional paths over bidirectional paths is far more simple traffic control.

Figure 5.6: A vehicle object

The next object in the simulation setup is the vehicle object. An image of a locomotive is taken for the purpose of this research, as shown in Figure 5.6. The basic properties that the vehicle object has are a desired speed, a loading capacity, size, weight, fleet size and a home location. The predefined states are the current location, speed, load and furthermore if it is allocated.

The vehicle has a corresponding cost function which tracks the cost throughout the simulation. The variable costs for a set of
The entity object is the material that requires transport in this simulation. The entity object is this research resembles a transport request. As noted in section 5.1.1, a transport task will only have a starting location, destination location, pickup time and delivery time. These entities are created in a source object on a random moment. In this research the planning of transport tasks is left out of context, as well as the scheduling of tasks. In other words, no time specific reservation of resources is used.

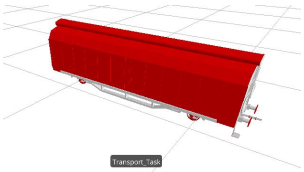


Figure 5.7: A entity object

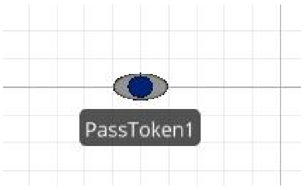


Figure 5.8: A resource object

Pass token are applied by using single resources. A pass token is needed in order to enter a certain section. If the resource is not available, since it is claimed by another locomotive, the locomotive must wait until the resource is released. In some sections, double pass tokens can be applied for more complex deadlock prevention.

5.3. Simulation layout

The simulation in Simio is set up on a scale equal to the real-life network. A geographical map is plotted on the background which can help with locating factories. In Figure 5.9 an image of the simulation layout is shown. Not all the factory labels are shown. 26 locations are used, being Centraal, NS, Bosweg, CPRCH, CPR, BUKA1, BUKA3, TRH, BIHA, CPR, KB1, WBH, WAW, CPP T, CPP W, PAA Oost, PAA West, PAB, PAC West, PAC Oost, PAD, PAF, BM, BO, BR and BT. Each location has its own data table where the average number of transport tasks per destination are denoted.

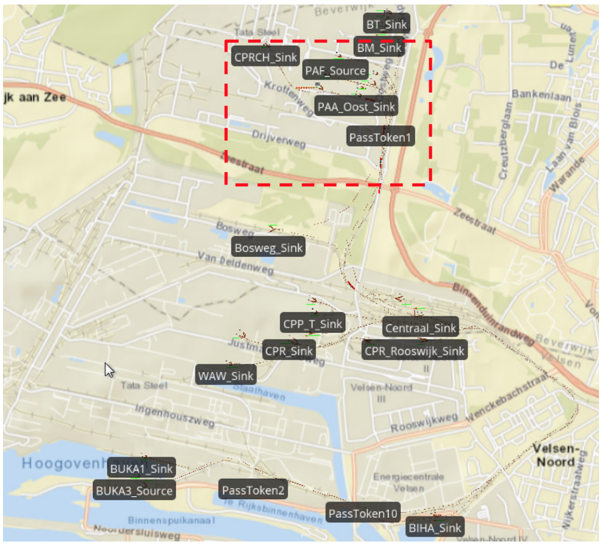


Figure 5.9: The layout of the simulation model. The simulation scale is set up equal to the real-life case. The box shows a zoomed-in selection of the network

Figure 5.10 shows a zoomed-in part of the network. Small simplifications to the rail network are made in order for the simulation to be practical. The current layout of the railway network is used. In the figure, both the locations as well as the resources needed for further logic are present. Labelled with PassToken, this resource needs to be claimed by a locomotive in order to continue its path to a critical section of the network where deadlocks can occur. More detail on deadlock prevention is noted in section 5.4.1. The purple box shows the selection of the network that is zoomed in on even further in Figure 5.11.

Figure 5.10: Zoomed-in selection of the network. The individual factory location consist of both a source and a sink object.

The further down detailed view of the network shown in Figure 5.11 shows a single location, in this case location PAA West. Each location contains a source and a sink object, a connection node to the network and 4 one-way connectors that connect the output of the source and the input of the sink to the single location node. The connections have a zero travelling time, meaning that if an entity arrives at the location node it can instantly be at either the source or the sink. The large red figure shows a transport task standing in the pickup queue of the source. When an entity is created, it gets placed in this queue. From here, it has to wait until a locomotive comes to pick up the entity. The entity resembles the transport task as defined earlier, and has a set of properties such as creation time and priority.

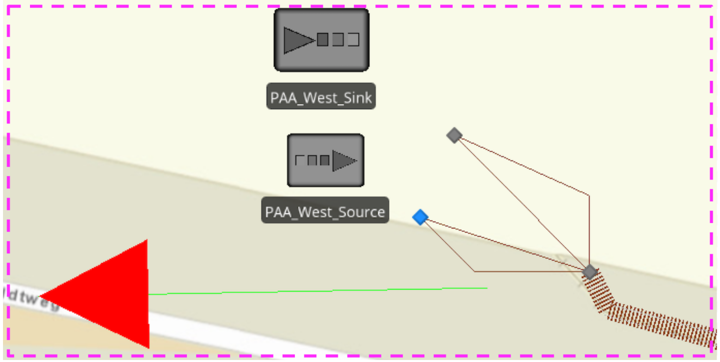


Figure 5.11: Detailed view on an individual location. Every location contains both a source and a sink object. A single node is used to connect the source and the sink to the network. 4 Connector objects are used at every location to connect the source and sink object to this single node, without having a transport time. Furthermore, the entry queue of the source is shown, where a single transport task stands ready to be picked up

5.4. Simulation logic

Discrete event simulation has multiple level processes. The initialization processes are the ones which are started at the beginning of the simulation. These processes initialize most properties of entities such as the locomotive fleet size. Add-on processes are run throughout the simulation when triggered. These processes can be triggered when an entity such as locomotive enters a node or path. Event processes can be triggered by a certain event, such as when a locomotive enters a destination.

5.4.1. Deadlock prevention

Deadlock prevention is a major requirement for the simulation model in order to work. In Figure 5.12 and 5.13 the applied logic for deadlock prevention of a bidirectional path with two destinations is visualized. Firstly, in figure (1) a single locomotive arrives. Its destination is location A. It arrives at the section, and blocks the red indicated parts (2) of the rail track by seizing the resource, shown by the round block. These two blocks are resources where only 1 is available of. So now that locomotive 1 has seized this resource PA, the resource inventory turns red because there in no more resource available.

In step (3) locomotive 2 arrives. It wants to drive to location B, but the section is blocked by locomotive 1. It must wait until the section is cleared in step (4). Now locomotive 2 can claim resource PB, as shown in step (5). Now that locomotive has seized resource PB and that the section is clear, it can continue its route. In step (6) locomotive 1 wants to use the section, but it is blocked by locomotive 2. It must stay in place until locomotive 2 has passed. Now the interesting part comes. If locomotive 2 would also have A as a destination, the two would collide. But since resource PA is needed for entering A, which was not available, it would never be possible for two locomotives to have a head on deadlock.

In step (7) the section is cleared, and locomotive 1 can enter the section. Step (8) shows that locomotive 1 now claims the section, and so it is locked for entry from both sides except for locomotive 1. In step (9) locomotive 2 wants to continue its route backwards, but locomotive 1 is still in the section. So it must wait since the section is blocked for locomotive 1. In step (10) locomotive 1 releases both the section as well as the pass token PA for entering the A destination. If another locomotive would arrive, it could now seize this resource. In step (11) locomotive 2 reserves the section for its cross over. And in step (12) it enters the section. Finally, in step (13) locomotive 2 releases both the section as well as the pass token for entering destination B with resource PB.

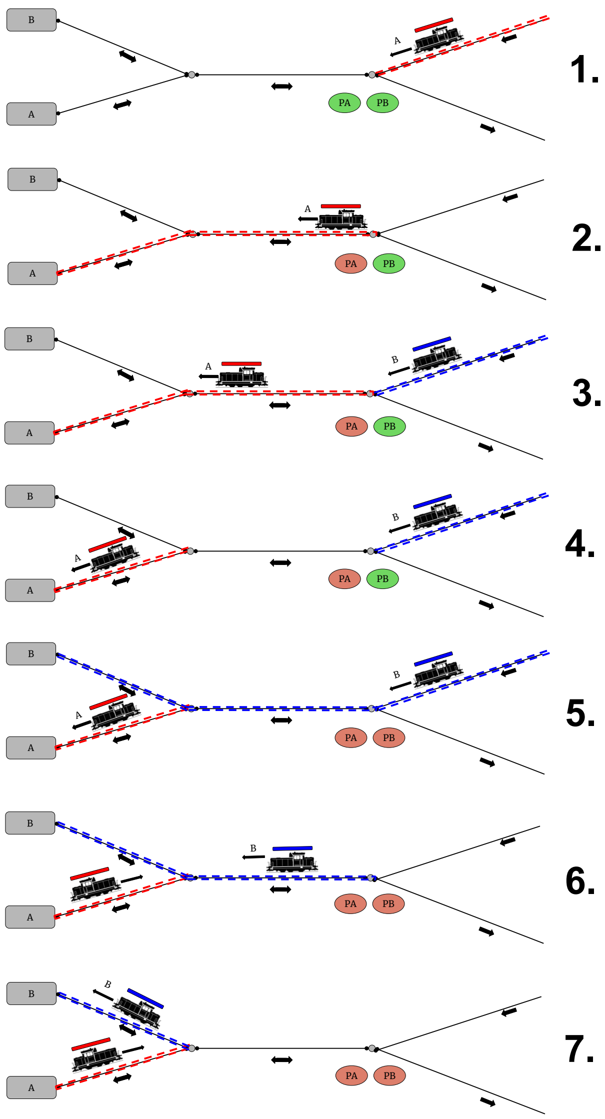


Figure 5.12: Deadlock prevention

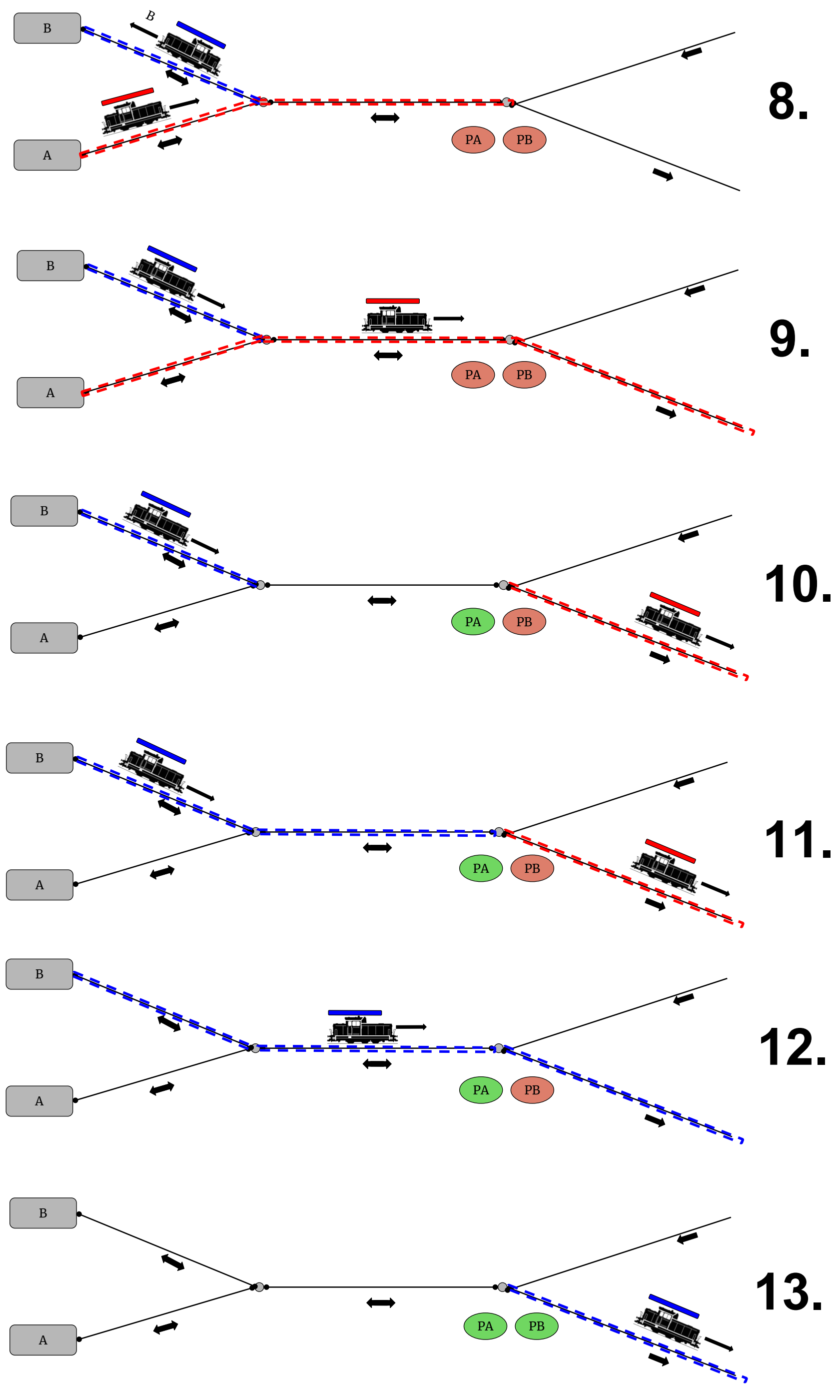


Figure 5.13: Deadlock prevention part 2

Figure 5.14: Deadlock prevention at track towards CPRCH and PAA West location. The lower locomotive has to wait for the locomotive above to be removed from the dead end section.

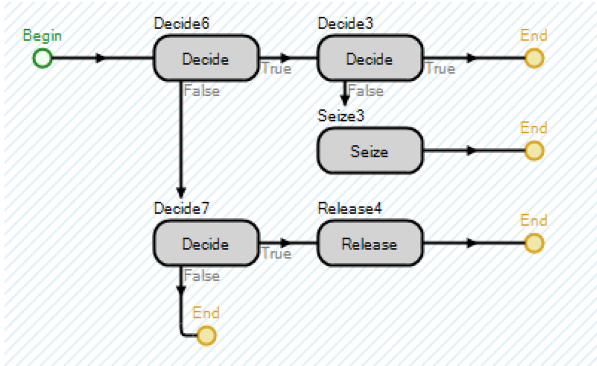


Figure 5.15: Decision process on seizing and releasing a pass token to enter a section.

An examples of the above method to prevent a deadlock situation is shown in Figure 5.14. In the simulation model, the above locomotive (1) is driving back from the CPRCH location. Its destination is the BIHA. Another locomotive (2) comes from below and needs to head to PAA West. Both locomotives want to use the same track, but locomotive (1) has entered the section at first. The implied logic can be seen in Figure 5.15. This process is triggered when an entity, being a locomotive in this case, enters the node located at the top of the bottom locomotive in Figure 5.14. The process starts by Decide6, where it is desided whether the destination of the locomotive is CPRCH/PAA West or not. If this is true, the process moves to the right side. If this is false, the process moves down. So if the locomotive does not have CPRCH/PAA West as a destination, it continues its path.

When Decide6 is true, the next block is Decide3. This process is only initiated if the locomotive has either destination CPRCH or PAA West. The Decide3 looks at if the locomotive has seized resource PassToken1. Of this pass token only 1 single unit is available for seizing. If the locomotive has pass token 3, the Decide3 step is true and the locomotive can continue onto the track towards its destination CPRCH or PAA West. If the locomotive does not have PassToken1, the Decide3 step is false, and the process goes down to Seize3. In this step, the locomotive tries to seize resource PassToken1. If is is not available, the locomotive has to wait until it gets available. In the example, locomotive 1 has seized the resource and so locomotive 2 has to wait until PassToken1 is released in order to seize it. Locomotive 2 is now waiting until it can seize resource PassToken1 and continue its route.

Locomotive 1 has just pickup an assignment and is headed to BIHA. The arrow in Figure 5.15 shows its direction. When locomotive 1 enters the node, the process starts again for this locomotive. At first, at Decide6 it is checked whether the locomotive has destination CPRCH/PAA West, which in this case is false since its destination is BIHA. The process flow goes to Decide7. Here it is checked whether the locomotive has the seized resource PassToken1. If this it true, the next step is Release4 and the locomotive releases the resource. If it is false, nothing happens. Locomotive 1 has resource PassToken1, and so it release this resource and drives over the node towards the north. Now the PassToken1 resource is available for seizing, and locomotive 2 can seize it now and enter the section for CPRCH/PAA West.

5.5. Key Performance Indicators

Based upon the objectives from section 4.1, the simulation key performance indicators (KPIs) are defined as followed:

- **# Completed tasks**: While being trivial, the number of transport tasks that have been successfully delivered is a first performance indicator. Since literature is clear on the fact that the performance of a railway network cannot be seen separately from its demand, this demand or amount of transport tasks is taken into account. A build-up in large differences between requested and performed transport tasks is an indicator of that the system is not able to handle the amount of requests, or that a logic problem exists.

- **Pickup time**: The pickup time is the time from the creation of the transport task until it is picked up by the locomotive for transport. It indicated how much the transport task has to wait, which is unwanted. A longer average pickup time will be an indication that the system is becoming less able to handle the demand scenario.

- **Transport time**: The transport time is the time from the moment the transport task is picked up until it is dropped of. It indicated the traffic on the tracks. If there is little traffic on the track present, the locomotive has little waiting time and the transport time is low. More traffic results is a less optimal operation and this can be indicated by an increase in transport time.

- **Priority time**: This bespoke KPI is the multiplication of the priority of the individual transport tasks times the total time from creation until delivery. A priority of 1,3 and 10 are present for transport tasks, with a distribution of 20, 75 and 5 percent. The priority time is also used in 4.1 for a final evaluation of the design alternatives.

- **Locomotive utilization**: The locomotive utilization can indicate how much of the locomotive resource is claimed. In lean thinking terms, as shown in section 2.10.3, the overall vehicle effectiveness (OVE) is a useful metric to compare different scenarios.

- **Track utilization**: Rail track utilization is an interesting performance indicator. The highest utilized part of the railway system are likely to form the bottlenecks in the system. Furthermore, the higher the utilization, the higher the impact would be on the system if the rail track would break down.

5.6. Model verification and validation

Model verification and validation are essential steps in a (simulation) model experiment. It provides information for the reliability of the model, and it helps in providing information regarding the scope of describing the system. No simulation model is able to describe the full content of a real-life system. Therefore, the model verification and validation aid in describing what is included, and what is not. Sargent [77] has made a illustrative figure consisting of the process regarding building a simulation model. In Figure 5.16 this process is shown. Sargent makes a 3-way separation of two validation and one verification step. Model verification and validation is not an at-the-end step. During the making of a conceptual model and simulation model, verification and validation is use to check the progress of a model in describing the system. Every new step added can be checked by these methods, and so errors can be resolved.

First, the conceptual model validation must be done. This must give answers to the questions *'How valid is the conceptual model in describing the system?'*. It must detail the potential of the model to describe the system. A conceptual model will not be able to describe the system completely, and a computerized model will do so even less. So every lack in the conceptual model will also be present in the computerized model. Conceptual model validation is not an at-the-end step. If the conceptual model is not correct, a simulation model that is based upon that can never be right.

The next step is the verification of the computerized model. Verification in this step must answer the question: *'Does the simulation model do what it is intended in the conceptual model?'*. During the implementation of the simulation model, this question must be answered at every added feature.

The third and final step is the operational validation. In this step, the simulation model is validated to the system. Here, the known outcomes of the system can be use to validate the computerized outcome. Large differences in the outcome of the simulation model and the described system can have two causes:(1) the simulation model has an error or a non-proper working process, (2) the simulation models works as described in the conceptual model, but the conceptual model has an error in the logic.

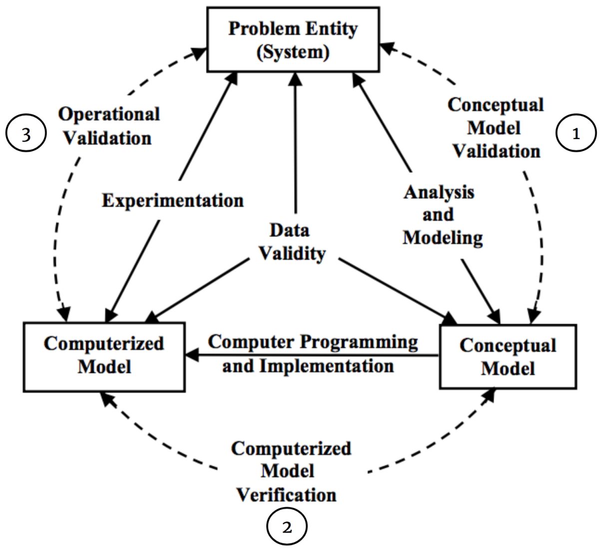


Figure 5.16: Model development process with model verification source: Sargent

5.6.1. Verification and validation techniques

Sargent describes techniques in order to verify and validate a model. Sargent notes that the techniques can be used in both an objective and in a subjective way. For objective approaches a numerical or mathematical control test will need to be given. A subjective verification of validation would be based upon personal feeling or opinion.

The techniques consists of (1) animation, (2) comparison to other models, (3) degenerate tests, (4) event validity, (5) extreme condition tests (6) face validity, (7) historical data validation, (8) interval validity, (9) multistage validation, (10) operational graphics, (11) parameter variability through sensitivity analysis, (12) predictive validation, (13) traces and (14) Turing tests.

5.6.2. Conceptual model validation

Below the techniques described by Sargent are used for the conceptual model validation. It is intended to show that the assumptions and models are correct, and that the structure and relationships are suited for the purpose of using the model [77].

Event validity: The events in the conceptual model are made up of three types: (1) the creation of transport tasks, (2) the locomotive driving, starting and stopping behaviour, which included the traffic rules and picking-up or dropping-off wagons (3) the assignment of transport tasks to locomotives. The first event validity, that of creating transport tasks, follows a random pattern in stead of using a planning. This is discussed more in the interval validity below.

The locomotive starting and stopping behaviour uses the assumption that all the locomotives drive at an average speed, and that every section takes a specific time to cover. It is assumed that the acceleration and stopping time is covered in this specific driving time of a section. The found section times are location in the Appendix D. GPS data is used to obtain an average route time, and this includes acceleration and stopping time. So therefore, it is assumed to be included in the route time. The picking-up and dropping-off of wagons does never take an exact time. The absolute value of a normal distribution is taken with a mean of 5 minutes and a standard deviation of 1 min. The absolute value is taken to ensure that the trivial non-negativity constraint is met by preventing negative pick-up or drop-off from happening.

Interval validity: The interarrival time of transport tasks from one single location happen at planned moments. This planning differs from day to day. To apply this change, a stochastic interarrival time of transport tasks is applied. An exponential distribution is taken with a mean of $1/d$ where d stands for the total amount of transport tasks per day per location. An exponential distribution is taken since it can only contain positive values and the major part lies closely to the left of the mean.

Comparison to other models: The conceptual model described in section 5.1 is used to describe the system of Chapter 3. Models have been used to describe railway systems, as shown in Chapter 2. Discrete event simulation of railway systems can therefore be seen as a valid way to describe a railway system. Although a real-life system will always have more influences, the basic idea of a railway simulation is to show relations and find possible improvements.

5.6.3. Simulation model verification

The software Simio is used for the discrete event simulation of the conceptual model. In order to check if the simulation model is implemented correctly, a verification is done. Within a simulation environment, errors can be made easily. Therefore, extensive testing has been done during construction of the model. A 100 percent verification can never be achieved. However, the fact that the key aspects such as the input, output and performance are in line with expectations aids the verification of the simulation model.

Animation: The most trivial verification method of the simulation model is the subjective looking at the simulation while it runs. *'Does the model looks as I expect it to do?'* is the most asked question. Locomotives do not run into each other, neither have they been spotted to crash or jump to another point. The locomotives stay on the railway track, besides at the start of the simulation. At that moment, the locomotives have to be initialized one after another at their home node near the Central location.

Historical data validation: The historical data regarding the number of transports between the locations that is obtained through GPS analysis described in Chapter 3. This data is used in the simulation model. Through a random distributed process described in Section 5.2, the input is set for the different location within the simulation. The expected and realized values for the number of transport tasks are shown in Table 5.1. The standard configuration is used, with a closest locomotive assignment strategy, standard configuration network and a shift working schedule. The demand in set for 7m ton. The difference between the expectation and the realization for both the outgoing and incoming values are small for this experiment for 100 days. The largest absolute percentile change is 13.7 percent. The average change is only 0.9 percent higher for the outgoing, and 0.8 percent for the incoming rides. This is not significant ($p<0.05$).

When errors regarding the network layout, entity creation or delivery in the simulation are not visually noticed, they are likely to be noted in the results of Table 5.1.

The locomotive hours are an important step. It is one of the few known parameters of the system. The locomotive hours at Tata Steel IJmuiden are kept, and for a year period can be found in Appendix D. As an example the driving hours of June 2016 are taken, which where 2566 hours in total. June 2016 has a high demand, and with an assumed average operating 5 locomotive it would mean a 71 percent utilization. In the simulation, with a shift work schedule, a utilization of 75 percent is obtained. These values do not differ substantially, which helps in the verification of the model.

Extreme condition test: Extreme condition testing is useful to check whether the expectations for the outcome of the experimental model are met. The first extreme test is a large number of locomotive addition to the base case. With 20 locomotives in place, it is expected that the system would fall into an unresolvable deadlock. This is the case. Only 3 transport tasks can be completed, and at the end of the run the locomotives are aligned in this specific deadlock position. Since the model consist of many bidirectional paths, every added locomotives must add another layer to the deadlock prevention solutions.

If a far too large demand is put into the system, for instance a demand that resembles 15m ton op steel production, the system is expected to have buildups. If this demand scenario is applied, the average pickup time is indeed large, 221 hours. There is a large difference between the number of performed transport tasks and the requested tasks, as expected. The same holds for large transport times, or large switch delays. A buildup

Table 5.1: Expected outgoing an incoming transport tasks from the different locations. The expected values are derived from historical data. The realization is the created output by the simulation model. A base case is used for this verification, where the demand is 7m ton, standard configuration, locomotive assignment is set for closest and a shift working schedule is used. The run length is 100 days of simulated time.

	Outgoing			**Incoming**		
Location	Expectation [#]	Realization [#]	Difference [%]	Expectation [#]	Realization [#]	Difference [%]
BIHA	8.10	8.62	6.4	8.00	8.02	0.3
BM	7.50	7.80	4.0	7.20	7.76	7.8
BO	4.60	14.60	-0.7	14.50	14.00	-3.5
BR	4.50	4.32	-4.0	4.20	4.24	1.0
BT	2.90	3.16	9.0	2.70	2.54	-5.9
BUKA1	2.40	2.54	5.8	2.40	2.46	2.5
BUKA3	5.40	5.28	-2.2	5.20	5.22	0.4
Centraal	71.90	70.60	-1.8	71.50	74.96	4.8
CPP T	4.50	5.00	11.1	4.40	4.06	-7.7
CPP W	4.40	4.24	-3.6	4.30	4.26	-0.9
CPR	0.80	0.82	2.5	1.60	1.56	-2.5
CPR Rooswijk	3.10	3.48	12.3	3.20	3.12	-2.5
CPRCH	8.30	8.72	5.1	8.20	8.08	-1.5
KB1	6.10	6.14	0.7	6.10	5.96	-2.3
NS	11.00	10.76	-2.2	11.60	11.76	1.4
PAA Oost	5.70	5.62	-1.4	5.70	6.08	6.7
PAA West	3.70	3.72	0.5	3.80	3.58	-5.8
PAB	4.90	5.36	9.4	4.90	4.80	-2.0
PAC Oost	2.40	2.08	-13.3	2.40	2.28	-5.0
PAC West	2.20	2.06	-6.4	2.20	2.28	3.6
PAD	6.50	6.52	0.3	6.70	6.18	-7.8
PAF	7.90	7.94	0.5	7.90	7.54	-4.6
TRH	3.90	4.22	8.2	4.10	3.54	-13.7
WAW	2.90	3.04	4.8	2.90	3.16	9.0
WBH	4.70	4.62	-1.7	4.70	4.86	3.4
Total	**205.0**	**206.8**	**0.9**	**205.0**	**206.68**	**0.8**

is seen in the transport time, pickup time and in the number of unperformed transport tasks.

If the priority of a single location is set at an extremely large number, and the locomotive assignment strategy is set at priority, the tasks from that specific location are indeed always pickup first. Another extreme test is the strategy to always pickup the ride with the largest travel distance first. This seems illogical from a efficiency point of view, since travelling to a certain location only because the transport task from that location takes up the longest distance and thus the most time will not help to increase efficiency. For the base case, the average pickup time increases by 32 percent with this strategy. While it was expected to be even larger, this performance can be explained by the fact that in the base case there is little to no buffer of transport tasks, and so the next single task has often to cover both the largest and smallest distance since it is the only one present. Another inefficient strategy it first-in-last-out (FILO). This would imply that the newest created transport tasks are pickup first. While it is possible it will not directly lead to a larger average pickup time, the maximum pickup time is expected to be far larger than with a FIFO or closest pickup strategy. This effect is noted. In the base case the FILO strategy resulted in a 290 percent larger maximum pickup time.

5.6.4. Operational validation

The operational validation must determine if the combination of the conceptual model with the implementation of the simulation model provides an output that can be used for its intended purpose [77]. Any large error in this validation can either be a an error in the conceptual model or an error in the simulation model (and so an error in the simulation model verification).

Operational validation can be done either subjective and objective, for both an observable of non-observable system. Sargent has made a classification as shown in Table 5.2

Table 5.2: Validation approach table source: Sargent

	Observable system	**Non-observable system**
Subjective approach	(1) Comparison Using Graphical Displays, (2) Explore Model Behavior	(1) Explore Model Behavior, (2) Comparison to Other Models
Objective approach	Comparison Using Statistical Tests and Procedures	Comparison to Other Models Using Statistical Tests

Explore model behaviour: The qualitative analysis shows that the output values are in line with natural non-negativity constraints, such as the pickup time, transport time, number of task completed, locomotive driving distance and averages. For the base case, the magnitudes of all of the above values for the outcome seem reasonable. The transport times are between 2 and 38 minutes, the pickup time between 0 and 58 minutes for the base case. This seems reasonable from personal experience with riding along with several locomotives.

More expected model behaviour is the occurrence deadlocks if no deadlock prevention is applied. Deadlocks can easily occur when using bidirectional paths and no slot or track allocation or reservation is applied.

Objective model behaviour that validates the model are the effects seen when an extra locomotive is added. Logic dictates that with an extra locomotive and with the same demand, the utilization per locomotive drops, and positive effects on several KPIs are expected such as the pickup time. This is indeed the case. When with a demand of 7m ton the number of locomotives is increased from 5 to 6, the utilization drops by 18 percent, and a decrease in pickup time of 8 percent is found.

Comparisons to outer behaviour: There is limited information available from the real-life system to check whether the output of the simulation model is correct. The information obtained through GPS analysis is the most extensive. The data provided in Table 5.1 shows that for the base case the input can be generated according the real-life normal 7m ton production. So this validates that the model is suited on this matter. However, in real-life a planner makes changes to the scheduled tasks to increase the efficiency of the system. In the simulation model, no planning and no scheduling takes place. It is expected that planning and scheduling can lead to great benefits, however for this research is left out of the scope. The smart assignment of transport tasks to locomotives is a way to improve the performance without having to make a schedule or a forecast.

Historical data shows an average route time of 15.32 minutes. In the simulation run used for the base case of this experiment, the average route time was 17.21 minutes. Although the value is higher, for a representation of the real-world this value is workable. A perfect representation of the real-world is never possible, and practical assumptions need to be made.

6

Experiments and Results

In this chapter, the experimental plan is detailed and worked out. The results of the experiments are placed in the results section. The question that an answer is sought for it:

> *What is a proper executable experimental plan in order to find the best performing designs and what is the performance of these design alternatives*

Simulation experiments with the help of scenarios are a useful tool to examine a variety of possible futures. Soria Lara [86] describes that when the future holds considerable uncertainty or if the business-as-usual cannot continue, scenario building and testing can give helpful insights. Furthermore, scenarios can help to identify the sensitivity of parameters on the outcome of a system.

6.1. Experimental Plan

The experimental plan has the following flow. There are 4 types of alternatives, being (1) the locomotive assignment strategy, (2) the network configuration, (3) the work schedule and (4) the locomotive fleet size. Instead if using a full factorial approach, this base case must identify system designs that are less performing than others. These will not be further used for experimentation, so that the focus can lie on well performing options. This means that for the largest groups of alternatives, being the locomotive assignment strategy and the design alternatives, a pre-experiment with a base case is done to select the best performing alternatives.

6.1.1. Base case

A base case is set up to reduce the number of experiments. The base case user the same parameters used in the model verification and validation. The base case uses the standard network configuration without any adaptions, a 7m and 8m ton demand scenario, 4 changing locomotive assignment strategies, and a normal shift working schedule.

6.1.2. Number of replication

An important step is to use independent seeds for the random variables that are used in the random distributions throughout the simulation. Every replication of a single experiment used another random seed. Simulation takes up time, and so the number of replications that can be performed is limited. In this subsection, the relevance of more replications per experiment is tested. More replication will lead to a more precise result. However, how much more precise it the question.

In Table 6.1 the experiment is set up with a 7m ton demand, standard configuration with altered switch time, 5 locomotives, shift working schedule and a closest locomotive assignment strategy. The number of replication go from 10 to 100, 1000 and finally 10000. The run time does not increase linear with the number of replication. It is unknown why this happens, but it could be due to initialization steps and memory reservation.

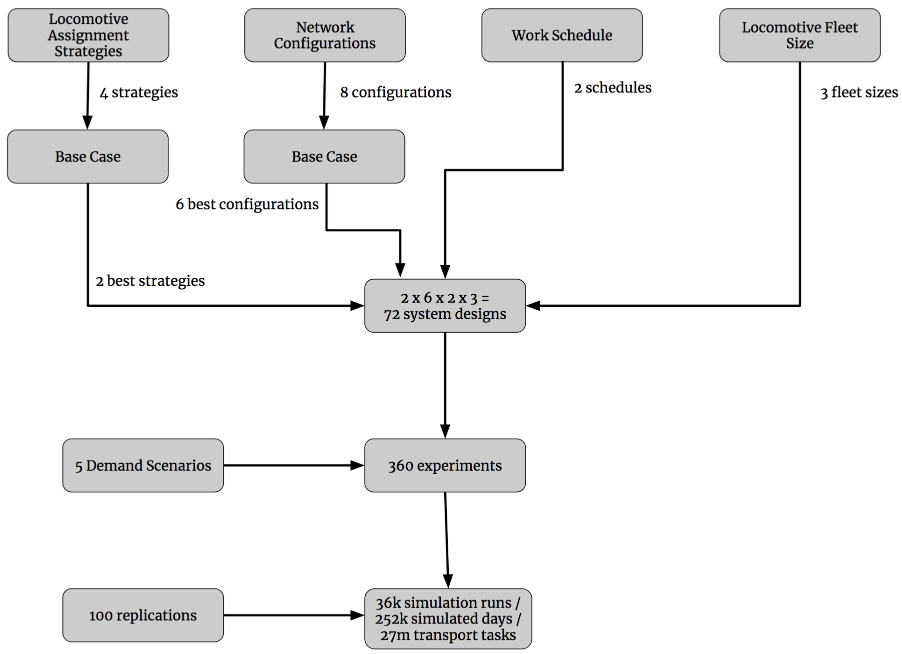


Figure 6.1: Experimental plan with the use of a base case.

Between 10 and 100 replications, the mean pickup time μ changes 1.5 percent. In the next step from 100 to 1000, the mean pickup time increases slightly with 0.2 percent. With a standard deviation of 2.31 and 2.07, a rise of 0.08 t

The standard deviation is calculated according equation 6.1:

$$SD = \sqrt{\frac{\sum |x - \mu|^2}{N}}. \tag{6.1}$$

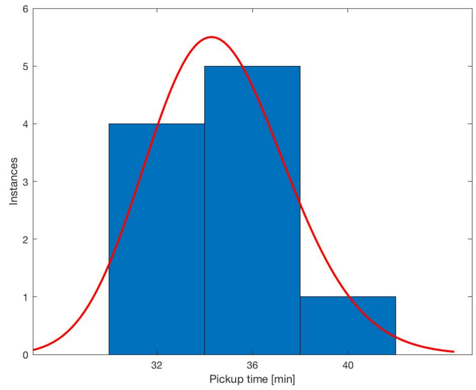
What can be noted from Table 6.1 is that the standard deviation does not drops substantially from 100 to 1000 experiments. The mean pickup time

Table 6.1: Replication test with a experiment setup of 7m ton demand, standard configuration with altered switch time, 5 locomotives, shift working schedule and a closest locomotive assignment strategy. The number of replication chosen is 100 replications. For the replication test an improved switch type is used. The simulated time is 7 days.

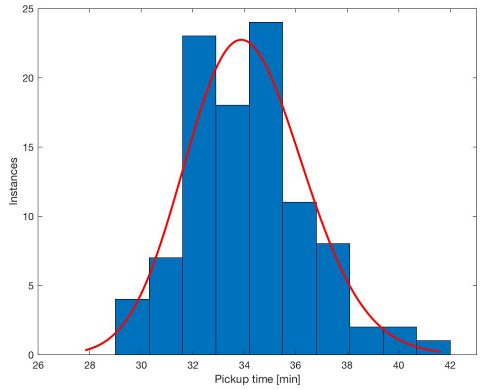
# Replications	**μ pickup time [min]**	**Standard deviation [min]**	**Run time [min]**
10	34.64	2.86	0.2
100	34.12	2.31	1.4
1000	34.20	2.07	13.1
10000	34.26	2.11	109.2

In Figure 6.2 the outcome of the replication experiment as of above is shown in a histogram. The top-left (a) shows the results for 10 replications, (b) for 100, (c) for 1000 and (d) for 10000. A log-normal distribution is fitted. The log-normal distribution is selected since the left tail of the distribution is shorter than the right tail. A subjective reason for this effect can be explained by that it is more likely for the locomotives in this system to have a substantial delay than it is to have nearly no delays.

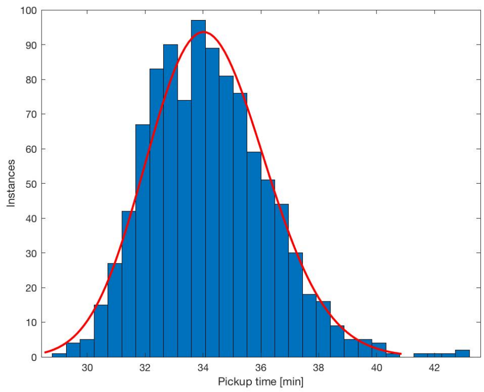
Since the standard deviation does not drops substantially from 100 to 1000 and more replications, and since the average shows no significant different, for future experiments a number of replications of 100 is chosen. Below, a list of the different scenario inputs is given. It is structured in the way as shown in Figure 6.1.



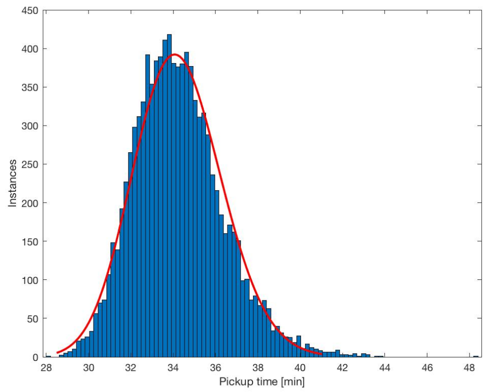
(a) 10 replications



(b) 100 replications



(c) 1000 replications



(d) 10000 replications

Figure 6.2: The mean pickup time of a 7m ton demand scenario with a standard configuration. The number of replications of the experiments are plotted in histograms. (a) shows the results for 10 replications of the same experiment, (b) for 100, (c) for 1000 and (d) for 10000.

- **Demand** : The demand for transport is the trivial changeable parameter. In the section A.2 the relevant information regarding the demand scenarios is given.
  - **6.5 million tons production**: This is a lowering of the current 7m ton produced.
  - **7.0 million tons production**: The current production of Tata Steel.
  - **7.5 million tons production**: A near future demand scenario of 5 years.
  - **8.0 million tons production** The current maximum allowable production at Tata Steel.
  - **8.5 million tons production**: A far future scenario.
- **Locomotive assignment strategy**
  - **FIFO**: Reserving the first created assignment of the global assignment queue.
  - **Closest available**: A locomotive evaluates all available transport tasks and selects the task with the closest distance to its current location.
  - **Priority**: The locomotive evaluates the transport tasks on priority and selects the task with the highest priority. If a tie occurs, FIFO is the second decision strategy.
  - **Designated zones**: The locomotive can only pickup transport tasks that are within its zone. When arriving to the end of its zone, the locomotive drops of the transport task and the locomotive from the next zone picks the transport task up from there.
- **Network Configuration**
  - Extra added section at Konijnenberg
  - Extra added section at Bosweg Facility
  - Extra connection Northern Bosweg
  - Improved switch type at a limited number of crucial locations
- **Work schedule**
  - 8 hour shift cycle
  - Relief schedule
- **Locomotive fleet size**
  - 4 locomotives
  - 5 locomotives
  - 6 locomotives

6.1.3. Hardware & Software

The experiments are run on a laptop. The hardware and software are detailed in Table 6.2.

Table 6.2: Hardware & Software used for the experiments

Hardware		Software	
Type	**Component**	**Type**	**Description**
Computer	Macbook Pro Mid-2015	Operating System	MacOS HighSierra
Processor	2.5 GHz Intel Core i7	Virtual Machine	VMWare Fusion 10
Memory	16 GB 1600 MHz DDR3	Virtual Machine Operation System	Windows 7 64gb
Cores	16 (8 for simulation)	Simulation software	Simio V 9.158
Graphical	Intel Iris Pro 1536 MB		

Initialization steps of the simulation model are detailed below in Table 6.3. The maximum speed is maintained the same as in the real system. The turnaround time is set according to a mean value found in the system analysis. An exponential distribution that is fit in the system analysis results is fitted. The interarrival time of transport tasks is set to be an average of 1 over the total number per day. In this was, on average, the found number of transport tasks from historical data is maintained the same in the simulation. The time it takes to manually flip a switch is 45 seconds. This has been found from both GPS analysis as well as hand-measurements of the real-life system. This is taken as the time that the locomotive is at full rest plus half the time when it is decelerating and acceleration, for compensation the covered distance in this time. A linear acceleration is assumed. The simulated time is set for 7 days. This is by far long enough to cover for warm-up effects, and for future research the weekly differentiating demand could be implemented. The number of replication is set according to the found significance, at a 100 runs with a different random seed.

Table 6.3: Parameter initialization of the simulation model

Parameter	**Mean value**	**Unit**	**Distribution**
Locomotive top speed	15	km/hr	-
Turnaround time	8	min	Exponential
Inter-arrival time	specific	min	Exponential
Switch delay time	45	sec	-
Simulated time	7	days	-
Number of replications per simulation	100	#	-

6.2. Base case: Locomotive assignment strategy selection

As shown in Figure 6.1, in order to reduce the number of experiments a pre-experiment is performed in order to determine which locomotive assignment strategies are likely to have the best performance. 4 strategies are tested, being (1) first-in-first out (FIFO), (2) looking for the closest available task, (3) Selection the task with the highest priority and (4) performing tasks only in the designated zones of the locomotive. An important aspects is that for strategy 1 to 3 the locomotive assignment strategy only matters when multiple tasks are present in the transport task idle queue. If zero tasks are available, the idle locomotive will pick the next upcoming task. If one task is available, the locomotive will assign that single task. From two tasks one, the locomotive will have a choice and can select a task based on the assignment strategy.

The **FIFO** strategy is the simplest one. Once a locomotive has performed the transport task and stands idle on the location, it looks into the transport tasks idle queue and selects the transport task which stands first in this chronological queue. For the second strategy, named the **closest**, the locomotive looks in the idle queue and determines the distance from its current location to each pickup location of the transport tasks. The locomotive does not uses the route length, but the direct distance between both the coordinates. It determines which location is the closest, and selects that transport task. If it would be that two transport tasks are at the same distance, the locomotive uses the FIFO strategy as a tie breaker.

The third locomotive assignment strategy is the one based on **priority**. As described before, transport tasks can have certain priority. The priority is arbitrary, being that it could be used to select certain tasks to be performed before others. In real-life, it occurs that certain tasks need to be transported quickly in order to prevent large delay costs further downstream. While this could be prevented by scheduling, it might still happen that a task needs prioritization. For this experiment, the standard priority is set to the arbitrary value 3. 5 percent of the tasks have a high priority of 10, 75 percent have the standard priority of 3, and 20 percent have a low priority of 1. The low priority tasks are the ones which do not have specific shirt delivery time or which will not cause large negative delay effects when delivered some time later.

The last strategy is the use of **designated zones** for the locomotives. These zones are represented in Figure 6.3. Each locomotive has a specific zone where he and only he can drive. At the end of the zones the load can be placed and so the locomotive from the other zone can pick up the load from there. The hypothesis is that since only one locomotive can drive in a zone, it will never encounter traffic. Traffic delays are reduces, and so the total transport time can be reduced. However, this assignment strategy reduces the flexibility of transport task demand. If it happens that in one zone several tasks are generated in quick repetition, no other locomotive can come do aid.

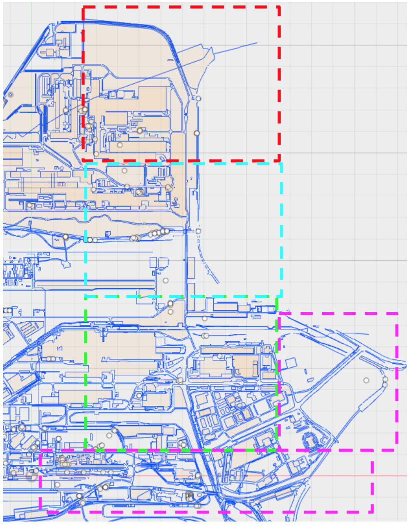


Figure 6.3: Usage of designated zones for locomotives assignment. The hypothesis is that since locomotives stay in their own zone, the traffic congestion in that zone is reduced to zero. At transfer locations at the end of the zone the transport task can be transferred to the next locomotive.

6.2.1. Experiment results

The experiment used the base case setup. A 7m ton demand and an 8m ton demand are put as an input. The network configuration is standard, without any improvements. The locomotive assignment strategies are changed. The work schedule is the shift schedule. The number of replications per experiment is 100 times and the simulated time is 7 days.

The results of the experiment are shown in Table 6.4. The KPI of pickup time, transport time, priority times the total time and the locomotive costs are displayed. The priority time is constructed by multiplying the priority of the individual transport tasks with the total time it took from creation until it arrived at its destination.

Table 6.4: Priority selection experiment.

	Pickup time [min]				Transport time [min]			
Loc strategy & demand	μ	Min	Max	Half Width	μ	Min	Max	Half Width
FIFO 7m	37.44	31.13	49.12	0.74	14.83	13.74	15.85	0.09
Closest 7m	34.55	30.18	41.47	0.41	14.68	13.56	15.58	0.08
Priority 7m	37.68	28.48	46.55	0.65	14.72	13.66	16.01	0.09
Designated zones 7m	66.75	34.17	166.78	3.94	15.13	13.56	18.09	0.15
FIFO 8m	48.00	35.15	78.54	1.47	15.29	14.31	16.41	0.10
Closest 8m	38.92	31.25	46.93	0.60	15.18	13.99	16.07	0.09
Priority 8m	48.38	34.94	80.64	1.73	15.33	13.96	17.98	0.14
Designated zones 8m	164.30	59.89	430.65	16.70	17.46	14.61	28.10	0.46

	Priority Time [prio x total time]				Locomotive costs [Euro]			
Loc strategy & demand	μ	Min	Max	Half Width	μ	Min	Max	Half Width
FIFO 7m	958.3	738.1	1282.0	22.8	69832	65769	74394	318
Closest 7m	896.6	704.4	1181.9	15.4	70376	64985	74033	351
Priority 7m	911.1	692.7	1227.8	18.5	69568	62673	74133	355
Designated zones 7m	1554.3	625.8	4259.3	107.4	62289	57760	67481	332
FIFO 8m	1314.2	949.4	2263.1	46.4	74774	70146	79059	387
Closest 8m	1117.4	809.6	1393.3	22.0	76280	70940	81504	414
Priority 8m	1182.7	149.9	1764.7	41.1	75105	70816	79529	346
Designated zones 8m	3424.1	1355.6	7870.4	302.9	65939	62423	68915	241

6.2.2. Pickup time

Th pickup time is the time it takes from creation of the transport tasks until it is pickup up by a locomotive for transport. It is an indication of the demand pressure. The more transport tasks are generated, the more pressure they perform on the networks capacity which will result in longer pickup times. For the pickup time for the 4 strategies the results are presented in Figure 6.4 for the 7m ton demand case and in Figure 6.5 for the 8m ton demand case. The for both the figures it holds that the designated zones strategy is the least favorable compared to the others. Since it holds less practicality, the designated zones strategy is dropped for further experiments.
If both the 7m ton and 8m ton demand with the 3 well performing transport assignment strategies are place side-by-side, the image of Figure 6.6 is obtained. From that is can be seen that the FIFO and the priority locomotive assignment strategy have similar pickup times, while the closest strategy outperforms on both the 7m and the 8m demand case.

6.2.3. Transport time

The transport time is the time it takes from the moment a transport tasks is picked up until it is delivered at the destination. In Figure 6.7. What can be seen from Figure 6.7 is that the transport time increases when a higher demand is used. This is expected. Furthermore, the transport time mean for the 7m demand for the closest strategy and the priority strategy are similair, while the FIFO strategy is slightly higher. For the 8m ton

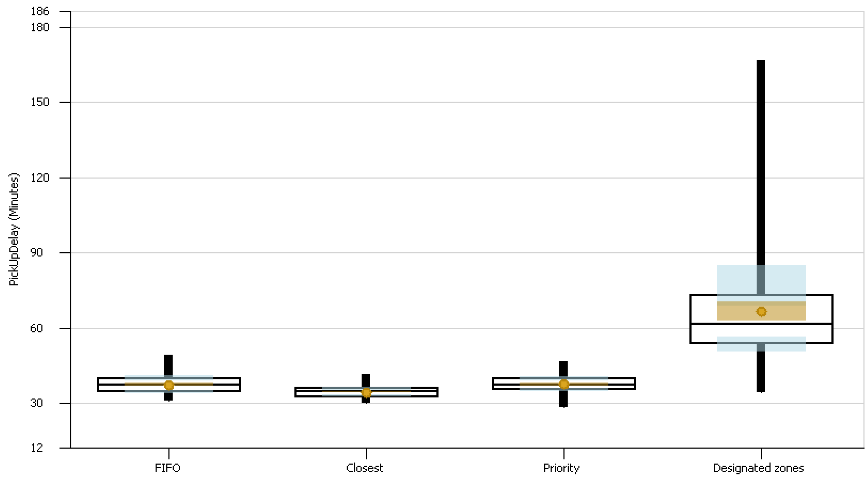


Figure 6.4: Pickup time for a 7m ton demand and 4 different locomotive assignment strategies

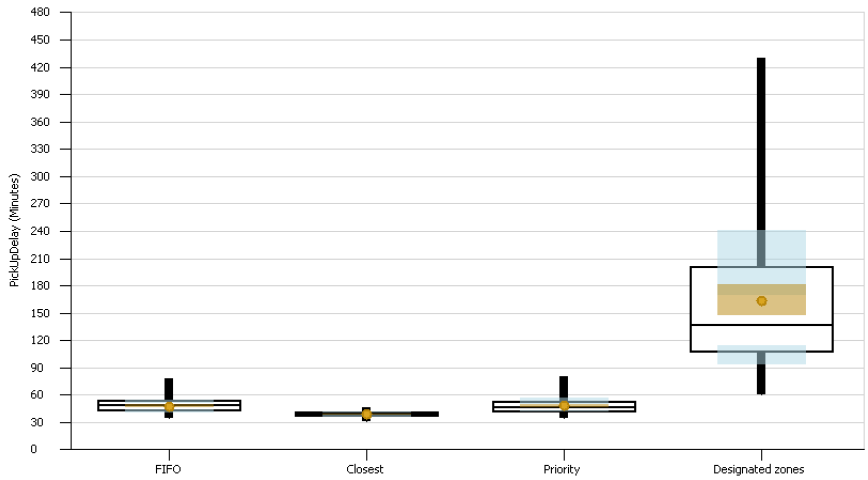


Figure 6.5: Pickup time for a 8m ton demand and 4 different locomotive assignment strategies

demand, the mean for the priority is slightly higher than for both the FIFO and the closest strategy, but the effects are marginal for both demand scenarios.

6.2.4. Priority time

The priority time is the KPI where the priority of each individual task is multiplied by the total time it took to complete the transport time. The total time is the pickup time plus the transport time. The total time is in hours, and the priority can have the value of 1,3 and 10 with 20, 75 and 5 percent contribution respectively.

For a 7 days simulated experiment, Figure 6.8 shows the results of the priority time for the 7m ton demand scenario. The FIFO strategy clearly has the highest value. What is interesting to see is that the mean average of the closest strategy is slightly lower than the priority strategy. This means that even while with the priority the tasks with high priority are performed first, the total priority time is still higher then when the strategy is to pickup a task which is the closest.

For the 8m ton demand scenarios the same can be concluded. Figure 6.9 shows the results. Interesting to see it that the priority strategy shows an experiment where the total priority time is very little. Furthermore, the width of the closest strategy distribution of results is significantly smaller than of the other two strategies. This shows that the strategy is more consistent that the others.

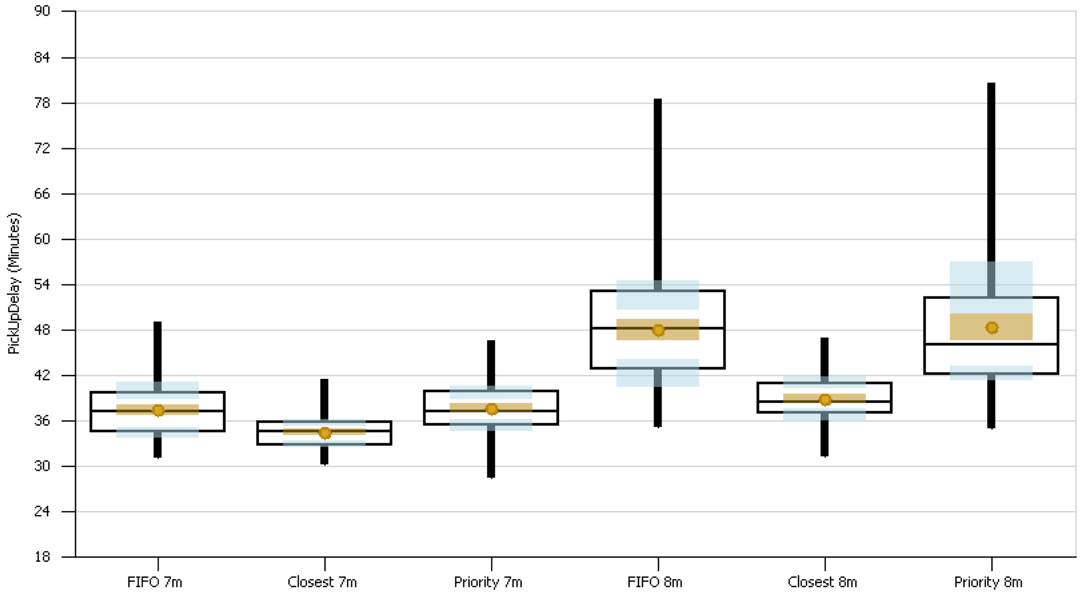


Figure 6.6: Both the 7m and 8m ton pickup delay time averages for the 3 best locomotive assignment strategies.

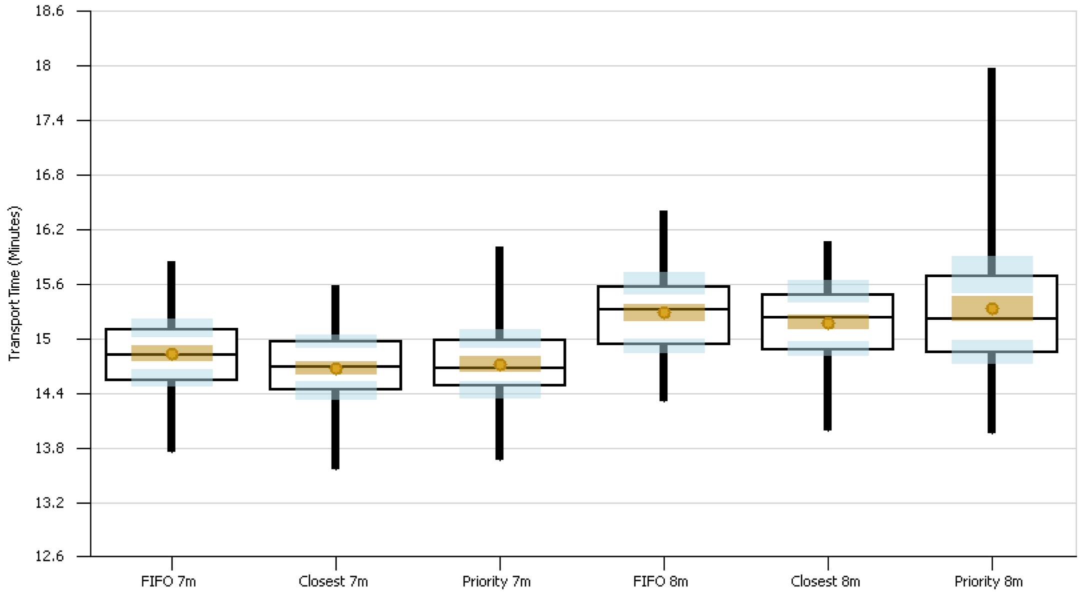


Figure 6.7: The transport time for both the 7m and 8m ton demand scenario for the best 3 locomotive assignment strategies. The transport time only increases slightly when the demand is increased.

6.2.5. Locomotive costs

The locomotive costs showed only a 1 to 2 percent change between the 3 different strategies. Since these differences are not significant, concluding on the performance of locomotive assignment strategies based upon locomotive costs is not applicable. For future experiments where different network configurations are tested, the locomotive costs is important.

6.2.6. Conclusion and selection of strategies

Since the designated zones strategy performed the worst based upon the pickup time, transport time and priority time, the strategy is dropped for further experiments. The closest strategy performed the best on all of the 4 showed KPIs, and so this strategy is selected for further experimentation. The FIFO and the priority assignment strategies show similar results for both the pickup time and the transport time, but the priority

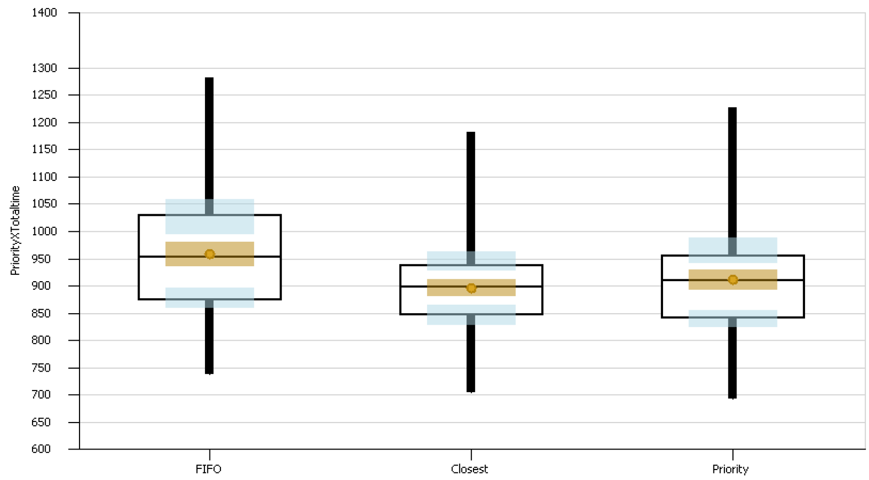


Figure 6.8: The priority value times the total transport time for the 7m ton demand scenario and 3 locomotive assignment strategies.

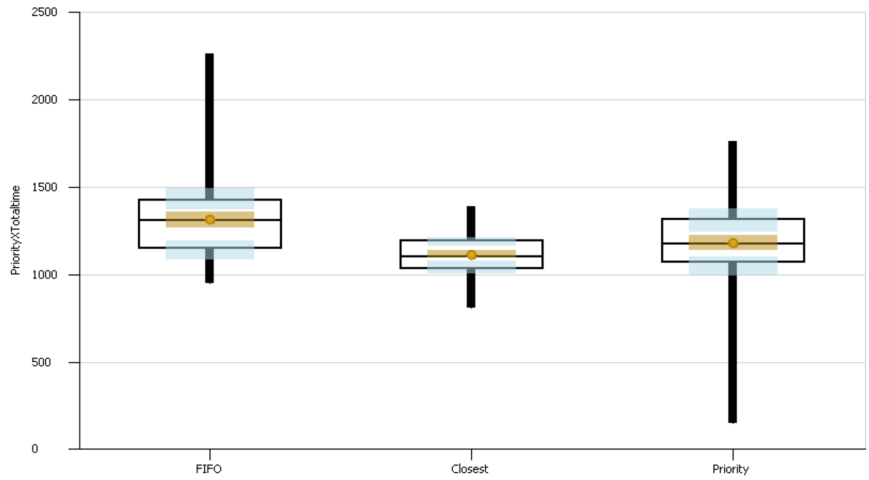


Figure 6.9: The priority value times the total transport time for the 8m ton demand scenario and 3 locomotive assignment strategies.

selection strategy outperformed the FIFO strategy in terms of priority time. Therefore the priority assignment strategy is chosen over th FIFO for further experimentation. Future experiments where the network configuration, working schedule and number of locomotives are altered will be performed with both the closest and priority assignment strategy.

6.3. Base case: Network configuration selection

4 different network configurations have been tested: (1) an improvement switch type for 9 manual switches, (2) an added piece of track in the northern section of the network, as shown before in Figure 4.4, (3) an added piece of track near the Konijnenberg, shown in Figure 4.5 and finally (4) two pieces of track added at the Bosweg, shown in Figure 4.6. To reduce the number of experiments, only the most effective network alterations are to be used. Figure 6.10 shows the results for the pickup time for 16 cases. The first 8 cases have a 7m ton demand scenario. The second 8 an 8m ton demand scenario. The first of both sets is a standard reference case with a standard network setup.

Table 6.5: Network configuration selection experiment.

	Pickup time [min]				**Transport time [min]**			
Experiment	μ	min	max	Half width	μ	min	max	Half width
Standard 7m	37.21	31.50	45.49	0.63	14.75	13.85	15.70	0.08
S 7m	33.85	29.21	39.69	0.39	14.49	13.53	15.35	0.09
N 7m	34.16	29.90	40.77	0.41	14.67	13.63	15.55	0.09
K 7m	33.59	29.04	38.22	0.39	14.31	13.24	15.36	0.09
B 7m	33.51	29.01	39.83	0.44	14.42	12.99	15.40	0.09
S + N 7m	33.95	29.04	39.31	0.42	14.58	13.63	16.04	0.09
S + K 7m	33.42	28.81	38.02	0.39	14.09	13.22	15.00	0.08
S + B 7m	33.44	29.97	39.43	0.36	14.30	13.40	15.20	0.08
Standard 8m	38.94	33.40	50.05	0.59	15.06	14.17	16.22	0.08
S 8m	38.20	32.66	43.83	0.50	14.84	13.70	16.26	0.09
N 8m	38.52	33.40	48.28	0.62	15.07	14.14	16.40	0.09
K 8m	37.37	31.79	47.07	0.56	14.51	13.51	15.83	0.08
B 8m	37.61	31.99	49.86	0.56	14.74	13.83	16.06	0.09
S + N 8m	38.31	32.66	51.14	0.60	14.90	13.70	16.10	0.09
S + K 8m	37.55	31.98	50.37	0.59	14.42	13.67	15.19	0.07
S + B 8m	37.47	32.48	45.06	0.48	14.68	13.23	16.25	0.09

6.3.1. Pickup time

Figure 6.10 shows that for both the 7m and 8m demand scenario the standard layout has the higher value for pickup time. Of the individual improvement. For the 7m ton scenario, all alterations have a substantial positive effect on the pickup time. For the 8m ton scenario, this effect is smaller. It is not known why, but it could be due to stochastic effects.

6.3.2. Transport time

The improvements seen in the transport time are less consistent than for the pickup time. The Konijnenberg improvement shows the best individual result in both the 7m as well as the 8m ton scenario. The effects for the 8m scenario are relatively larger.

6.3.3. Conclusion and selection

All network alterations have different effects. The worst performing improvement is the Northern added section. This option is therefore excluded from future experimentation, which can reduce the number op experiments substantially.

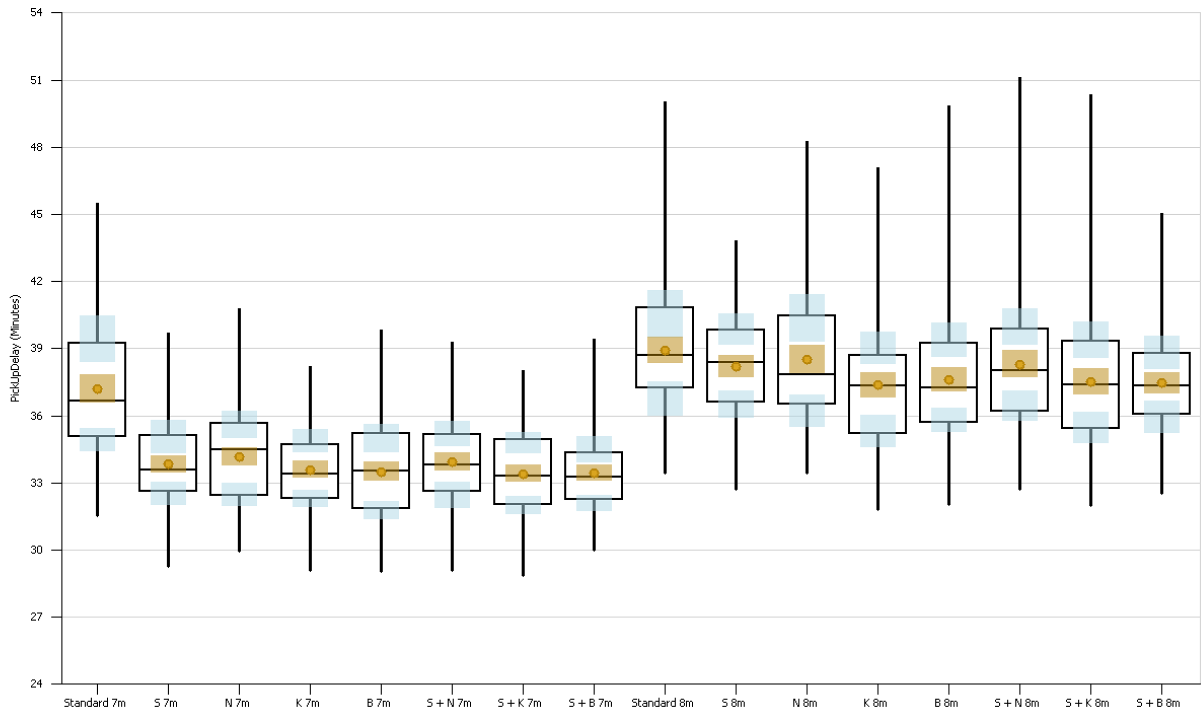


Figure 6.10: Pickup time for the different network configurations. S = Switch improvement, N = Northern improvement, K = Konijnenberg improvement, B = Bosweg improvement

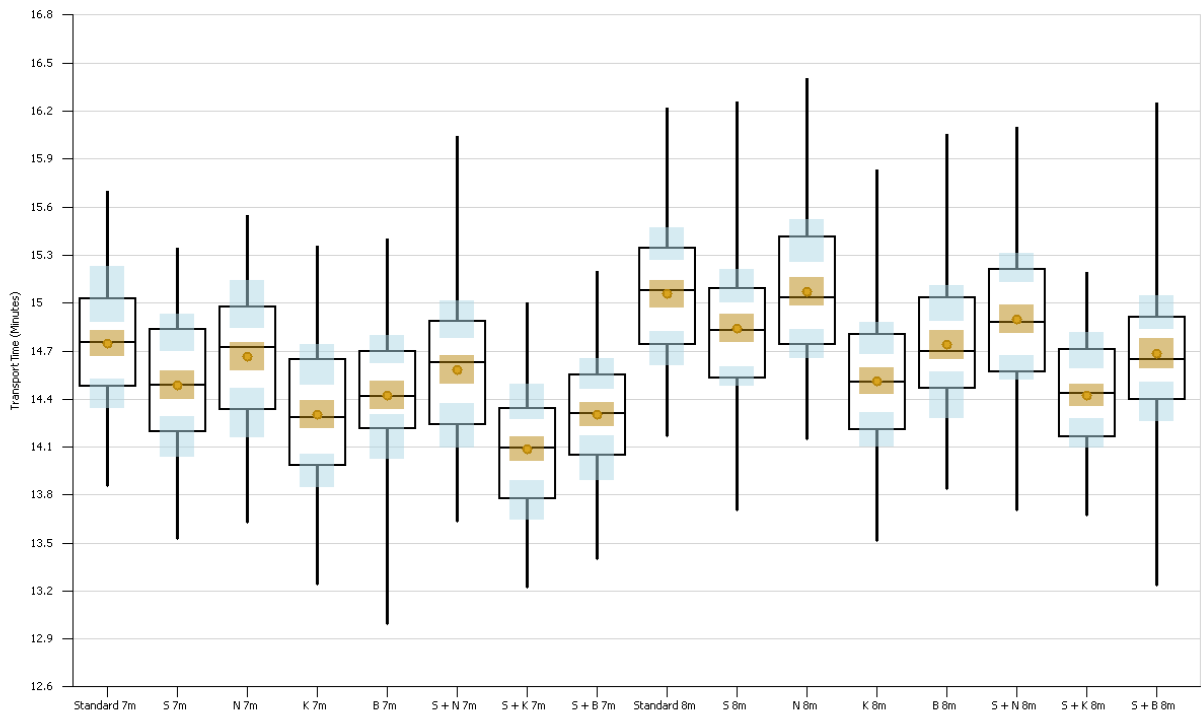


Figure 6.11: Transport time for the different network configurations. S = Switch improvement, N = Northern improvement, K = Konijnenberg improvement, B = Bosweg improvement

6.4. Main Experiment Results

The total number of experiments is 370. This is the full factorial of 5 demand scenarios, 3 locomotive fleet sizes, 2 assignment strategies, 2 work schedules and 6 network configurations. Firstly, for the total 360 experiments a Pareto optimality is performed by obtaining the total costs per experiment compared to the number of transport tasks. Further on, the results of the number of locomotives versus the assignment strategy is discussed. Next, the results for the two work schedules is presented, and hereafter the results of the network configurations.

6.4.1. Pareto optimality: Transport tasks versus costs

The figure 6.12 shows the Pareto optimality for the transport tasks versus the total costs. The total costs are the summation of the costs per locomotive and the priority costs, which are set to be 100 Euro per time per priority. This means that is an assignment has priority 3, and it is delivered at an hour after creation, the total priority costs are $3x100x1 = 300$. The results in Figure 6.12 show a nearly linear Pareto optimality field. The fitted polynomial of the minimum values is:

$$\text{Pareto optimality fitted field curve} = -0.0013x^2 + 2.3936x - 880.63 \tag{6.2}$$

The fitted equation shows a strong linear behaviour. This means that the minimal total costs per transport task over the different demand scenarios has a nearly linear behaviour. The 5 vertical groups shown in Figure 6.12 are the demand scenarios with their stochastic differences. The vertical spacing is the difference in costs. As can be seen, the costs for the 6.5m ton demand, or around 675 transport tasks per week, differs from 128 thousand Euro to 230 thousand Euro. This is an 80 percent difference. For the higher demand scenarios, the difference is even larger. This high difference between experiment need a closer specific look, which is performed in the following subsections. the top line shows the design which is closest to the current real-life system. Large gains in potential performance are shown.

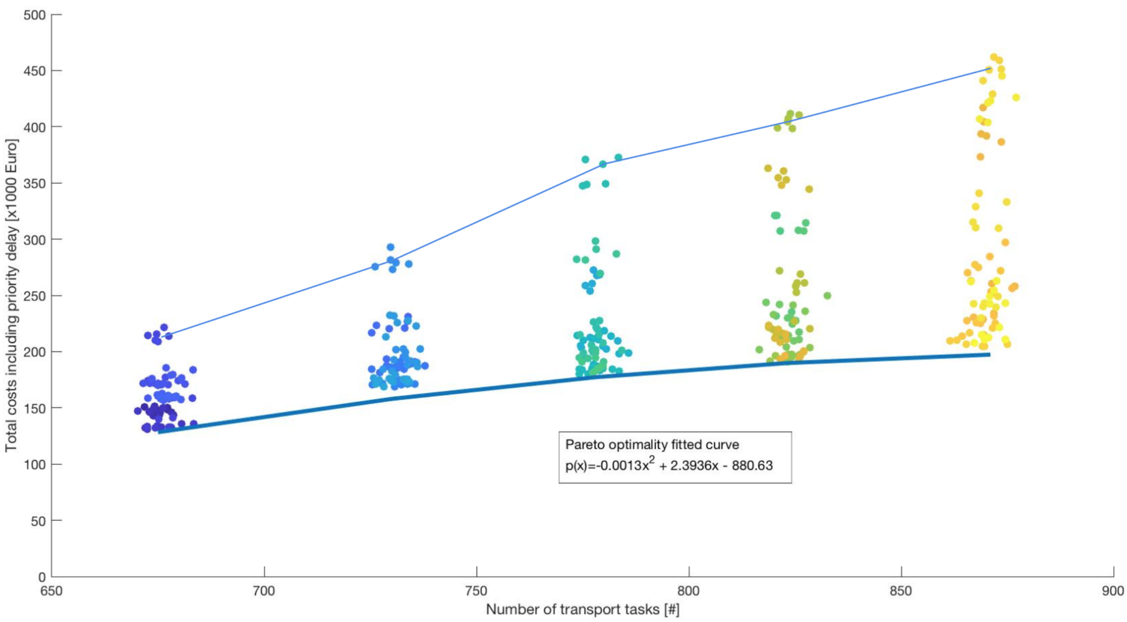


Figure 6.12: Pareto optimality of all experiments. On the x-axis the total costs for transport including a delay costs of 100 Euro per hour of delayed priority is shown. On the y-axis the total number of transport tasks is given. A polynomial curve is fitted.

If the average costs per transport task is plotted for all the experiments, the scatter of Figure 6.13 is obtained. The linear behaviour of the minimum total costs is present by the inserted line. This behaviour is expected. Performing more transport tasks will require more fuel and so the linear component is present. The negative higher order coefficient shows that more transport tasks lead to a less efficient operation. More transport task require more movements, and more movement will lead to higher traffic on the rail track. Traffic stops or delays are inevitable in the network as is present at Tata Steel IJmuiden.

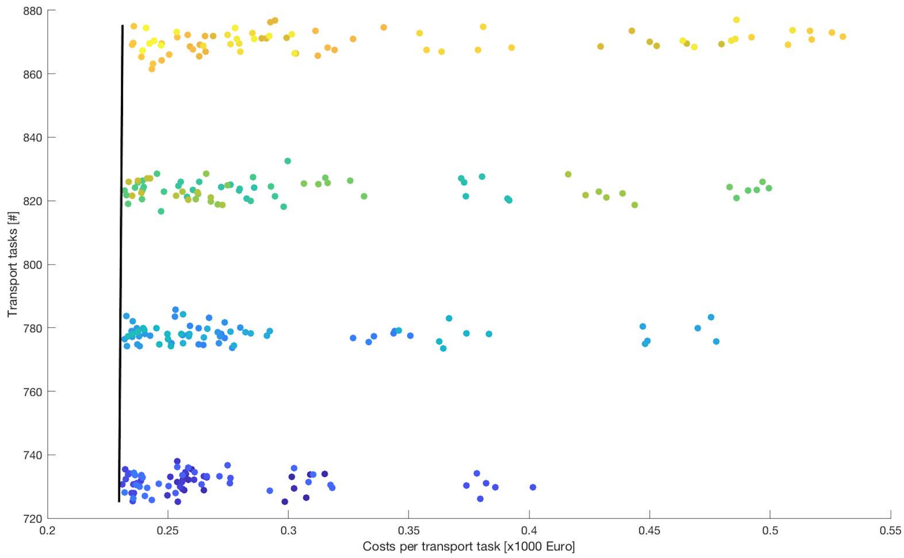


Figure 6.13: The Pareto optimality of the total costs per transport task versus the number of transport tasks.

Table 6.6: Best performing experiments per demand scenario

Demand	Experiment	Customer value	Improvement from base case
6.5m ton	Closest, 4 locs, Relief, Konijnenberg + switch	5.13	10.5 %
7.0m ton	Closest, 5 locs, Relief, Konijnenberg + switch	4.45	13.8 %
7.5m ton	Closest, 6 locs, Relief, Konijnenberg + switch	4.31	11.7 %
8.0m ton	Closest, 6 locs, Relief, Konijnenberg + switch	4.30	13.1 %
8.5m ton	Closest, 6 locs, Relief, Konijnenberg + switch	4.25	14.2 %

In Table 6.6 the best performing experiments per demand scenario are given. The performance is expressed in the created customer value, which is calculated according equation 4.1 from Chapter 4. For the improvement versus the base case the best performing number of locomotives, a shift working schedule, closest assignment strategy and a standard network configuration.

6.4.2. Number of locomotive versus assignment strategy

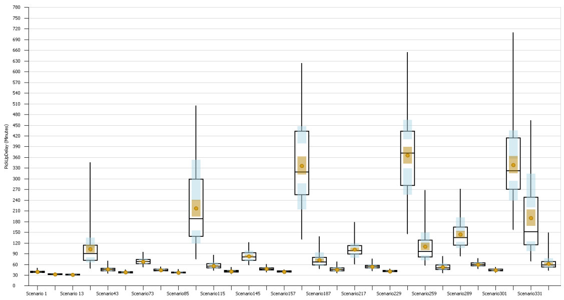
Table 6.7 shows the results of the experiments for a changing demand and a changing number of locomotives. The rest of the parameters are left the same as in the base case. The effects of having more locomotives are as expected. More locomotives mean a shorter pickup time, transport time and priority time. Interesting to see is that the locomotive costs do not rise linear with the number of locomotives. The locomotive simulated costs have split into operation costs, at 254 Euro per hour, and idle cost of an estimated one fifth of that.

Table 6.7: Priority selection experiment.

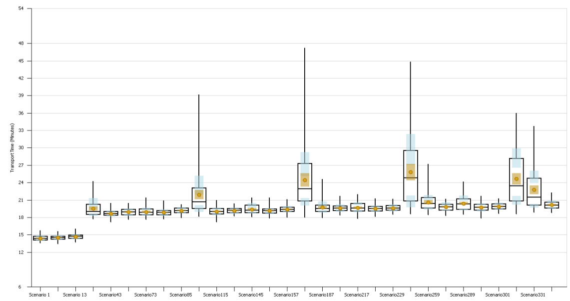
Demand [m ton production]	Locomotives [#]	Assignment strategy	Pickup time μ [min]	Transport time μ [min]	Total Time μ [min]	Priority time μ [prio x tt[hr]]	Loc costs μ [x1000 Euro]	Observations [#]	Customer value
6.5	4	Closest	39.19	14.40	53.59	907.44	60.45	674.26	4.46
6.5	5	Closest	32.32	14.51	46.83	786.61	67.43	678.25	4.64
6.5	6	Closest	31.19	14.68	45.87	771.40	73.33	674.04	4.48
6.5	4	Priority	103.61	19.53	123.14	1493.11	64.94	672.65	3.14
6.5	5	Priority	45.99	18.65	64.64	1035.34	73.42	676.71	3.82
6.5	6	Priority	37.77	18.91	56.69	934.44	80.82	679.81	3.90
7.0	4	Closest	68.27	18.97	87.24	1594.54	71.83	733.89	3.17
7.0	5	Closest	43.74	18.84	62.58	1151.00	78.06	728.86	3.77
7.0	6	Closest	37.12	19.19	56.32	1015.89	85.06	729.16	3.91
7.0	4	Priority	217.33	21.90	239.23	2258.23	67.15	729.79	2.49
7.0	5	Priority	55.98	19.03	75.00	1249.14	76.63	731.10	3.63
7.0	6	Priority	40.92	19.16	60.08	1071.32	84.59	734.49	3.83
7.5	4	Closest	82.99	19.39	102.38	1972.31	75.29	777.48	2.85
7.5	5	Closest	47.51	19.15	66.66	1306.51	81.88	776.75	3.65
7.5	6	Closest	39.49	19.39	58.87	1134.95	88.84	780.53	3.86
7.5	4	Priority	336.93	24.45	361.38	3027.30	67.85	775.71	2.09
7.5	5	Priority	71.90	19.73	91.63	1483.79	79.34	778.98	3.42
7.5	6	Priority	45.84	19.58	65.43	1201.57	87.63	779.74	3.75
8.0	4	Closest	101.45	19.68	121.13	2422.49	78.58	820.75	2.56
8.0	5	Closest	53.86	19.49	73.34	1501.31	85.38	824.19	3.50
8.0	6	Closest	41.16	19.61	60.77	1236.05	92.07	822.58	3.81
8.0	4	Priority	366.08	25.82	391.89	3434.61	68.05	823.88	2.00
8.0	5	Priority	110.19	20.61	130.80	1903.90	81.75	821.39	3.02
8.0	6	Priority	52.40	19.78	72.19	1360.32	90.68	824.89	3.64
8.5	4	Closest	144.27	20.42	164.69	3339.06	83.20	869.29	2.08
8.5	5	Closest	59.93	19.74	79.67	1740.66	88.58	866.39	3.30
8.5	6	Closest	43.99	19.89	63.88	1387.23	95.67	871.85	3.72
8.5	4	Priority	339.27	24.64	363.91	3942.32	67.93	871.75	1.89
8.5	5	Priority	190.85	22.76	213.61	2572.46	83.71	868.31	2.55
8.5	6	Priority	62.33	20.16	82.49	1555.48	93.34	872.75	3.51

In order to compare the two strategies, results of the experiments of Table 6.7 are place into Smore plots in Figure 6.14. The order of the experiments from Table 6.7 is the same in the Figures of 6.14. To start, the first comparison is made in the pickup time, as shown in Figure 6.14 (a). The pickup time increases with an increasing demand. The Closest assignment strategy outperforms the priority assignment strategy in every experiment. The second decision in the priority assignment strategy is the creation time of the task, for if the locomotive must choose between two task of the same priority. For both the closest and priority assignment strategy, the 4 locomotive option is not able to perform well with a demand over 7m ton.

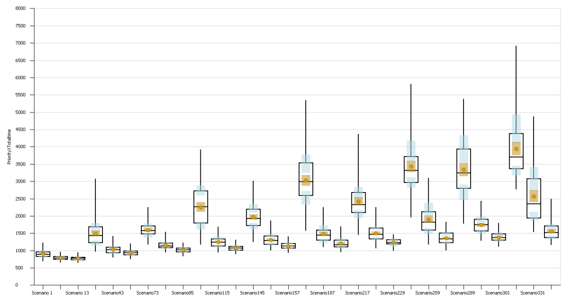
The differences in the transport time are less distinct than in the pickup time. The average transport time for experiments with a demand of over 7m and at least 5 locomotives is far less influenced by the strategy. The most interesting figure is Figure 6.14 (c) where the priority time is given. The priority time is the total time times the priority per individual assignment. The priority assignment strategy favors tasks with a high priority. It is expected that the priority time will therefore be lower if this assignment strategy is present. However, Figure 6.14 shows the opposite. The priority time is larger for the priority assignment strategy than for the closest assignment strategy. Apparently the second strategy can be in a shorter time to its next assignment, and so the average priority time is lower.



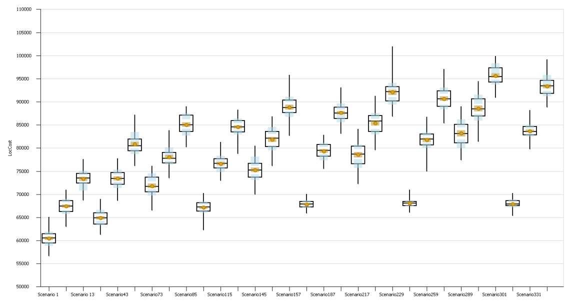
(a) Pickup time



(b) Transport time



(c) Priority time



(d) Locomotive costs

Figure 6.14: The pickup time, transport time, priority time and locomotive costs for the 5 demand scenarios and a changing locomotive assignment strategy.

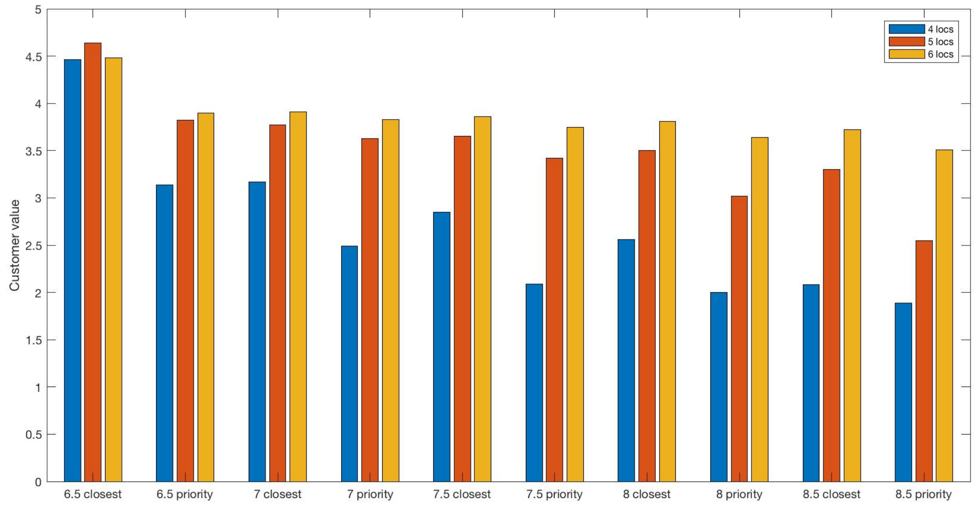


Figure 6.15: Customer value for three fleet sizes and different locomotive assignment strategies

Table 6.8: Priority selection experiment.

Demand [m ton production]	Locomotives [#]	Assignment strategy	Customer value
6.5	4	Closest	4.46
6.5	5	Closest	4.64
6.5	6	Closest	4.48
6.5	4	Priority	3.14
6.5	5	Priority	3.82
6.5	6	Priority	3.90
7.0	4	Closest	3.17
7.0	5	Closest	3.77
7.0	6	Closest	3.91
7.0	4	Priority	2.49
7.0	5	Priority	3.63
7.0	6	Priority	3.83
7.5	4	Closest	2.85
7.5	5	Closest	3.65
7.5	6	Closest	3.86
7.5	4	Priority	2.09
7.5	5	Priority	3.42
7.5	6	Priority	3.75
8.0	4	Closest	2.56
8.0	5	Closest	3.50
8.0	6	Closest	3.81
8.0	4	Priority	2.00
8.0	5	Priority	3.02
8.0	6	Priority	3.64
8.5	4	Closest	2.08
8.5	5	Closest	3.30
8.5	6	Closest	3.72
8.5	4	Priority	1.89
8.5	5	Priority	2.55
8.5	6	Priority	3.51

6.4.3. Work schedule

Two work schedules are experimented with. The standard work schedule, as can be found in Appendix D. The shift work schedule consists of 8 hour shifts. This is the current operational work schedule at Tata Steel IJmuiden. In this 8 hours, the locomotive driver has 3 breaks. 2 smaller coffee breaks and 1 longer lunch break. The driver drives the locomotive back to the Central location to have its break there, and continues after the break from the same location. At the end of a shift, the driver drives back to the Central location and the shifting of the team happens. The new team starts from the Central location again.

The relief work schedule has a different flow. The breaks of the drivers do not occur at the same time, nor do they have to drive back to the Central location with their locomotive. The team of drivers work on relief, meaning that when 1 driver can have a break, another takes over the spot at that specific locomotive. A car must be available for them to drive to the canteen. The locomotives keep on driving, and no requirement to drive back to the Central location is necessary.

In Table 6.9 the results of the experiments regarding two different work schedules is shown. 5 different demand scenarios and 3 different locomotive fleet sizes are used besides the altering work schedules. A closest locomotive assignment is used with the standard network configuration.

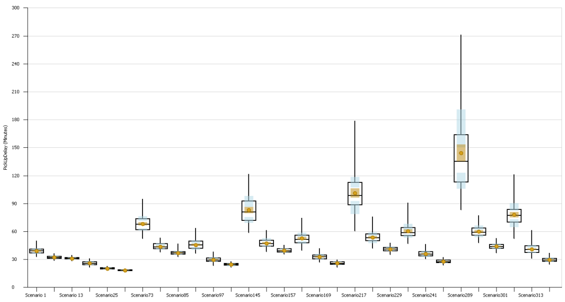
Table 6.9: Work schedule

Demand [m ton production]	Locomotives [#]	Work Schedule	Pickup time μ [min]	Transport time μ [min]	Total Time μ [min]	Priority time μ [prio x tt[hr]]	Loc costs μ [x1000 Euro]	Observations [#]	Customer value
6.5	4	Shift	39.19	14.40	53.59	907.44	60.45	674.26	4.46
6.5	5	Shift	32.32	14.51	46.83	786.61	67.43	678.25	4.64
6.5	6	Shift	31.19	14.68	45.87	771.40	73.33	674.04	4.48
6.5	4	Relief	25.88	13.93	39.81	684.81	67.34	680.50	5.01
6.5	5	Relief	20.27	13.93	34.20	586.52	77.19	683.34	5.03
6.5	6	Relief	18.57	14.02	32.59	552.37	86.22	678.50	4.80
7.0	4	Shift	68.27	18.97	87.24	1594.54	71.83	733.89	3.17
7.0	5	Shift	43.74	18.84	62.58	1151.00	78.06	728.86	3.77
7.0	6	Shift	37.12	19.19	56.32	1015.89	85.06	729.16	3.91
7.0	4	Relief	45.69	18.52	64.22	1192.63	75.79	732.85	3.76
7.0	5	Relief	29.77	18.36	48.13	890.31	85.73	731.76	4.19
7.0	6	Relief	24.59	18.47	43.06	794.79	95.80	733.21	4.18
7.5	4	Shift	82.99	19.39	102.38	1972.31	75.29	777.48	2.85
7.5	5	Shift	47.51	19.15	66.66	1306.51	81.88	776.75	3.65
7.5	6	Shift	39.49	19.39	58.87	1134.95	88.84	780.53	3.86
7.5	4	Relief	52.63	18.81	71.45	1396.82	78.73	780.10	3.57
7.5	5	Relief	32.83	18.63	51.46	1004.16	88.23	777.48	4.12
7.5	6	Relief	25.87	18.66	44.53	862.56	98.30	774.19	4.19
8.0	4	Shift	101.45	19.68	121.13	2422.49	78.58	820.75	2.56
8.0	5	Shift	53.86	19.49	73.34	1501.31	85.38	824.19	3.50
8.0	6	Shift	41.16	19.61	60.77	1236.05	92.07	822.58	3.81
8.0	4	Relief	60.41	19.15	79.56	1628.54	81.10	818.21	3.35
8.0	5	Relief	36.10	19.00	55.10	1131.88	91.11	822.90	4.03
8.0	6	Relief	27.75	18.92	46.67	964.19	101.39	826.33	4.18
8.5	4	Shift	144.27	20.42	164.69	3339.06	83.20	869.29	2.08
8.5	5	Shift	59.93	19.74	79.67	1740.66	88.58	866.39	3.30
8.5	6	Shift	43.99	19.89	63.88	1387.23	95.67	871.85	3.72
8.5	4	Relief	78.03	19.62	97.66	2118.00	85.30	874.59	2.94
8.5	5	Relief	40.95	19.24	60.19	1319.73	93.91	867.74	3.84
8.5	6	Relief	29.51	19.34	48.85	1056.21	104.00	861.43	4.11

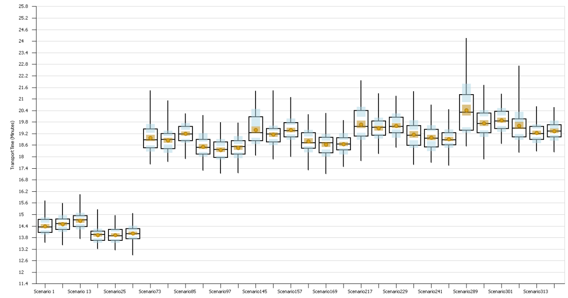
The results shown in Table 6.9 are set out in Smore plots in Figure 6.16. What must be noted is that the relief working schedule of 4 locomotives must be compared to 5 locomotives of the standard shift work schedule.

Figure 6.16 (a) shows the pickup time. The 7.5m ton demand scenario shown by the third set of 6 Smore plots shows that the relief schedule of 4 locomotives is nearly the same, while the transport time shown in Figure 6.16 (b) clearly shows that the relief schedule requires substantially less time. In fact, the relief schedule outperforms the shift schedule in every experiment. For a higher demand, the effects of using a relief schedule in stead of a shift schedule grows larger. This can be explained by the fact that a higher demand will result in more movements on the track, and so it will be more likely for traffic stops to occur. Having less unwanted movements, by not having to drive back to the central location every 2 hours, substantially favors all 3 factors, being the pickup time, transport time and priority time. The locomotive cost do show an increase. This can be explained by the fact that the faster work schedule of relief will have an effect of quicker delivery of transport task. And so the idle queue of new task will be small, therefore less moments for selection a preferred task for a locomotive based upon strategy can take place. With a proper planning, this can easily be resolved. And the fact that a locomotive less needs to be available is not taken into account here, which will reduce the costs.

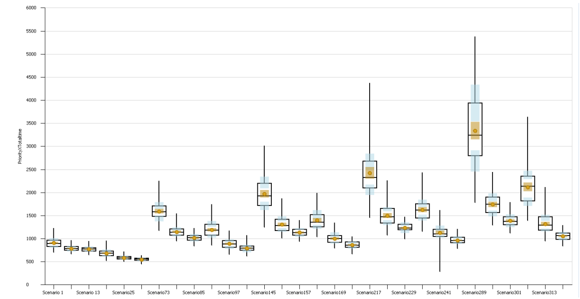
In order to evaluate the work schedule concepts more clearly, the customer value model is applied to the results. In Figure 6.17 the customer value for the two work schedules with varying fleet size are shown. The figure starts with the set of 6.5m ton production demand with the standard shift cycle, then the relief work schedule set starts. What can be seen is that all of the fleet sizes with 6.5 demand ton show a substantial



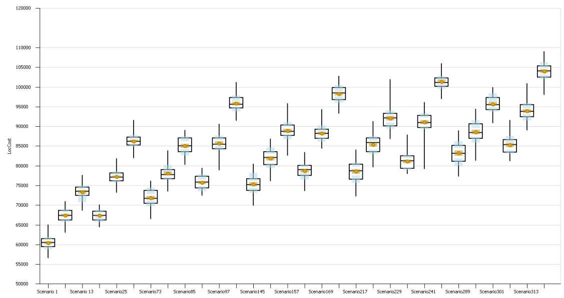
(a) Pickup time



(b) Transport time



(c) Priority time



(d) Locomotive costs

Figure 6.16: Pickup time, transport time, priority time and locomotive costs for the 2 work schedules, with variable fleet size and the 5 demand scenarios.

higher customer value than the shift work schedule. So for low demand cases it shows a clear improvement. The customer value was the highest in the standard scenario with 5 locomotives, being 4.64 tasks/k Euro and for the relief schedule it is 5.03 tasks/k Euro. This is an 8.6 percent improvement.

For the 7m ton demand scenario the overall customer value drops significantly compared to the 6.5m ton case. What can be seen is that for the shift schedule the 6 locomotive case generates the most customer value. For the relief schedule, the 5 and 6 locomotive fleet sizes both have similar customer value. While the shift schedule has a maximum value of 3.91, the relief has a value of 4.19, a 7.1 percent increase. What is interesting to see is that the fleet size of 5 locomotives of the shift schedule has more or less the same customer value as the 4 locomotive fleet size for the relief schedule. So with a locomotive less on the network, still the same performance can be achieved.

For the 7.5m ton scenario the 4 locomotive fleet size of the shift cycle shows a clear drop compared to the previous demand. This drop continues, and the pickup time delay does get above 1.5 hours which seems far to long to be practical. The relief schedule of 5 locomotives versus the shift schedule of 6 shows a 6.7 percent improvement, while the 6 locomotive fleet size is at 8.5 percent. The advantage for the relief cycle continues for the 8m ton case. 3.81 tasks/kEuro is the customer value for the 8m ton, shift, 6 locomotive case, while the relief, 5 locomotive has 4.03 and the 6 locomotive an even higher 4.18. If the production would increase to an 8.5m ton, the customer value for the shift and relief schedule decreases. The network will be more utilized, and so the congestion and traffic will rise.

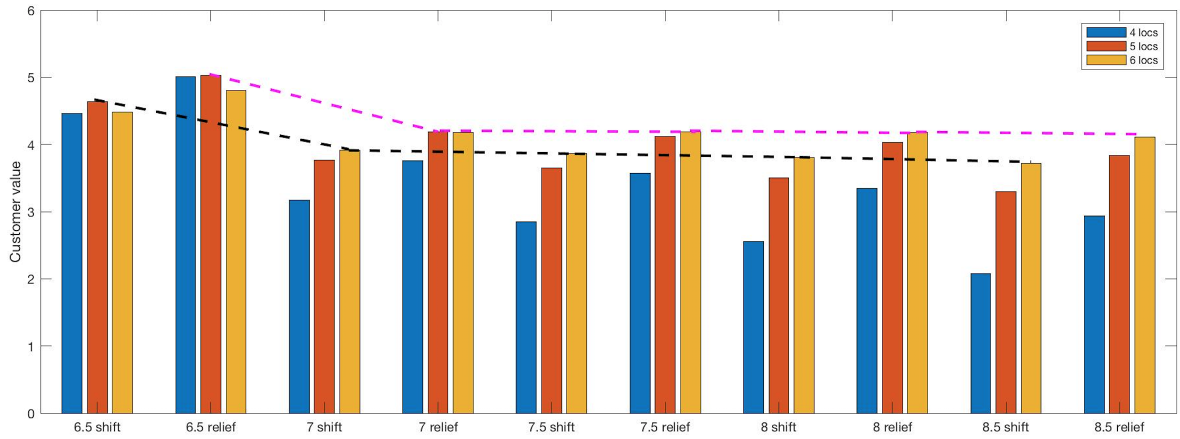


Figure 6.17: Customer value for two work schedules and a variable fleet size.

6.4.4. Network configuration

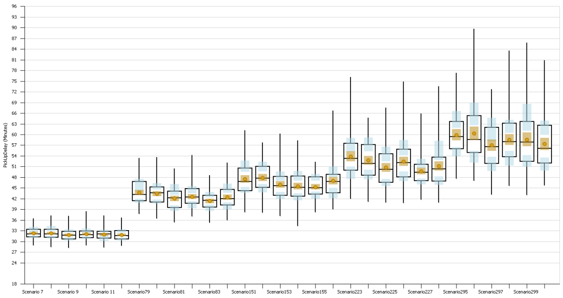
The network configurations detailed previously are examined in the following set of experiments. The demand scenarios are present, with a single fleet size of 5 locomotives. The effects of the improvements are worked out below. The details on the network configurations are shown in subsection 4.3.3.

The switch improvements in the simulation have a positive effect on the transport time. But a shorter transport time in a single location could lead to more throughput, and so more congestion in another place. The effects of the switch improvements on the transport time are positive. The improved design for the 6.5m, 7m, 7.5m, 8m and 8.5m ton demand have on percentage a shortened transport time of 1.1, 0.7, 0.4, 0.5 and 0.8 percent over the standard design.

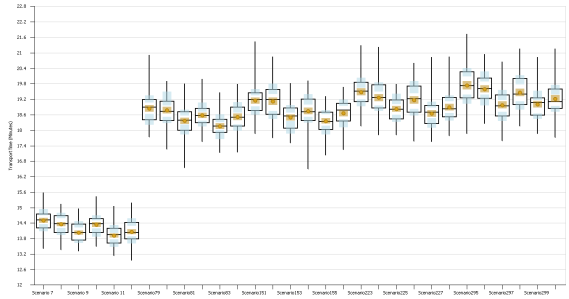
The Konijnenberg improvement the best of the three single improvements. The reduction in transport time was 3.8, 3.9, 3.3, 3.2 and 3.9 percent with the standard design. The combination of both the improved switched combined with the Konijnenberg improvement shows the best results, although the switches plus the Bosweg improvement has similar results.

Table 6.10: Comparison results of the network improvements. A standard work cycle, with a fleet size of 5 locomotives and a closest assignment strategy is used. The order of improvements is (-) standard, (S) improved switches, (K) track Konijnenberg, (B) track Bosweg, (S+K) switches + Konijnenberg, (S+B) switches + Bosweg.

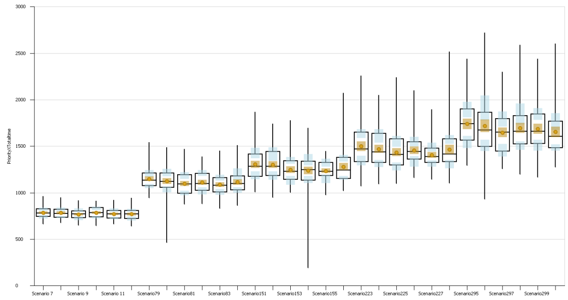
Demand [m ton production]	Network improvement	Pickup time μ [min]	Transport time μ [min]	Total Time μ [min]	Priority time μ [prio x tt[hr]]	Loc costs μ [x1000 Euro]	Observations [#]	Customer value
6.5	-	32.32	14.51	46.83	786.61	67.43	678.25	4.64
6.5	S	32.33	14.36	46.69	784.74	66.84	674.75	4.64
6.5	K	31.79	14.03	45.82	768.75	66.28	673.84	4.71
6.5	B	32.09	14.34	46.43	786.28	66.93	675.40	4.64
6.5	S+K	31.90	13.91	45.82	771.74	66.31	678.70	4.73
6.5	S+B	31.85	14.06	45.91	770.46	66.40	675.24	4.71
7.0	-	43.74	18.84	62.58	1151.00	78.06	728.86	3.77
7.0	S	43.37	18.78	62.15	1127.70	78.44	735.44	3.85
7.0	K	42.04	18.36	60.40	1100.62	77.05	728.79	3.89
7.0	B	42.59	18.58	61.17	1111.97	77.72	733.96	3.89
7.0	S+K	41.37	18.15	59.52	1088.08	76.83	731.46	3.94
7.0	S+B	42.41	18.52	60.93	1116.17	77.61	732.19	3.87
7.5	-	47.51	19.15	66.66	1306.51	81.88	776.75	3.65
7.5	S	47.91	19.12	67.03	1301.31	81.68	778.11	3.67
7.5	K	45.97	18.49	64.46	1248.26	80.27	774.50	3.78
7.5	B	45.53	18.75	64.28	1239.94	80.97	779.83	3.80
7.5	S+K	45.33	18.36	63.69	1236.39	80.02	774.69	3.80
7.5	S+B	47.05	18.66	65.71	1282.08	81.04	783.18	3.74
8.0	-	53.86	19.49	73.34	1501.31	85.38	824.19	3.50
8.0	S	52.77	19.27	72.04	1472.18	84.73	820.63	3.54
8.0	K	50.76	18.82	69.58	1436.39	84.07	825.10	3.62
8.0	B	52.46	19.17	71.63	1456.78	84.44	823.23	3.58
8.0	S+K	49.74	18.65	68.39	1408.53	83.44	824.29	3.68
8.0	S+B	51.20	18.89	70.10	1464.32	84.08	823.86	3.57
8.5	-	59.93	19.74	79.67	1740.66	88.58	866.39	3.30
8.5	S	60.32	19.60	79.92	1720.71	88.59	871.30	3.34
8.5	K	57.02	18.98	76.00	1647.55	87.03	871.20	3.46
8.5	B	58.61	19.46	78.07	1697.25	88.52	876.75	3.40
8.5	S+K	58.63	19.00	77.63	1688.44	87.57	876.19	3.42
8.5	S+B	57.36	19.22	76.58	1654.21	87.98	871.25	3.44



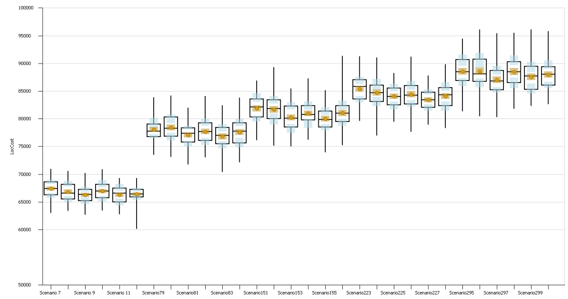
(a) Pickup time



(b) Transport time



(c) Priority time



(d) Locomotive costs

Figure 6.18: The average and standard deviation of critical parameters: Region R4

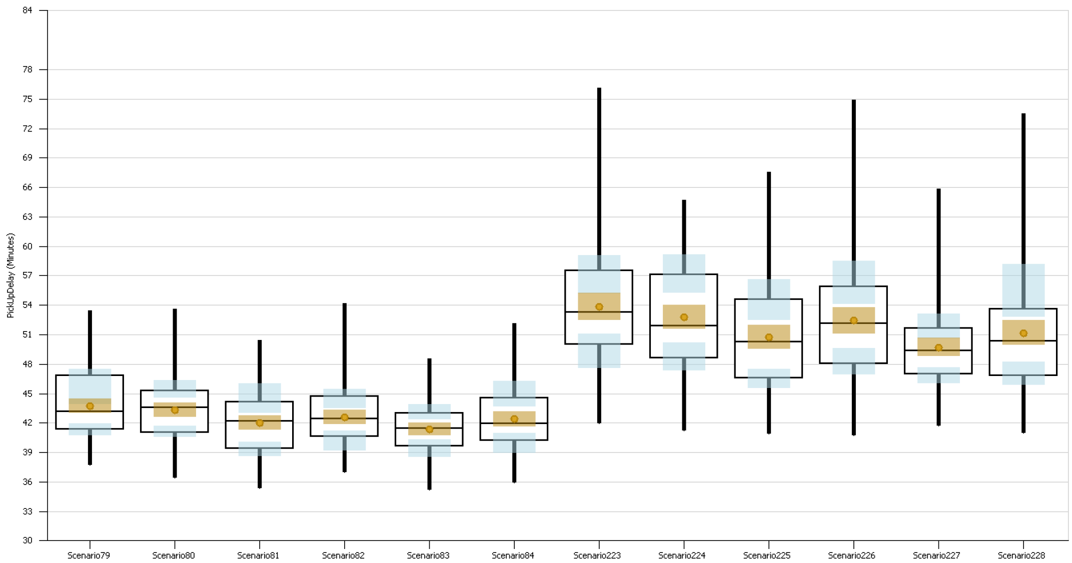


Figure 6.19: Pickup time for the system with network alterations according to Table 6.10. The first set of 6 experiments are for a 7m ton demand input, the second set of 6 for an 8m ton. For the six network configurations, the order is (1) standard, (2) improved switches, (3) track Konijnenberg, (4) track Bosweg, (5) switches + Konijnenberg, (6) switches + Bosweg

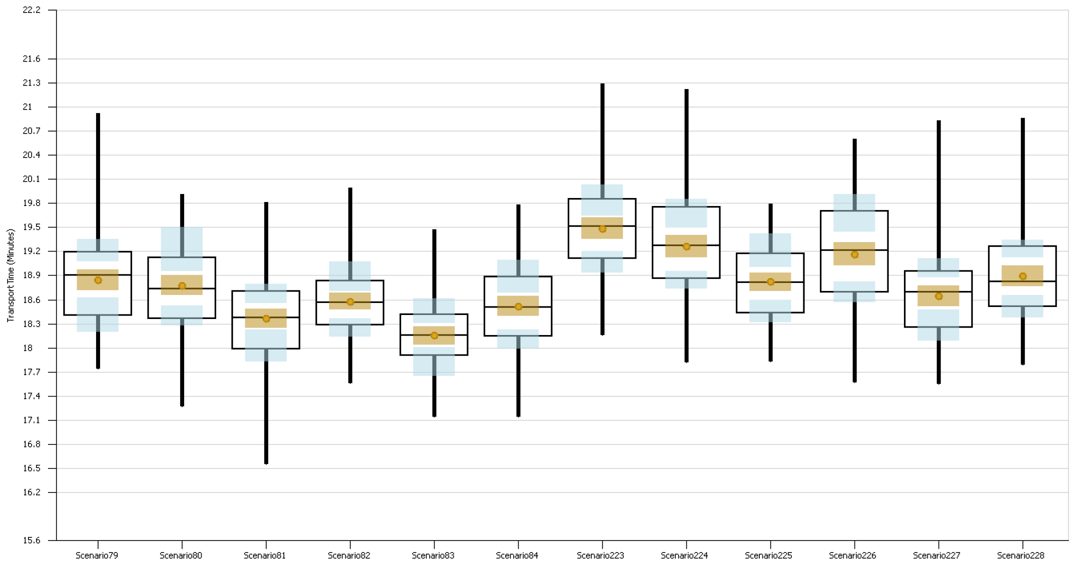


Figure 6.20: Transport time for the system with network alterations according to Table 6.10. The first set of 6 experiments are for a 7m ton demand input, the second set of 6 for an 8m ton. For the six network configurations, the order is (1) standard, (2) improved switches, (3) track Konijnenberg, (4) track Bosweg, (5) switches + Konijnenberg, (6) switches + Bosweg

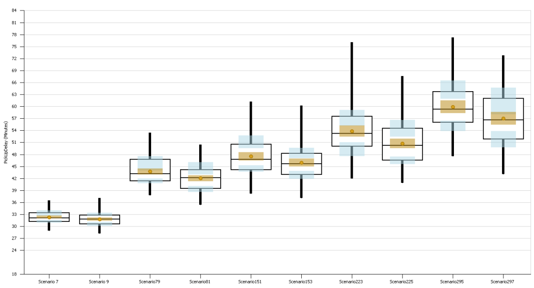


Figure 6.21: Pickup time for the standard configuration versus the configuration including the Konijnenberg added track.

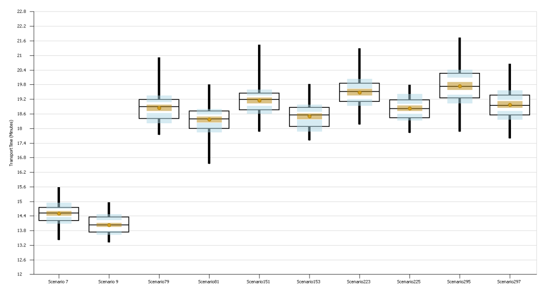


Figure 6.22: Transport time for the standard configuration versus the configuration including the Konijnenberg added track.

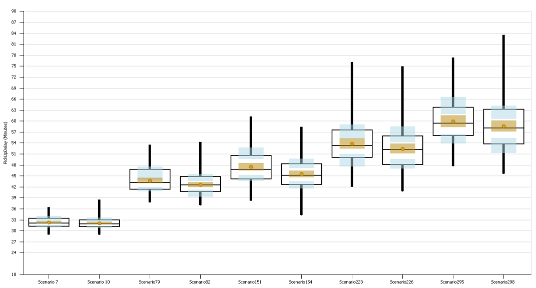


Figure 6.23: Pickup time for the standard configuration versus the configuration including the Bosweg added track.

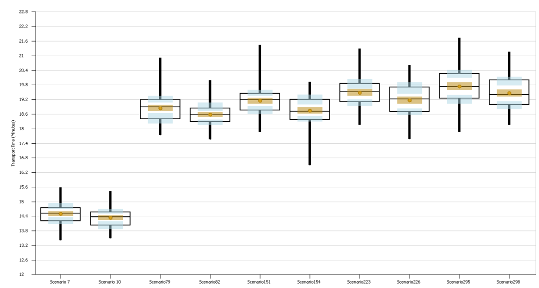


Figure 6.24: Transport time for the standard configuration versus the configuration including the Bosweg added track.

Since the performance of a railway system is correlated to multiple metrics, a model to define the customer value is used as described in Chapter 4. This model is applied to the experiments of this section where the different design configurations are tested. Figure 6.25 shows the customer value for the 5 demand scenarios, with in each set the 6 design configurations for a fleet size of **5 locomotives**. The bottom part of Figure 6.25 shows a zoomed-in figure on the tops of the results to illustrate the differences more clearly.

The same trend as for results earlier can be seen where the customer value declines even for designs with improvements with an increase in demand. The Switch + Konijnenberg improvement (green) shows for every demand scenario the most customer value, with a 5 locomotive fleet size. The switch improvement has the smallest effect on the customer value. The improvements on the network have a sustainable improvement on the customer value, but cannot improve the system is such way that the customer value stays at the same level when increasing the demand. A downward trend is certain. What can be seen is that the difference in customer value increases slightly with an increase in demand. For the 7m ton scenario, the customer value for the standard configuration (3.77 [task/x1000 Euro]) and the switch + Konijnenberg configuration (3.94 [task/x1000 Euro]) differ .17 [task/x1000 Euro]. For the 8m ton demand scenario the same difference is .18 []task/x1000 Euro].

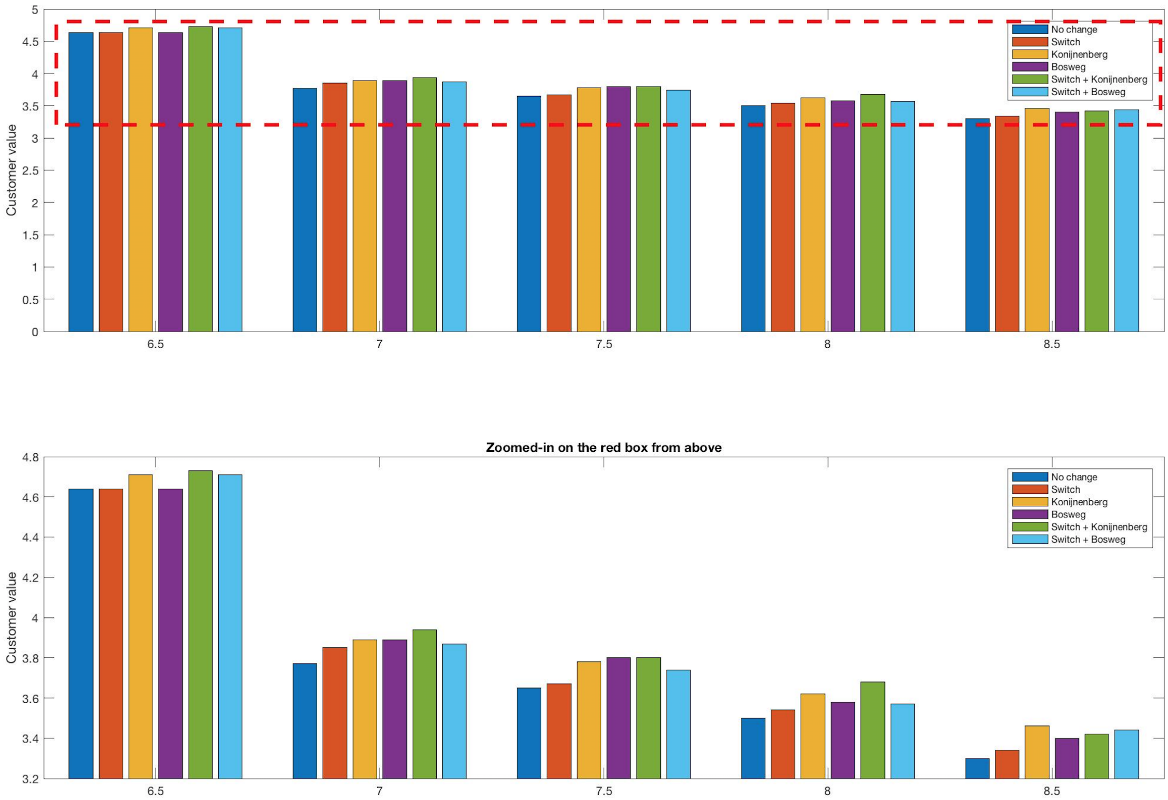


Figure 6.25: Customer value for different network designs. A fleet size of 5 locomotives is used with a shift work schedule and a closest assignment strategy. For the six network configurations, the order is (1) standard, (2) improved switches, (3) track Konijnenberg, (4) track Bosweg, (5) switches + Konijnenberg, (6) switches + Bosweg

The same experiment as above has been performed, but now for a fleet size of **6 locomotives**. The results of the comparison are noted in Table 6.11. The switch improvement shows a slight decrease in transport time, but an increase in pickup time. This could be caused by the displacement of congestion in the system to another location. If a locomotive does not have to wait at a certain location for a delayed switch, it can drive along. The next location where it then has to wait has a higher change of being for another locomotive to pass. It occupies a different part of the network, which might be a more utilized section of the network.

Table 6.11: Comparison results of the network improvements. A standard work cycle, with a fleet size of 6 locomotives and a closest assignment strategy is used. The order of improvements is (-) standard, (S) improved switches, (K) track Konijnenberg, (B) track Bosweg, (S+K) switches + Konijnenberg, (S+B) switches + Bosweg.

Demand [m ton production]	Network improvement	Pickup time μ [min]	Transport time μ [min]	Total Time μ [min]	Priority time μ [prio x tt[hr]]	Loc costs μ [x1000 Euro]	Observations [#]	Customer value
6.5	-	31.19	14.68	45.87	771.40	73.33	674.04	4.48
6.5	S	30.92	14.52	45.44	762.72	73.21	676.04	4.52
6.5	K	30.92	14.11	45.03	747.52	72.09	672.95	4.58
6.5	B	30.86	14.48	45.34	767.90	73.23	676.30	4.51
6.5	S+K	30.77	14.07	44.84	738.85	72.08	673.06	4.61
6.5	S+B	30.62	14.27	44.89	746.23	72.44	670.19	4.56
7.0	-	37.12	19.19	56.32	1015.89	85.06	729.16	3.91
7.0	S	37.42	19.05	56.47	1025.78	85.13	732.38	3.90
7.0	K	36.76	18.44	55.20	1003.31	83.73	732.96	3.98
7.0	B	36.88	18.79	55.68	1001.38	84.14	725.26	3.94
7.0	S+K	35.87	18.30	54.18	983.62	83.23	727.19	4.00
7.0	S+B	37.00	18.69	55.70	1026.23	84.73	737.91	3.94
7.5	-	39.49	19.39	58.87	1134.95	88.84	780.53	3.86
7.5	S	39.03	19.32	58.35	1125.27	88.58	777.94	3.87
7.5	K	37.96	18.75	56.71	1082.84	86.59	775.09	3.98
7.5	B	38.33	18.90	57.23	1105.66	88.50	777.59	3.91
7.5	S+K	38.53	18.60	57.13	1114.63	87.49	785.73	3.95
7.5	S+B	37.98	18.80	56.78	1103.32	87.92	783.51	3.95
8.0	-	41.16	19.61	60.77	1236.05	92.07	822.58	3.81
8.0	S	41.45	19.52	60.97	1250.84	92.07	826.00	3.80
8.0	K	40.22	18.97	59.20	1178.79	91.88	824.66	3.93
8.0	B	40.49	19.33	59.82	1229.50	91.42	823.35	3.84
8.0	S+K	40.26	18.79	59.05	1202.12	90.77	825.93	3.91
8.0	S+B	40.35	19.08	59.43	1210.67	90.82	821.28	3.88
8.5	-	43.99	19.89	63.88	1387.23	95.67	871.85	3.72
8.5	S	43.56	19.73	63.29	1350.07	95.41	867.04	3.76
8.5	K	43.05	19.12	62.17	1350.90	93.76	869.21	3.80
8.5	B	43.42	19.48	62.90	1364.60	95.01	871.86	3.77
8.5	S+K	42.03	18.98	61.01	1317.44	93.48	868.70	3.86
8.5	S+B	42.71	19.30	62.02	1333.99	94.15	865.53	3.80

The comparison in terms of customer value for the 6 locomotive fleet size is shown in Figure 6.26. The bottom part of the figure is a zoomed-in version of the essential part of the bars. Truly interesting to see is that for a 7.5m ton and 8m ton demand scenario the best network design is that with only the Konijnenberg improvement without the switch. If it is not caused by stochastic differentiation combined with small effects on the network, the hypothesis is that is is caused by the congestion displacement to the end of the rail section. If locomotives build up near the end of the track, their waiting time can increase due to this traffic congestion. It might be that an increased travel time at certain point in the network lead to an overall improvement in the system, by not having these locomotives at the essential locations.
To evaluate the different alterations to the network, the average time saved by that specific measure is displayed in the following table. First off, the demand is set for 7m ton. Hereafter the same calculation is done for the 8m ton demand scenario. This is done in Table 6.12. The Konijnenberg improvement shows the absolute largest improvement in terms of total transport time. When combined with the switch improvement, it leads to an 1.6 percent improvement for the 7m demand case, and for the higher 8m ton demand is rises to 2.3 percent. The switches improvement show no improvement in the total transport time for the 7m ton demand scenario. This is highly unlikely for a real case deal. The cause for this result can not be identified with certainty, but it is likely that the shortened transport time at a certain location leads to a buildup of locomotives in another place. It could also be back traced to stochastic behaviour, present only for this demand scenario.

Table 6.12: Comparison for the different network alterations. The estimated implementation costs are noted, and the savings in the average total time for both the 7m and 8m ton demand scenario are given.

Improvement	Improvement @ 7m	Improvement @ 8m	Estimated costs [x1000 Euro]	x1000 Euro / minute saved @ 7m	x1000 Euro / minute saved @ 8m
Switches	-0.5%	0.8%	90	-237	138
Konijnenberg	1.3%	1.5%	110	110	84
Bosweg	0.4%	1.1%	200	594	213
Switches + Konijnenberg	1.6%	2.3%	200	163	103
Switches + Bosweg	0.6%	1.5%	290	644	223

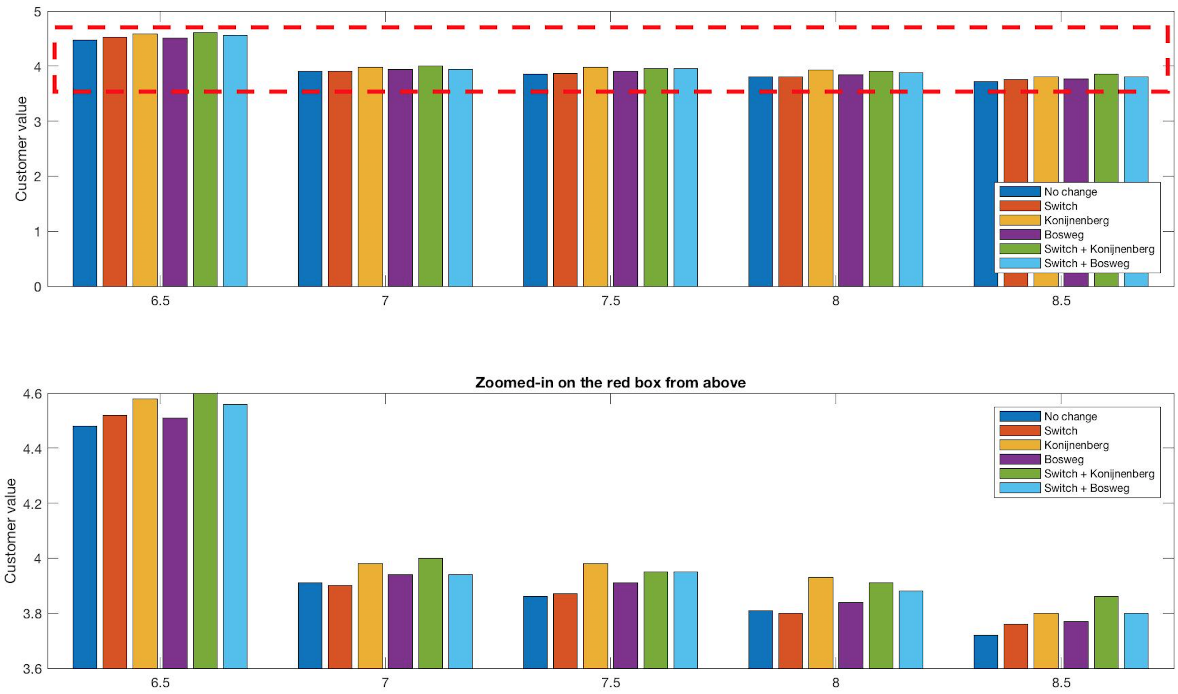


Figure 6.26: Customer value for different network designs. A fleet size of 6 locomotives is used with a shift work schedule and a closest assignment strategy. For the six network configurations, the order is (1) standard, (2) improved switches, (3) track Konijnenberg, (4) track Bosweg, (5) switches + Konijnenberg, (6) switches + Bosweg

6.4.5. Best performing designs

This subsection shows the results for the best performing complete designs of the network versus a standard setup. For each demand scenario, the top 3 performing full designs in terms of fleet size, assignment strategy, work schedule and network configuration is shown. The designs are evaluated with the customer value model suggested in chapter 4. The standard reference case is the current unimproved network configuration with a shift working schedule and a closest assignment strategy. The fleet size is determined based upon the one which has the highest customer value performance of the three experimented value. The values for the experiments are shown in Table 6.13.

The percentage improvement with the suggested designs deliver a customer value improvement of 10.8 percent for the 6.5 m ton scenario, a 10.7 percent for the 7m ton scenario, 11.7 percent for the 7.5m ton scenario, 13.1 for the 8m ton scenario and 14.2 percent for the 8.5m ton scenario. For the 7m ton scenario, the standard configuration delivers a customer value performance of 3.91. If the demand rises to 8m ton, this value drops to 3.81. The pickup time increases from 37.12 minutes to 41.16 minutes, and the transport time stays nearly the same.

Table 6.13: Best performing designs versus a standard design.

Demand [m ton production]	Network design	Customer value	Pickup time μ [min]	Transport time μ [min]	Total Time μ [min]	Priority time μ [prio x tt[hr]]	Loc costs μ [x1000 Euro]
6.5	5 locs, current, shift, closest	4.64	32.32	14.51	46.83	786.61	67.43
6.5	4 locs, S+K , relief, closest	5.14	24.53	13.38	37.90	647.01	66.23
6.5	4 locs, S+B , relief, closest	5.12	24.88	13.54	38.41	656.61	66.73
6.5	5 locs, S+K , relief, closest	5.11	19.80	13.36	33.16	565.63	76.04
7	6 locs, current, shift, closest	3.91	37.12	19.19	56.32	1015.89	85.06
7	5 locs, S+K , relief, closest	4.33	28.20	17.64	45.84	842.58	84.64
7	6 locs, S+K , relief, priority	4.31	24.14	17.46	41.60	754.64	93.49
7	5 locs, K , relief, closest	4.30	28.57	17.79	46.36	858.95	84.99
7.5	6 locs, current, shift, closest	3.86	39.49	19.39	58.87	1134.95	88.84
7.5	6 locs, S+K , relief, closest	4.31	24.82	17.69	42.52	833.75	96.72
7.5	6 locs, K , relief, closest	4.30	25.14	18.05	43.20	846.79	97.66
7.5	6 locs, S+B , relief, closest	4.29	24.80	18.10	42.90	828.13	97.51
8	6 locs, current, shift, closest	3.81	41.16	19.61	60.77	1236.05	92.07
8	6 locs, S+K , relief, closest	4.31	26.43	18.04	44.47	914.38	99.67
8	6 locs, K , relief, closest	4.30	26.24	18.17	44.41	913.94	99.86
8	6 locs, S+B , relief, closest	4.28	26.73	18.40	45.13	913.56	99.97
8.5	6 locs, current, shift, closest	3.72	43.99	19.89	63.88	1387.23	95.67
8.5	6 locs, S+K , relief, closest	4.25	28.31	18.38	46.69	1019.01	102.59
8.5	6 locs, S+B , relief, closest	4.24	28.45	18.66	47.11	1016.76	103.25
8.5	6 locs, K , relief, closest	4.24	28.75	18.46	47.21	1034.99	102.93

With an increasing demand, the standard setup decreases in customer value 15.7, 1.3, 1.3 and 3.6 percent from 6.5m to 7m, 7m to 7.5m, 7.5m to 8m and 8m to 8.5m respectively. This decrease in value is shown in Figure 6.27. The overall decrease in performance, even if improvements to the system are done, can be seen. The

In Table 6.14 results of the experiments the designs with singled out improvement to the system are shown. From this, it can be seen that the work schedule improvement has the highest overall single improvement gain, 11.1 and 6.9 percent for a 7m ton demand with 5 and 6 locomotives, and 15.1 and 9.7 percent for 8m ton. The applying of the switches and Konijnenberg improvement only adds a small amount to the customer value on top of that, 1.2 and 1.4 percent respectively

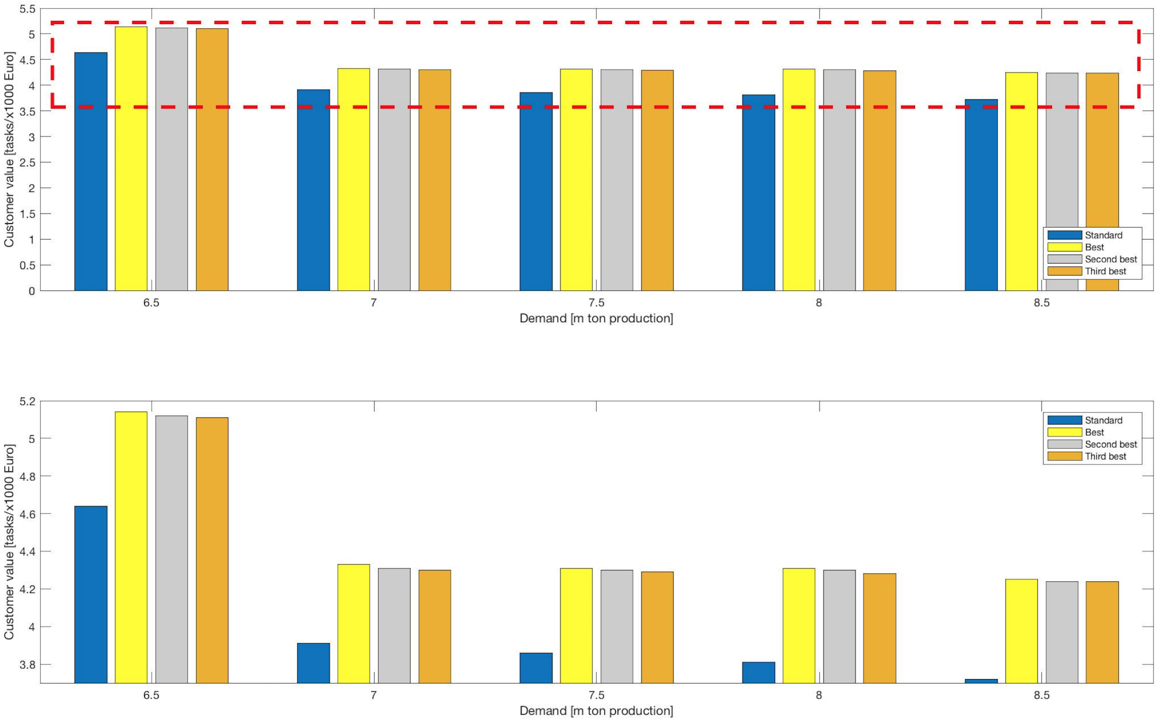


Figure 6.27: Customer value for the standard configuration (blue) and for the top 3 performing designs according to Table 6.13. The bottom image shows a zoomed-in section of the essential part of the graph.

Table 6.14: An overview of multiple improvements, only for two demand scenarios. The locomotive costs are expressed for a week.

Demand [m ton production]	Locomotives [#]	Work Schedule	Network improvement	Total Time μ [min]	Loc costs μ [x1000 Euro]	Loc util [%]	Customer value
7.0	5	Shift	-	62.58	78.06	87.01	3.77
7.0	6	Shift	-	56.32	85.06	74.03	3.91
7.0	5	Relief	-	48.13	85.73	61.90	4.19
7.0	5	Relief	S	47.56	85.12	61.15	4.24
7.0	5	Relief	K	46.36	84.99	60.67	4.30
7.0	5	Relief	S+K	45.84	84.64	59.68	4.33
7.0	6	Relief	-	43.06	95.80	49.99	4.18
7.0	6	Relief	S	42.69	95.38	49.47	4.22
7.0	6	Relief	K	41.77	94.54	48.90	4.27
7.0	6	Relief	S+K	41.16	94.35	48.17	4.30
8.0	5	Shift	-	73.34	85.38	99.40	3.50
8.0	6	Shift	-	60.77	92.07	84.86	3.81
8.0	5	Relief	-	55.10	91.11	72.87	4.03
8.0	5	Relief	S	53.94	90.34	71.55	4.05
8.0	5	Relief	K	52.03	89.69	70.56	4.17
8.0	5	Relief	S+K	51.30	89.58	69.62	4.23
8.0	6	Relief	-	46.67	101.39	58.83	4.18
8.0	6	Relief	S	45.91	101.17	57.77	4.18
8.0	6	Relief	K	44.41	99.86	56.65	4.30
8.0	6	Relief	S+K	44.47	99.67	56.56	4.31

6.5. OPEX improvement

The improvements to the system are expressed in a customer value, which involves both the associated cost of transport and the cost of delay. The cost of delay is a subjective matter, but the cost of transport is objective. With an estimated average locomotive OPEX of 252 Euro per hour in operation, and a fifth of that when it is standing idle, the simulation provides a value for the locomotive cost for the total OPEX for one single week.

The improvements to the system, which will require a substantial CAPEX, do deliver a performance improvement to the system. A shorter transport time is a fact. If this positive effect is compensated for, assuming a linear regression of the OPEX, the following weekly savings for two demand scenarios can be formed. Table 6.15. The actual savings are less, but for a fair overview of OPEX this compensation is required.

The largest single savings is for the Konijnenberg improvement, with a performance compensated saving of 3.48k Euro a week for the 7m ton scenario, and 3.03k Euro for the 8m ton. Non compensated this value would be 1.01k Euro and 0.19k Euro.

Table 6.15: An overview of multiple improvements, only for two demand scenarios. The locomotive costs are expressed for a week.

Configuration	Demand [m ton]	Performance improvement [%]	OPEX [x1000 Euro/week]	OPEX Compensated[x1000 Euro/week]	Weekly savings [x1000 Euro/week]
Standard	7	-	78.06	-	-
Switches	7	1.93	78.44	76.92	1.14
Konijnenberg	7	3.22	77.05	74.57	3.48
Bosweg	7	2.96	77.72	75.42	2.64
K+S	7	4.42	76.83	73.44	4.62
B+S	7	2.54	77.61	75.63	2.43
Standard	8	-	92.07	-	-
Switches	8	-0.27	92.07	92.32	-0.25
Konijnenberg	8	3.08	91.88	89.04	3.03
Bosweg	8	0.70	91.42	90.78	1.29
K+S	8	2.64	90.77	88.38	3.69
B+S	8	1.63	90.82	89.35	2.72

7 Conclusion

In order to come to a conclusion, the research questions that are set up in the introduction are answered here. First, the main research question is answered below:

> **Main RQ:** *What is the impact of an increasing future transport demand on the performance of an industrial railway system and in what way can this performance be improved?*

The concept of transport capacity of an industrial railway system does not exist in the common form of the amount of goods that can be transported over a certain period of time. Instead, the capacity for an industrial railway system can only be identified as the performance of the system at a certain transport demand. A new model is proposed which combines the concept of customer value from the lean thinking theory with a pricing mechanism on the delay time of prioritized transport tasks.

This model is applied to a case study at an industrial railway system at Tata Steel IJmuiden. The developed model is implemented in a discrete event simulation. The future demand scenarios are tested in the simulation environment. When no modifications to the system are done, the performance of the system will decrease with an increase in demand for the set parameters with. For an increase of the current demand with 15 percent the performance will drop with 2.6 percent. This drop in performance is not severe, meaning that the system will be able to perform the future demand of rail transport. However, improvements to the system can improve the performance significantly. In order to come find improvements the theory of lean thinking is applied.

The theory of lean thinking is applied for the search for system improvements. A process can contain value adding and non-value adding aspects. The non-value adding aspects are known as wastes. These wastes are categorized in multiple types specific for a transport system, and the identification of waste of the industrial railway system at Tata Steel IJmuiden is performed. Using GPS analysis, a set of unnecessary stops at specific locations of locomotives other than at their final location where found. These stops were found to be caused by hand-operated railway switches, traffic stops, incorrect planning or the lack of available tasks. Suggested improvements in the system where evaluated on the estimated cost of implementation, the possible improvement in performance and the effort of development. From this evaluated 4 fields of improvements were selected: (1) locomotive assignment strategy, (2) work schedule, (3) network modifications and (4) fleet size management.

An experimental plan for a series of discrete event simulation experiments has been set up. The most valuable network designs that have been found are to use a locomotive assignment strategy where the locomotive chooses its next task based upon the shortest distance. The work schedule had the greatest influence in the results. A new suggested relief work schedule which substantially improves continuity showed to be the best performing. Two network alterations with improved switch type and an added track at a severe bottleneck improved the performance further. The influence of fleet size on the customer value is in two fold. A too low fleet size results in a larger delay in delivery, and so a higher delay costs. A too large fleet size results in a higher OPEX and in more possible traffic delays.

For the specific industrial railway system at Tata Steel, 5 demand scenarios of 6.5, 7 (current) , 7.5, 8 and 8.5m ton production have been defined, where the 8m ton production is the 5 to 10 year goal. The percentage improvement with the suggested designs deliver a customer value improvement of 10.8 percent for the 6.5 m ton scenario, a 10.7 percent for the 7m ton scenario, 11.7 percent for the 7.5m ton scenario,13.1 for the 8m ton scenario and 14.2 percent for the 8.5m ton scenario.

Of these possible improvements, a newly suggested work schedule where in stead of fixed breaks the driver work on a relief schedule can lead to an improvement of 6.9 percent for the current demand, and rises to a 9.7 percent improvement for the 8m ton future scenario. It must be noted that these values where obtained with a simulation model. In real life this improvement is expected to be slightly less due to the fact that the transport coordinator can assign a task to a locomotive driver just before it needs to go on a break which has a destination on the route of the central location.

In Figure 7.1 the possible improvements on the performance for a current 7m ton demand scenario and a future 8m ton are shown. Each improvement adds a stack onto the current performance. In terms of time, the improvement for the 7m ton scenario can combined improve the average total transport time by 34 percent and for the 8 ton case by 26.9 percent. This does come at a higher costs.

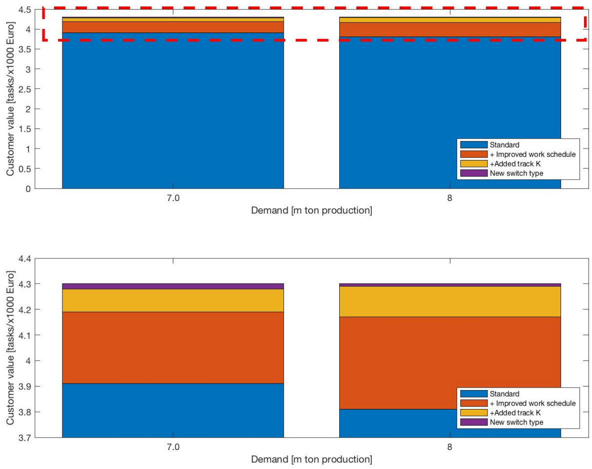


Figure 7.1: For the 7m and 8m ton demand scenario the performance expressed in the customer value is given. The stacks shown are the customer value when an improvement is added, where the work schedule shows the highest possible performance gain. The bottom image is a zoomed-in version of the top.

For the following sub research questions a more detailed answer is given. Starting with the first question, which accentuates the vague concept of performance.

> **Sub RQ 1:** *How can the performance of an industrial railway system be defined and how can such a system be modelled?*

To start with, the capacity of a railway system, and in specific an industrial railway system, has no single definition. The capacity of a railway system cannot be seen separate of the demand that is set upon the system. Therefore, the capacity of an industrial railway system can only be identified as a certain performance of a set or model of metrics at a certain demand scenario. The question that rises then is: *What is performance*? The performance of a railway system is only slightly less undefined as the capacity. The performance must provide information for the two questions: *how much?* and *in what way?*.

Industrial railway systems are characterized by complex networks consisting of many locations with bidirectional paths connecting them. These systems are often privately owned and commonly have an inefficient layout of the network due to the historically expansion of industrial sites. In industrial railway systems it is common that the planning of transport is separated from the railway operation. The planning will provide production orders and so construct a set of transport tasks. The task of the railway operation is to perform these tasks, which are to pickup a certain set of wagons from one location and deliver it at another. What the load is does not matter. This is where the system scope of this research lies. The planning of tasks, in order words the production orders of loads on wagons, is left out of scope. So the performance of an industrial railway system contains the amount of transport tasks that can be handled, which answered the question *how much?*.

The second part of the performance is the way that these tasks are fulfilled. For that the theory of lean thinking is applied. Most of this theory is focused on manufacturing processes and the identification of waste and customer value. The process of an industrial railway system cannot be split up into multiple individual processes. It is generally seen as one single process, since the effects of operations on a network can be noted in a variety of locations. For instance, a traffic delay at a single location can be caused by limited capacity of the tracks, an inefficient planning, a dysfunctional locomotive of railway track, a holdup at a destination, weather influences or a variety of human errors. What can be done is to focus on the customer. The customer in an industrial railway system is the planning department which sets out a required set of transport tasks. This customer values if these tasks are performed, and more performed transport tasks mean more value for the planning department. This is the upside side of the performance. The downside is that the operation of picking up, driving and delivering the loads come at a certain cost and require a certain time. These two are to be minimized.

In short, the performance of an industrial railway system is a coherent mix of the number of performed transport tasks, the time it takes to perform such these tasks and the costs that the railway department makes during the operation. A final important aspect in the value for the customer, being the planning department, is the fact that not all transport tasks are equally urgent. Some facilities will have a shorter storage capacity, and so require a more adequate discharging of their filled wagons in order to maintain continuity in production further up. Unplanned delays in a large operation such as found in industrial railway are common. This further causes the prioritization of tasks a necessity. So for the planning department the prioritization of tasks is another aspect for customer value.

Sub RQ 2: *How does an industrial railway system work, what is the current and future demand for railway transport for a specific industrial railway system and where can inefficiencies be found?*

Industrial railway systems are characterized by their many locations, bidirectional paths and an improvised unscheduled operation execution. The main task of an industrial railway system is to perform the requested transport tasks, not to transport a certain load to a certain location. This separation is important to notice, since the planning of production orders for transport is another aspect part of the system. To efficiently plan and schedule the loads onto wagons is not the task of an industrial railway system. The system has the task to perform a certain set of requested transport tasks. This transport task contains the following information:

$$\text{Transport task} = \begin{cases} \text{Origin}, & [t_{o,1},\ t_{o,2}] \\ \text{Destination}, & [t_{d,1},\ t_{d,2}] \\ \text{Load}, & [\#\,\text{Wagons},\ \#\,\text{Coils},\ \text{Weight}] \end{cases}$$

The transport task has a time frame for when at the origin the set of wagons must be picked up and a time frame when it must be delivered at its destination. Furthermore, information regarding the load is made present in order for the driver to know what the load is for operational purposes such as required locomotive power, brake distance but mainly for the flow of information. In the studied case at Tata Steel IJmuiden, the railway system has the function of temporary storage as well, since loaded wagons are parked at less utilized railway sections if the emptying of a factory is needed. This lesser understood function makes the railway system more complex.

For the purpose of improving the system, the theory of lean is applied to the railway operation in order to find waste. The identified waste types are overproduction, waiting, incorrect processing, unnecessary movement, defects, resource utilization and uncovered assignments. Using GPS analysis the location of unnecessary stops of the locomotive are identified. The waste identification has the function of being the input for possible fields of improvements.

Sub RQ 3: *In what way can design alternatives be found which potentially improve the operation of an industrial railway system?*

In order to modify an industrial railway system, the theory of lean thinking suggests to start with the identification of waste. Hereafter, an ideal state is defined where these wastes are not present. Next, the levels of control are noted. In a pyramid structure, the levels of control for the strategical, tactical and operational level has been found. The suggested improvements are at some level of control of the system and have the hypothesis to resolve one or several wastes. The possible improvement which are evaluated are smart fuelling, work schedule improvements, prioritization of tasks, smart deployment, locomotive assignment strategy, smart scheduling by slot allocation, infrastructure changes, automated coupling/decoupling, automated speeding, automated maintenance sensing and fully automated driving, loading and unloading.

This set of improvement fields is then set out in a graph where on on axis the expected cost of implementation is set, on the other axis the expected possible performance improvement and the size of the balloon shows the effort level to develop such an improvement. From this set, the most promising fields of improvement are locomotive assignment strategy, work schedule improvements, infrastructure changes and fleet size management.

In order to evaluate concepts, a new model is developed which uses the components described above which must be present in order to define a performance of an industrial railway system. The theory of lean thinking not only suggests to eliminate waste, but does prescribe to focus on creating value for the customer. *Is the customer paying for this?* is a question which has been answered multiple times in order to find only the essential part where a customer, in this case the planning department, is paying for. The customer value is created through reliability, punctuality and costs. the first two are positive factors, which mean that in order to create customer value these factors are sought after to be maximized. The cost is the negative factor, which must be minimized for more customer value. For this model the subjective delay of transport tasks must be made comparable with the other components, being the transport costs and the number of transport tasks. This is done by a pricing mechanism. The subjective cost of delay is expressed in an objective price. By doing so, the suggested model can compare multiple outcomes objectively. This newly developed method to evaluate the performance based upon pricing delay can be steered by the customer through prioritization. The customer must provide a priority number for a transport task. The cost of delay is then the multiplication of the total transport time times the priority times times the cost per priority time.

The performance of an industrial railway system through the concept of customer value can be measured, in completed transport tasks per Euro which contains a monetary value for priority delay. The search for system improvements for an industrial railway system is the next step. In order to do so, lean thinking describes the waste identification and resolution to make processes more efficient. Value added time must be maximized, and waste minimized.

The customer value (CV) for the planning department is made up into a model as shown in equation 7.1. . In order to compare an outcome to another, the model must be made into a single metric, as shown in equation 7.1. This customer value definition uses the aspects defined above. The

$$\begin{aligned}
\text{CV} &= \frac{\#\ \text{Transport tasks}}{\sum \text{Cost of delay} + \sum \text{Cost of transport}} && (7.1)\\
&= \frac{q}{\sum c_p \Big(p_t (t_{\text{pick-up}} + t_{\text{delivery}}) \Big) + \sum \Big(c_{t,o}\, t_{loc,o} + c_{t,i}\, t_{loc,i} \Big)} && (7.2)
\end{aligned}$$

In this model, c_p [Euro/prio hr] is the cost per priority time, p_t [#] is the priority of a transport task, $t_{\text{pick-up}}$ [hr] is the time between the creation and the pickup by a locomotive of a transport tasks, and t_{delivery} [hr] is the time between the pickup and the delivery of a task. $c_{t,o}$ [Euro/hr] times $t_{loc,o}$ [hr] is the multiplication of the operational costs per hour for a locomotive times the operational hours of the locomotive. The operation hours are the hours when the locomotive is driving. The $c_{t,i}$ [Euro] times $t_{loc,i}$ [hr] part is cost per hour when the locomotive stands idle, so it does not consume fuel but personnel is being paid and stands ready for work. This results in the customer value to have the unit of [Tasks/Euro].

Sub RQ 4: *In what way can modelling the railway system and discrete event simulation be used to experiment and evaluate the performance of design alternatives for a future demand of railway transport?*

A simulation model is a powerful tool to construct experiments which can aid in evaluating system designs. Simulation however has the downside of never being truly realistic with the real world, and so a proper model verification and validation is done in order to check whether the results from the experiments can be used. The goal of a simulation is not to resemble the real-world case in its full detail. A simulation must resemble the real-world enough so that is can be used to evaluate design alternatives with a certain significance. For the simulation of moving entities with individual processes in an enclosed network, discrete event simulation is a proper performance evaluation tool.

To start with, a conceptual model of the railway system found at Tata Steel IJmuiden is made. The major challenge in simulating such a railway system is found to be the deadlock prevention. Since many of the railway tracks are used in bidirectional way, an extensive deadlock prevention logic system is installed with the help of limited resources in the terms of pass tokens. Stochastic distributions where taken for the loading and unloading process at the facilities, which followed the curve of lognormal distribution. Stochastic differentiation is applied to the creation of transport tasks as well.

The modelling of the industrial railway system found at Tata Steel IJmuiden does not cover the shunting of wagons. This is a process which takes substantial time in the real world. Furthermore, the simulation does not operate at a schedule. In the real-world, a human coordinator tries to optimize the transport tasks by experience. In the simulation the locomotives drives as autonomous guided vehicles which make decisions based upon predefined rules.

Sub RQ 5: *What is a proper executable experimental plan in order to find the best performing designs and what is the performance of these design alternatives*

8
Recommendations

8.1. Future research

8.2. Tata Steel IJmuiden

By being present at

Continuity in transport capacity: It is noted that over the whole production site in IJmuiden a substantial drop in deliverance or worker availability is noted at the changing of work shifts. This drop in productivity can take up to an hour. At the rail department, when the work pressure is low, the last deliveries before the end of a shift have been noted to happen an hour in advance. When the work pressure is higher, the last delivery is shorter to the end time of the shift. This effect can be addressed to the efficient scheduling of the transport coordinator that determines which locomotive needs to perform a certain task. From interviews with locomotive drivers it is noted that some transport coordinators are substantially more skilled in making an efficient schedule or work plan than other. A near-future improvement can be to identify the transport coordinators of the different teams and discuss tactics. In some teams there is a rotation in the person who is transport coordinator. While from a reliability point of view it is justified to have multiple people able to perform this task, from an efficiency point of view the best transport coordinators should always perform this task.

The noted effect of drops in productivity at the end of a shift is caused as well by the unreliability of the railway system as a whole during the final hour of a shift. Factories know that scheduling a transport request in this final hour has a higher change of substantial delay, and so the amount of transport tasks in this hour is lowered. Productivity in the individual factories are assumed to have a similar effect. No new batch of processes is started at the end of a shift is there is a serious change of the ending time being after the shift change. This effect is strengthened by the lack of transport capacity available at this final hour of a shift. It is the causality dilemma of *'Which comes first?'*. It is the task of the railway system to provide reliability and continuity of transport capacity, and so the railway system should start by providing capacity at all time. Especially with a growing production, the factories must rely even more on the railway system to transport their loads so that the flow of products is not blocked. The more reliability the railway system can provide, the more efficient the individual factories can set up their processes. But it must all start at the railway system.

Smart scheduling by slot allocation: Slot allocation is the reserving of a piece of track for a certain moment in time for a specific train or locomotive. By doing so, a mathematically optimized schedule of movement for the complete system can be derived. In this schedule, no sudden traffic stops or inefficient movements are present. A slot allocation system would potentially be substantially beneficial for the performance and reliability. It does however require a far more punctual operation than the current system is able to provide. No significant differentiation in the turnaround time at facilities must be present, neither on the travel time of trains. Furthermore, monitoring of the trains, wagons, tracks and factories must be automated in order to supply the slot allocation model with the correct data. The effects of such a model is a field of study for future optimization.

Time monitoring and planning: In order for any smart solution regarding the railway system operations to work, the information flow must be improved. In the current system a detailed scheduling which uses transport time is not present. The planning of transport tasks is highly improvised and mostly based on personal experience rather than on data. The first thing to do is to create an information system where the transport time of tasks are presented after they have been delivered. The process then must be split into parts. First, the coupling of wagons and the exiting of a facility must be monitored. If any improvement is to be made, the current state must be know. Delays in this part of the process could result in higher delays up ahead. Secondly, the time between the moment the locomotive starts driving until it arrives at its destination is needed. And finally the delivery and decoupling needs to be monitored. When such a system is present, the schedulers can work with an average time and start making a time/track schedule where certain trains occupy certain parts of the track. An example is set up above in the slot allocation recommendation. But far before any allocation could happen, the information flow must be present. If this stands, the identification of waste in the process is far more easily identified. Tact time are the most important factor for a reliable system. The current variation in the process inside factories makes it impossible to start scheduling the rail tracks occupation,

Appendices

A

Scientific Paper

Capacity optimization of industrial railway systems

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***Abstract*—Industrial railway systems can be found within companies where the production and processing of goods require large quantities to be transported. These underdeveloped systems are often privately owned and are characterized by short to cover distances, many locations, inefficient layout due to historical expansion and bidirectional driving. Local optimization in such a system does not directly lead to a global improvement. This research suggest a new model to define and measure the performance of the system as a whole by using customer value from the theory of lean thinking combined with prioritization of transport tasks. In order to test the model and to optimize the capacity of an industrial railway system a case study is performed at the railway system of Tata Steel IJmuiden, the Netherlands. Through implementing the new customer value model into a discrete event simulation, a set of improvements in the field of locomotive assignment strategy, work schedule, network configuration and fleet size resulted in a global 10.7% improvement in performance.**

Keywords—railway system, prioritization, locomotive assignment, simulation.

I. Introduction

A non-typical form of rail transport can be found at large industrial sites where the internal and/or external processes require an extensive quantity of goods to be transported. Rail transport is the most efficient means of transport for these companies. Most industrial railway systems are privately owned, and are characterized by short to cover distances and many locations. Examples of these systems can be found in mining operations, port operations in both container and bulk material, agriculture goods, lumber and other natural goods, natural goods such as lumber and steel manufacturing. The grain handling facility at Penny Newmain, the bulk commodity handling at Milpitas , the Salinas lumber site and the Alberta Midland Railway Terminal are just a handful of examples of these industrial railway systems.

What characterizes industrial railway systems beside the fact that most are privately owned and that the covered distances are short, is that heavy-loaded wagons and thus heavy-load railway track is in place. On public, national-wide railway track stricter rules are applied and the axle and track load is more limited. Furthermore, the tracks in an industrial railway system are commonly used in bidirectional way, and a large number of locations can be visited with only a selection of tracks.

What complicated industrial railway systems is that it is generally a system which has been present for a long time, and have historically grown into the present layout. Facilities that are added over the course of the history of the production site result in a far from optimal layout of the network. Furthermore, most of these railway systems lack transparency in the essential railway processes. The real-time location of locomotives is not known and little information regarding the service and processing time is known. Planning of transport is limited when little information of the current operation is known. This can be caused by the large variations in the processes, which results in low reliability and punctuality.

At Tata Steel IJmuiden, one of Europe's steel production giants located in the Netherlands, the industrial railway system transports the 7m ton of steel production to numerous production factories until the end product is send out for external transport. Here, the future performance of the railway system is under pressure since a growing production leads to an increase in rail transport. A case study on the capacity of this specific railway system is performed, in order to test the suggested model and obtain insight in the effects of system modifications.

II. Literature review

A. Railway capacity

The determination of the capacity of a rail network is less straightforward, since more variables play a role. The infrastructure, timetable and rolling stock all influence the capacity of a rail network [Lindfeldt, 2015]. This complicates a formal definition. In literature many definitions of railway capacity are found. In literature, many different definitions of the capacity of a railway network are given. Most railway operation is in a nation-wide network where passenger and freight trains drive among each other. So most research on railway operations is focused on such a network. An overview of possibles definitions is formed in the research of Landex [Landex, 2008]. Definitions found in literature on the capacity of a railway network are:

- Railway capacity is the ability of the carrier to supply as required the the necessary services within acceptable service levels and costs so as to meet the present and projected demand [Khan, 1979].
- The theoretical capacity is defined to be the maximal number of trains that can be operated on a railway link [Rothergatter, 1996].
- Capacity does not exist. Railway infrastructure capacity depends on the way it is utilized [UIC, 2004].
- The capacity of an infrastructure facility is the ability to operate the trains with an acceptable punctuality [Kaas, 1998].
- The infrastructure, timetable and rolling stock all influence the capacity of a rail network, and therefore a formal definition is would be complex [Lindfeldt, 2015].
- Capacity is a measure of the ability to move a specific amount of traffic over a defined rail line with a given

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set of resources under a specific service plan [Krueger and Harald, 1999].
- The only true measure of capacity therefore is the range of timetables that the network could support, tested against future demand scenarios and expected operational performance [Wood and Robertson, 2002].
- Capacity can be defined as the capability of the infrastructure to handle one or several timetables [Hansen, 2004].
- Capacity is defined as the maximum number of trains which can pass a given point on a railway line in a given time interval [Stok, 2007].
- Capacity may be defined as the ratio between the chosen time window and the sum of average minimum headway time and required buffer time [Oetting, 2007].
- The capacity of the infrastructure is room on the track that can be used to operate trains [Jernbaneverket, 2007]
- The number of trains that can be incorporated into a timetable that is conflict free, commercially attractive, compliant with regulatory requirements, and can be operated in the face of anticipated levels of primary delay whilst meeting agreed performance targets [Barter, 2008].

These definitions of the capacity of a railway network are mostly focused on passenger transport combined with freight on a large or national scaled network. In the next section, the topic of an industrial railway network is discussed, which is operated differently than the standard passenger railway network.

B. Industrial railway systems

In literature, the subject of industrial railway system and performance measurement systems for this system has not been studied in detail. Clausen [Clausen and Rotmann, 2014] has provided an overview of the literature regarding the subject in 2014, but has came to the conclusion that the level of research on general railway systems is far more advanced. This is due to the fact that in industrial railway systems little optimization can be performed since most processes cannot be seen separate of the system. Even more, Clausen concludes that industrial railway systems lack the needed basic information flow such as real-time location, accurate transport and processing times and scheduling or slot allocation on the network in order to perform intelligent optimization. His 4 findings are (1) Any service provider has more difficulty to measure their service compared to the production of goods. In industrial railway systems this is no different. (2) An industrial railway systems provides service in logistics, which does not generate any performance within an open market. Therefore, no market conform payment is done, from which a monetary performance can be extracted such as an return-on-investment (ROI). (3) Logistics performance of an industrial railway system is generated throughout the complete company site. Measuring the performance cannot be done at a single point, but requires a system of observation points. (4) The flow-orientated perception of logistics in order to control and manage processes requires unusual information. According to Schonnemann [Schönemann, 2016], complex freight hubs consist of two organizational parts: a logistic department for cargo handling and an associated rail yard. Rail yards are the main cause for inefficiencies due to their complex structure, many handling processes and little coordinated interrelations between the actors from different hubs. Schonnemann showed that for many European freight hubs which had a rail network, the processes between the transport chains are poorly adjusted. The railway-specific processes are practised on a improvised policy rather than a scheduled one. This way of handling is known as undisciplined or timetable free dispatching policy.

C. Research gap

Industrial railway networks have not been studied extensively. This research contributes in in the process defining and optimization of industrial railway systems by interpreting the system as a single process. The effects of local optimization of railway processes to the system as a whole are unknown unless the scope is to contain the complete railway system. Optimization of these systems is complex, since the movement of trains is not scheduled but carried out on operational basis. This research aims to provide insights in the effects of (local) optimizations on the global performance of an industrial railway system, which has not been done before. Since it is concluded that the capacity of a railway network cannot be identified without its demand, the necessity of a bespoke approach rises. Each railway system is different, and therefore the performance is measured differently. Even more, the way the performance of a complete railway system is influence is system dependent. This research provides a view on how this can be done for a real-life case. Furthermore, lean thinking in freight rail networks has not been performed before. This is a new field of study, and this research aims to provide knowledge for this research gap.

III. System Analysis

An industrial railway system has the main task of performing the requested transport tasks (TT). The planning of production orders and requesting rail transport is another system. While the two have to work closely together, their distinction is important to keep in mind. A planning department will try to make efficient transport orders, where a maximum of load is transported each time with proper filled wagons. A transport task can thus be defined as the following:

$$\mathrm{TT} = \begin{cases} \text{Origin}, & [t_{o,1},\ t_{o,2}] \\ \text{Destination}, & [t_{d,1},\ t_{d,2}] \\ \text{Load}, & [\#\ \text{Wagons},\ \text{Coils},\ \text{Weight}]. \end{cases}$$

The value for $t_{o,1}$ is the earliest allowed pick-up time for this transport, and the latest time the task needs to be picked-up is $t_{o,2}$. The same holds for delivery at the destination location, $t_{d,1}$ and $t_{d,2}$. In this way, the future performance of the railway system is not based upon load, but rather on the number of transport tasks. A section function of the railway system found

at the case study is to provide temporary storage of goods on the rail track. Some factories will have small storages and require swift unloading of wagons to maintain continuity further upstream.
Real-time flow of information regarding route timings, locomotive movements and number of performed transport tasks are all unknown. In order to analyze the system, GPS locating of the locomotives for a period of 4 months provided the useful information. This data is then used to define the system metrics. By using MATLAB as a software tool, individual visits to locations by locomotives could be identified using GPS boxing as shown in Figure 1.

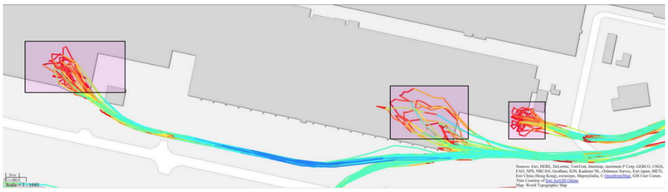


Fig. 1: GPS boxing technique

A. *Identifying waste*

In order to improve the system, lean thinking shows that the way to do so is to identify waste in the process. Improvements in the process can help to reduce this waste. Value stream mapping (VSM) cannot be applied to a railway system since the processes that make the railway system cannot be singled out. However, the waste identification can be done for a railway system. In this section, this is done for the railway system at Tata Steel IJmuiden. The analysis follows the waste types defined for transport systems by Villareal [Villarreal et al., 2016]; (1) overproduction, (2) waiting, (3) incorrect processing, (4) unnecessary movement, (5) defects, (6) resource utilization and (7) uncovered assignments.
(1) Overproduction: Waste of overproduction in a transport system is less straightforward than it is in a manufacturing environment. Villareal [Villarreal et al., 2016] defines overproduction mostly in processes regarding the management of the system; in production of reports that no one reads, entering repetitive information in multiple documents and ineffective meetings. It can be subjective if some reports that are created at Tata Steel IJmuiden are unnecessary because they are not read. However, the repetitive entering of information is certainly a waste type that can be found at Tata Steel. Continuously looking for waste and figuring a way to resolve this waste is what Kaizen is about. Overproduction is a waste type that can be resolved with Kaizen. People need to find out if their reports are essential, if they are entering repetitive information in systems or if meetings are ineffective. The awareness on these matters is little. Most people at the rail department have worked here or at Tata Steel for a long time. Continuous improvement is certainly not happening. For example, the locomotive driving hours are entered by hand into an excel sheet multiple times are various locations.
(2) Waiting: Waiting is the most recognizable noticeable waste type, but the cause why someone or some process is in hold can be less straightforward for a railway system. The most noticeable waiting time are the moments that the locomotives are not moving. From a customer point of view, value is created in a transport system when the locomotives make a useful movement. Unnecessary movement is another waste type, discussed later. When the movement of a locomotive stops, waiting occurs. Locomotive stops at the pickup and drop off locations are necessary in order to couple or decouple the load of wagons. In Figure **??** the turnaround time of the locomotives over a period of time is presented. The coupling and decoupling of wagons takes time, and this time can be seen as value adding. However, a large variation in time can be seen in Figure **??**. This means that most transport tasks take much longer than the average. All excessive time here can be seen as waste. The process of arriving and departing at a location has multiple components. In short, the locomotive arrives near a destination. The driver stops the locomotive, and signs up through an intercom to the responsible person of that location to communicate that he is arriving. While it has some safety and mostly a regulatory function, this process can be identified fully as waste. When the driver has announced its presence, it must accelerate the train and enter the facility. Here, the driver inspects the load and couples the primary wagon to the locomotive. While being necessary, the coupling and decoupling could be automated. The customer is not paying for the coupling or decoupling time. When there is something wrong in the process, the transport gets delayed. This can be seen from the turnaround time. It happens often that the locomotive stops for a certain amount of time due to mishandled loading, waiting for the local responsible person, bad coupling or other factors. So far only waiting in or close to the facilities is discussed. Stopping of locomotives occurs along the track as well. From the GPS analysis stopping locations are identified. All these stops which are not at factory locations can be identified as a waste. The customer is not paying for these stops, and so it is not value adding.

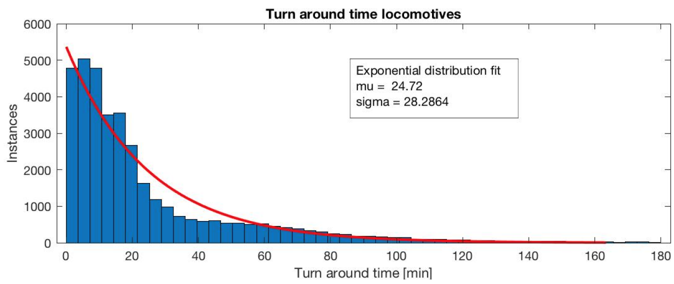


Fig. 2: Simulation setup with a black box principle.

(3) Incorrect processing The waste type of incorrect processing is identified with inefficient routing or driving, or with consuming more resources for moving an entity than is needed [Villarreal et al., 2016]. This type of waste is less seen in an industrial railway system. The inefficient routing can hardly be done, since nearly always only one single route lies between the origin and the destination. A fully automated ideal system could help in inefficient driving by adapting its speed to traffic, in a way so that it would not have to brake and accelerate. The major waste in the type of incorrect processing is the driving of all locomotives to the central location at every driver break and at the end of a shift. Here again, the customer is not paying for the drivers to go here. So this can be seen as incorrect processing.

(4) Unnecessary movement: Unnecessary movement of employees is the next waste type. Unnecessary movement of a locomotive is of the type of waste of incorrect processing. The current handling and safety checking of the locomotive driving employees now lead to movement back and forth from the cabin to the front wagon. This movement is unnecessary because the primal task is to inspect of couple the wagon, not to walk there. With a proper camera system, the walking would become unnecessary. Therefore, most of this movement can be seen as a waste. In an ideal future state, no movement occurs. Everything is monitored either locally or externally with sensors and cameras. Only in case of a problem a visual checkup will need to be made.

(5) Defects: In an industrial environment with human operated cranes loading and unloading wagons inevitable defects occur due to human misjudgment or inattentiveness. A slight touch of a crane will damage a wagon in such a way that it has to be send in for repair. These human inflicted defects will cause delay, but random material failure will happen as well. Railway track cracks, excessive locomotion wear or other driving essential material will break down. While being inevitable, the effects in terms of delays and costs caused by these failures of material can be reduced by proper management and maintenance. Currently the experts at Tata Steel IJmuiden maintaining the equipment do their job well. The rail tracks are check by human visual inspection. Still it occurs that the track breaks down. Robotic sensing could aid in maintenance in a future design. Locomotive breakdowns form in the current state little delays since a larger fleet of locomotives are maintained. So a replacement locomotive is present.

(6) Resource utilization: The largest resource utilization that can be identified as a waste type and being unclear is the use of wagons. Around 250 wagons are used and maintained at the site of Tata Steel IJmuiden. Many of them have only a slightly different coil holding feature. Exchangeable between holding features does not occur. In the central part of the railway system around 7 wagon types are used for internal and external transport. The system would benefit from a reduction of wagon types, even if it would mean that for some wagons the capacity will drop slightly. Not being able to perform a transport task because no wagons are available will in the future occur more often.

(7) Uncovered assignments: Villareal shows a final waste type for the carrying out of unprofitable transport work due to lack of information or planning [Villarreal et al., 2016]. From a global perspective the loading of wagons with sufficient steel coils and a large set of wagons per train highly effects the performance. From a local perspective, the task of the OSL-Rail department is to perform the requested transport tasks. From this scope it does not matter what the load is. A certain capacity is requested, not a value in tons or number of coils delivered. From the global perspective the lack of information will lead to this type of waste. There is no precise understanding on what the capacity of the railway system is, neither are the effects of their planning back tested. The information flow is missing. Measuring the system is the first essential step in identifying the effects of a certain planning. Driving times, number of performed tasks and locomotive movements are missing. Literature dictates a clear message on that the performance of a railway system cannot be separated from the demand that is put onto it. The demand input starts at the planning of tasks. So the performance of the system at a certain demand planning must be measured in order to predict what the influence of planning alterations will be. Since this is not done, it is currently noted as a waste.

IV. Improvement design

Value Stream Mapping (VSM) and Transport Value Stream Mapping (TVSM) cannot be applied to rail transport properly since the individual processes cannot be separated. The influence of one process to another can have multiple outcomes. An industrial railway system can only be addresses properly as a single process, and so the performance of the system must be measured globally. Lean thinking does subscribe a focus on customer value. Creating more customer value can be seen as a way to improve the system, and so can function as a performance metric. Customer value in transport systems can be defined by:

1) **Reliability**: Multiple factories at an industrial railway system rely on the railway system to deliver their requested orders and to send out specific products at specific times. This reliability is the most important factor. If the railway system would not work, storage buildups could lead to major problems further downstream. if a customer, being the factories, can rely more on a secure service from the rail department, the factories will likely be able to hold less inventory which is one of the lean thinking waste types.
2) **Punctuality**: If a time schedule is present, the punctuality of the arrival of a train can create customer value. Arriving at an accurate time will provide customer value since the customer can plan its own operations more precise towards this arrival. If for instance a loading/unloading crane needs to be present during the arrival and departure of a train, the more precise the train arrives, the more precise this resource, being the crane, can be reserved. More precise planning of this resource will in the end eliminate the waste in the form of waiting resources.
3) **Cost**: Like any customer in any system, customer value is created when the price is lowered and the service stays the same.

These customer values are made into measurable metrics in Table I.

Now that the customer value and the waste are defined, the levels where control can be exercised are noted. In Figure **??**. These levels of control are categorized in 3 fields, a strategical

TABLE I: Customer value metrics formed into KPIs

Customer value type	KPI	Unit
Reliability	Number of performed transport tasks	#
Punctuality	Pickup time	hr
	Delivery time	hr
Cost	Locomotive fuel	Euro/hr
	Personnel	Euro/hr
	Overhead	Euro/hr

level where control types are located which take more than 24 hours to perform, the tactical level for control types for 5 minutes to 24 hours, and operational level control of 5 minutes or less.

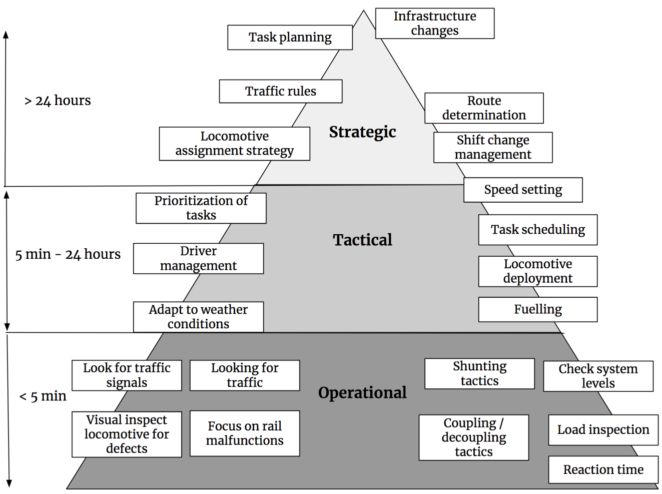


Fig. 3: Levels of control in an industrial railway system

Since the time for this research is limited, a selection of improvement fields must be chosen for this research to investigate further. The goal of applying any improvement is resolve waste from the railway system process. From the found waste shown in section combined with the levels of control, the following set of system modifications for industrial railway systems is given.

Smart fuelling: Waste: *Incorrect processing*. The locomotives are driven by a diesel combustion engine. Multiple times per week a locomotive needs to be refuelled. A smart fuelling model could be formed in order to find an optimal moment in time and location for refuelling.

Work schedule: Waste: *Unnecessary movement, incorrect processing*. Since industrial railway sites often have a 24 hour/day operation, the sites have workers who come in 8 hours shifts. In the specific case at Tata Steel IJmuiden, it is found that the locomotive driving all change shift at a single time, and that combined lunch and coffee breaks are planned. The driver have to drive their locomotive to a single location where all the drivers meet, and the transport capacity is on a hold. This process is inefficient, and a new relief work schedule is suggested where the drivers have breaks after each other.

Prioritization Waste: *Resource utilization*. Prioritization of task is in fact present in the system, but only in a subjective matter. The transport coordinators have substantial knowledge on which transport task will need to have priority based on experience. The problem is that the prioritization of tasks is not made explicit. No priority is assigned to tasks, and so no clear privilege to a certain tasks can be done. Furthermore, from historical data the effects of giving a certain priority cannot be analyzed if it is not made explicit.

Smart deployment Waste: *Resource utilization, uncovered assignments*. In the current system the locomotive deployment is done impulsively. Average 5 locomotives are in constant operation, and a 6th is often added to the fleet. The choice to use this 6th locomotive in high demand moments is done to complete transport tasks in time. However, the total effect on customer value where the costs are also present in is unforeseeable. So the use of this 6th locomotive could also lead to more traffic on the railway system and so more traffic delays, more costs and finally less choosing option for the current locomotives for their next assignment. Logically when a larger variety of transport tasks are ready to be performed, there is more choice in choosing the best suitable tasks. This effect disappears when a large number of locomotives are present. A smart deployment of locomotives where a single customer value is optimized can combine all parameters, so that the optimal fleet size can be determined.

Locomotive assignment strategy Waste: *Resource utilization*. If multiple transport tasks are present in either a schedule or a general queue, there is a choice to which transport task is assigned to the locomotive. From the possible set of transport tasks the assignment to a locomotive can be done by selection of a property of the transport task. This can be aspects such as its location, priority, scheduled departure time, load, total weight, wagon size, wagon type, or destination. The effects of different strategies can help to reduce inefficient driving.

Smart scheduling by slot allocation Waste: *Incorrect processing, resource utilization, uncovered assignments*. Slot allocation is an advanced method where the locomotive will reserve a specific part of the track at a specific moment in time. By doing so the amount of traffic stops can be reduced to a minimum. This method requires a highly reliable operation with little differentiation in processing times and driving times. A mathematically optimized time schedule can be constructed as shown in the literature review. However, is a certain train gets delayed during the loading or unloading process inside a facility, the schedule needs to be rerun with the newly estimated departure times. Such models take a serious amount of run time, and it must be done well in advance. So this method can only work is all processes are far more reliable than they are in the current system. The turnaround time as shown in the system analysis is far to variable to make precise scheduling possible. The mathematically optimized schedule can have the goal to maximize the total customer value.

Infrastructure changes Waste: *Waiting*. The infrastructure of industrial railway systems in general often have an inefficient layout. The construction of railway track is expensive. Experts provide an estimated price for the deployment of railway track of 1000 Euros per meter, excluding the switches. The layout has historically been developed with the growth of new factories at Tata Steel IJmuiden. New location needed to be attached to the rail network, and so a more distributed inefficient layout is present. Furthermore, the variety railway switches cause unnecessary waiting in the system. Automated railway switches have been around for many years, however the purchase, installation and maintenance of these switches can drive up the cost. A manual switch can take a total of 50 second to stop the train, flip the switch and accelerate the train again. This causes unwanted fuel cost and most of all a higher transport time. The average transport time of a transport task is between 8 and 12 minutes, so 50 second is a substantial part of that.

Automated coupling/decoupling Waste: *Unnecessary movement, waiting, defects*. The coupling and decoupling of wagons takes the drivers precious time. They need to walk to the coupling location to visually inspect the process. Either a camera system or a full automatic coupling system can reduce this waste. Another advantage of automated coupling is that it can happen in a more constant matter. Now the driver needs to drive the locomotive with a certain speed onto the wagon's coupling mechanism. The impact must not be to small because the coupling mechanism will not work. The human involvement in this matter results in overpowered coupling, which causes excessive wear and breakage of the systems. Furthermore, automated coupling could potentially be faster.

Automated speeding Waste: *Incorrect processing*. The acceleration and braking of the trains require fuel, and fuel is a main post of the costs. The more efficient the locomotive can maintain their speed, the less fuel they will consume. Automated speeding can reduce the fuel costs. Even better, automated speeding can be used combined with a locating system do adapt the speed to future traffic. Automated speeding will also lead to a more reliable driving time process. For automated systems, the reliability that the train takes a certain amount of time to cover a part of the network is more important than for the train to drive as fast as possible. Automated system can provide this reliability, since human operated locomotives will always experience differences in driving behaviour. Each driver has slightly different tactics, which results in unreliability and less punctuality. For the concept of slot allocation, the punctuality is the most important factor.

Automated maintenance sensing Waste: *Defects*. If defects of the railway system are found in an earlier stage before it leads to a sudden breakdown, the reliability of the system rises and so the overall performance could potentially increase. Currently, manual inspection is the main way to find little defects in the railway tracks. Every part of the track is visually inspected on average once every two weeks. An automated robotic maintenance sensing unit could drive along the track and visually inspect the train far more often and potentially more precise. The development and sensor technology of these systems is in development.

Fully automated driving, loading and unloading Waste: *Waiting, incorrect processing, resource utilization, uncovered assignments*. The ideal state goal is to have a fully automated railway system with as little human involvement as possible. Mathematically determined schedules could provide the optimal way to transport the wagons. Automated locomotives with automated coupling and decoupling would require far less turnaround time since the complete registration part would be skipped. Locomotives would not have any traffic stops along the way, and fully automated robotic maintenance sensing units could find defects in the track in a short time. The development of such a fully automated system can take a serious time, but in other AVG (automated guided vehicle) systems it has been a proven concept.

Since this research has limited time and cannot investigate all modifications, a selection is made. In Figure 4 the modifications are shown in a graph with on the x-axis the estimated cost of implementation, on the y-axis the potential performance improvement and the size of the balloon shows the effort in order to develop and evaluate the modification. The selected fields combined provide the largest possible performance improvement and are taken for further investigation.

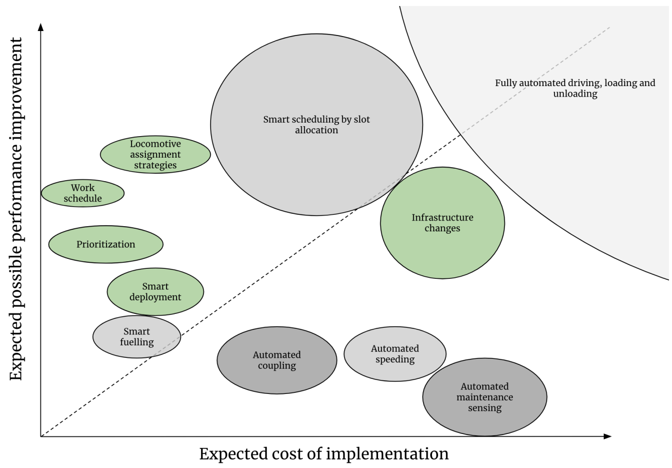


Fig. 4: Selection of most promising system modifications.

A. *Evaluation model for design concepts*

The customer in an industrial railway system is the planning department which sets out a required set of transport tasks. This customer values if these tasks are performed, and more performed transport tasks mean more value for the planning department. This is the upside side of the performance. The downside is that the operation of picking up, driving and delivering the loads come at a certain cost and require a certain time. These two are to be minimized. In short, the performance of an industrial railway system is a coherent mix of the number of performed transport tasks, the time it takes to perform such these tasks and the costs that the railway department makes during the operation. A final important aspect in the value for the customer, being the planning department, is the fact that not all transport tasks are equally urgent. Some facilities will have a shorter storage capacity, and so require a more adequate discharging of their filled wagons in order to maintain continuity in production further up. Unplanned delays in a large operation such as found in industrial railway are common. This further causes the prioritization of tasks a necessity. So for the planning department the prioritization of tasks is another aspect for customer value. In order to evaluate concepts, a model to asses the customer value, and so the performance of the system, is constructed. For this model the subjective delay of transport tasks must be made comparable with the other components, being the transport costs and the number of transport tasks. This is done by a pricing mechanism. The subjective cost of delay is expressed in an objective price. By doing so, the suggested model can compare multiple outcomes objectively. This newly developed method to evaluate the performance based upon pricing delay can be steered by the customer through prioritization. The customer must provide a priority number for a transport task. The cost of delay is then the multiplication of the total transport time times the priority times times the cost per priority time. The model is shown in equation 1 can be used.

$$\mathrm{CV} = \frac{\#\text{ Transport tasks}}{\sum \text{Cost of delay} + \sum \text{Cost of transport}} \tag{1}$$

$$= \frac{q}{\sum c_p \Big(p_t(t_\mathrm{p} + t_\mathrm{d})\Big) + \sum \Big(c_{t,o} t_{loc,o} + c_{t,i} t_{loc,i}\Big)} \tag{2}$$

In this model, c_p [Euro/prio hr] is the cost per priority time, p_t [#] is the priority of a transport task, t_p [hr] is the time between the creation and the pickup by a locomotive of a transport tasks, and t_d [hr] is the time between the pickup and the delivery of a task. $c_{t,o}$ [Euro/hr] times $t_{loc,o}$ [hr] is the multiplication of the operational costs per hour for a locomotive times the operational hours of the locomotive. The operation hours are the hours when the locomotive is driving. The $c_{t,i}$ [Euro] times $t_{loc,i}$ [hr] part is cost per hour when the locomotive stands idle, so it does not consume fuel but personnel is being paid and stands ready for work. This results in the customer value to have the unit of [Tasks/Euro].

V. Simulation model

In order to evaluate the performance of the system with the suggested modifications, a simulation model is build. Simulation models are a powerful tool to test the effects of specific scenarios or cases on the systems performance. For a large variety of system real-life testing is not feasible due to a variety of reasons such as costs, practicality or safety. For simulating the system a discrete event simulation in the Simio software tool is build. Stochastic processes are implemented in the creation of transport tasks. A transport task for simulation (TTs) is defined below.

$$\mathrm{TTs} = \begin{cases} \text{Origin}, & [-] \\ \text{Destination}, & [-] \\ \text{Pickup time}, & [\mathrm{t_{pickup}} - \mathrm{t_{creation}}] \\ \text{Delivery time}, & [\mathrm{t_{delivery}} - \mathrm{t_{pickup}}] \\ \text{Priority}, & [1, 3, 10] \end{cases}$$

Initialization of the simulation model requires all the physical aspects of the railway system such as the network layout, existing tracks, switches, junctions, locomotives number. Secondly, the traffic control group contains all rules and logic such as the basic traffic rules, routing, traffic priority, allowed directions of driving, pickup times, locomotive speed. Thirdly, the locomotive assignment policy is the group where the strategy is placed on the determination of locomotives to assignment. Finally, deadlock prevention control is implemented.

A. *Verification and validation*

Validation and verification of the model is done by historical data. The train movements and performed transport tasks where comply with the real-life measurement from GPS analysis. At 7 days simulation time, the number of tasks where only 0.9 percent higher for the outgoing, and 0.8 percent for the incoming rides. This is not significant (p¡0.05). The driving times where kept according to the found values through GPS analysis. Stochastic behaviour was implemented for switch delays. The locomotive hours are an important step. It is one of the few known parameters of the system. As an example the driving hours of a single historical month where taken. With an assumed average operating 5 locomotive it would mean a 71 percent utilization. In the simulation, with a shift work schedule, a utilization of 75 percent is obtained. These values do not differ substantially, which helps in the verification of the model.

VI. Experiments and results

The experimental plan has the following flow. There are 4 types of alternatives, being (1) the locomotive assignment strategy, (2) the network configuration, (3) the work schedule and (4) the locomotive fleet size. Instead if using a full factorial approach, this base case must identify system designs that are less performing than others. These will not be further used for experimentation, so that the focus can lie on well performing options. This means that for the largest groups of alternatives, being the locomotive assignment strategy and the design alternatives, a pre-experiment with a base case is done to select the best performing alternatives.

A base case is set up to reduce the number of experiments. The base case user the same parameters used in the model verification and validation. The base case uses the standard network configuration without any adaptions, a 7m and 8m ton demand scenario, 4 changing locomotive assignment strategies, and a normal shift working schedule.

Five demand scenarios are taken for experimentation according to future production forecasts. Four locomotive assignment strategies are tested, which are **FIFO**: Reserving the first created assignment of the global assignment queue, **closest available**: A locomotive evaluates all available transport tasks and selects the task with the closest distance to its current location, **priority**: The locomotive evaluates the transport tasks on priority and selects the task with the highest priority. If a tie occurs, FIFO is the second decision strategy and **designated zones**: The locomotive can only pickup transport tasks that are within its zone. When arriving to the end of its zone, the locomotive drops of the transport task and the locomotive from the next zone picks the transport task up from there.

The experiments where run on a Macbook Pro mid-2015,

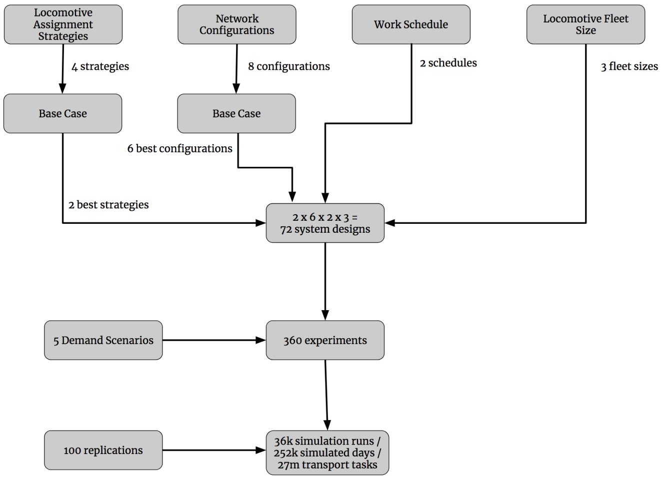


Fig. 5: Experimental plan with the use of a base case.

8 core 2.5 gHz processor with the Simio 8.0 simulation software. A single experiment where 7 days were simulated took 1.2 seconds. 100 replications per each 360 experiment were performed, which showed to be significantly accurate in a pre-experiment with 10, 100, 1000 and 10000 experiment runs.

All the results are shown in Figure 6. Here, on the x-axis the amount of transport tasks are shown and on the y-axis the total cost including the priority delay cost with a 100 Euro per priority hour value according to equation 1. The Pareto optimality field is plotted below. The system design with resembles the current system the most is shown in the line at the top.

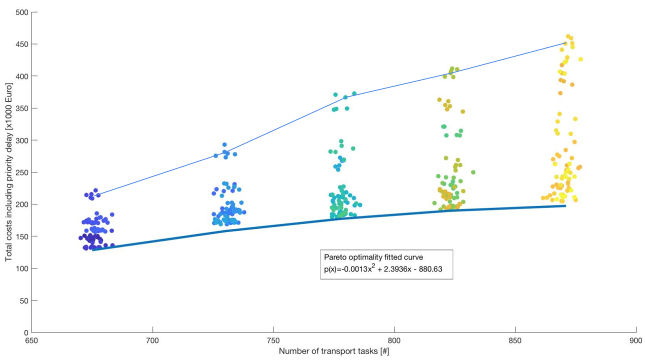


Fig. 6: Pareto optimality of all experiments. On the x-axis the total costs for transport including a delay costs of 100 Euro per hour of delayed priority is shown. On the y-axis the total number of transport tasks is given. A polynomial curve is fitted.

The applied model for customer value is used in the simulation, and the most promising designs are shown next to the current system performance in Figure 7. Large potential improvements to the system are possible. What can be seen furthermore is that with an increasing demand the performance for this specific system will drop.

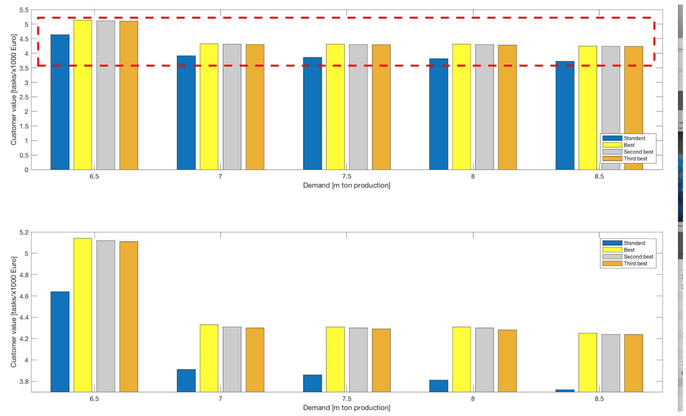


Fig. 7: Customer value for the standard configuration (blue) and for the top 3 performing designs. The bottom image shows a zoomed-in section of the essential part of the graph.

VII. Conclusion

The concept of transport capacity of an industrial railway system does not exist in the common form of the amount of goods that can be transported over a certain period of time. Instead, the capacity for an industrial railway system can only be identified as the performance of the system at a certain transport demand. A new model is proposed which combines the concept of customer value from the lean thinking theory with a pricing mechanism on the delay time of prioritized transport tasks.

This model is applied to a case study at an industrial railway system at Tata Steel IJmuiden. The developed model is implemented in a discrete event simulation. The future demand scenarios are tested in the simulation environment. When no modifications to the system are done, the performance of the system will decrease with an increase in demand for the set parameters with. For an increase of the current demand with 15 percent the performance will drop with 2.6 percent. This drop in performance is not severe, meaning that the system will be able to perform the future demand of rail transport. However, improvements to the system can improve the performance significantly. In order to come find improvements the theory of lean thinking is applied.

The theory of lean thinking is applied for the search for system improvements. A process can contain value adding and non-value adding aspects. The non-value adding aspects are known as wastes. These wastes are categorized in multiple types specific for a transport system, and the identification of waste of the industrial railway system at Tata Steel IJmuiden is performed. Using GPS analysis, a set of unnecessary stops at specific locations of locomotives other than at their final location where found. These stops were found to be caused by hand-operated railway switches, traffic stops, incorrect planning or the lack of available tasks. Suggested improvements in the system where evaluated on the estimated cost of implementation, the possible improvement in performance and the effort of development. From this evaluated 4 fields of improvements were selected: (1) locomotive assignment strategy, (2) work schedule, (3) network modifications and (4) fleet size management.

An experimental plan for a series of discrete event simulation experiments has been set up. The most valuable network designs that have been found are to use a locomotive assignment strategy where the locomotive chooses its next task based upon the shortest distance. The work schedule had the greatest influence in the results. A new suggested relief work schedule which substantially improves continuity showed to be the best performing. Two network alterations with improved switch type and an added track at a severe bottleneck improved the performance further. The influence of fleet size on the customer value is in two fold. A too low fleet size results in a larger delay in delivery, and so a higher delay costs. A too large fleet size results in a higher OPEX and in more possible traffic delays.

For the specific industrial railway system at Tata Steel, 5 demand scenarios of 6.5, 7 (current) , 7.5, 8 and 8.5m ton production have been defined, where the 8m ton production is the 5 to 10 year goal. The percentage improvement with the suggested designs deliver a customer value improvement of 10.8 percent for the 6.5 m ton scenario, a 10.7 percent for the 7m ton scenario, 11.7 percent for the 7.5m ton scenario,13.1 for the 8m ton scenario and 14.2 percent for the 8.5m ton scenario.

Of these possible improvements, a newly suggested work schedule where in stead of fixed breaks the driver work on a relief schedule can lead to an improvement of 6.9 percent for the current demand, and rises to a 9.7 percent improvement for the 8m ton future scenario. It must be noted that these values where obtained with a simulation model. In real life this improvement is expected to be slightly less due to the fact that the transport coordinator can assign a task to a locomotive driver just before it needs to go on a break which has a destination on the route of the central location.

In Figure 8 the possible improvements on the performance for a current 7m ton demand scenario and a future 8m ton are shown. Each improvement adds a stack onto the current performance. In terms of time, the improvement for the 7m ton scenario can combined improve the average total transport time by 34 percent and for the 8 ton case by 26.9 percent. This does come at a higher costs.

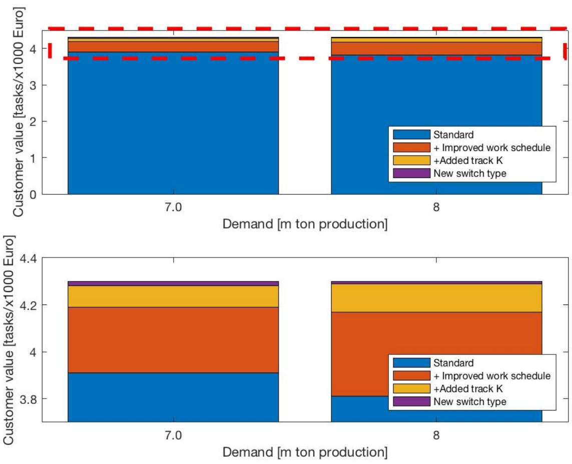


Fig. 8: Customer value performance for two demand scenarios

REFERENCES

[Barter, 2008] Barter, W. (2008). ERTMS Level2: effect on capacity compared with best practice conventional signalling. In *Proceedings of the 11th International Conference on Computers in Railways, eds. J. Allan, E. Arias, C.A. Brebbia*, page 213, Great Britain. WIT Press.

[Clausen and Rotmann, 2014] Clausen, U. and Rotmann, M. (2014). *Efficiency and Innovation in Logistics,*.

[Hansen, 2004] Hansen, S. (2004). Large transport infrastructure investments and their strategic impacts with a special focus on enterprises (store transportinfrastrukturprojekter og deres strategiske virkninger med saerlig fokus pa effekter for virksomheder).

[Jernbaneverket, 2007] Jernbaneverket (2007). Capacity 2007 (Kapasitetsrapporten 2007).

[Kaas, 1998] Kaas, A. H. (1998). Methods to calculate capacity of railways (Metoder til beregning af jernbanekapacitet).

[Khan, 1979] Khan, A. M. (1979). Railway capacity analysis and related methodology.

[Krueger and Harald, 1999] Krueger, H. and Harald (1999). Parametric modeling in rail capacity planning. In *Proceedings of the 31st conference on Winter simulation Simulation—a bridge to the future - WSC '99*, volume 2, pages 1194–1200, New York, New York, USA. ACM Press.

[Landex, 2008] Landex, A. (2008). *Methods to estimate railway capacity and passenger delays*. PhD thesis, DTU.

[Lindfeldt, 2015] Lindfeldt, A. (2015). *Railway capacity analysis - Methods for simulation and evaluation of timetables, delays and infrastructure*. PhD thesis, KTH Royal Institute of Technology.

[Oetting, 2007] Oetting, A. (2007). Capacity in Saturated Railway Nodes and Networks. In *Capacity in Saturated Railway Nodes and Networks*. PTRC Education and Research Services on behalf of the Planning and Transport Research and Computation International Association. Proceedings of the 2nd International Seminar on Railway Operations Modelling and Analysis, eds. I.A. Hansen, A. Radtke, J.P. Pachl and E. Wendler, International Association of Railway Operations Research, Hannover, Germany.

[Rothergatter, 1996] Rothergatter, W. (1996). Bottlenecks in European transport infrastructure. In *pan-European transport issues*, page 300, Brunel University, England. PTRC Education and Research Services on behalf of the Planning and Transport Research and Computation International Association.

[Schönemann, 2016] Schönemann, R. (2016). *Scheduling rail freight node operations through a slot allocation approach*. PhD thesis, Technischen Universität Berlin.

[Stok, 2007] Stok, R. (2007). *Estimation of railway capcatiy cunsumption using stochastic differential equations*. PhD thesis, Universita di Trieste.

[UIC, 2004] UIC (2004). UIC 2004.

[Villarreal et al., 2016] Villarreal, B., Garza-Reyes, J. A., and Kumar, V. (2016). A lean thinking and simulation-based approach for the improvement of routing operations. *Industrial Management & Data Systems*, 116(5):903–925.

[Wood and Robertson, 2002] Wood, D. and Robertson, S. (2002). Planning tomorrow's railway -role of technology in infrastructure and timetable options evaluation. *Computers in Railways VIII*.

A

X

Origin	Amount of coils	Total transported weight [kg]	Average coilweight [kg]
CA	12181	2.02E+08	16545
CH	41805	6.68E+08	15981
CE	15975	2.30E+08	14390
CC	13784	1.10E+08	7973
BO	44112	7.27E+08	16486
XX	1045	2.68E+07	25651
DH	8634	2.17E+08	25106
BM	42553	7.32E+08	17192
BR	22731	4.05E+08	17809
BT	13544	2.67E+08	19725
F	3448	5.95E+07	17247
DK	3849	9.17E+07	23823
SEG	6508	1.04E+08	16003
RW	1088	1.16E+07	10647
BF	25491	6.37E+08	24973
MO	69	6.76E+05	9795
PAD	22555	4.85E+08	21499
O	4	5.95E+04	14886
BI3	15	2.98E+05	19842
CF	582	1.38E+07	23739
PAE	28966	7.28E+08	25124
BK	4083	9.44E+07	23122
BJ	2066	6.55E+07	31688
BD	40304	9.43E+08	23401
TRH	401	8.08E+06	20160
PAC	16616	3.18E+08	19157
PAB	40246	8.72E+08	21666
PAA	108416	2.40E+09	22134
PAO	8093	2.01E+08	24834
BVM	2752	6.75E+07	24517
E	23994	4.43E+08	18443
PAF	795	1.74E+07	21948
BOS	25946	5.83E+08	22488
WBH	1049	1.95E+07	18613
HHP	27	5.27E+05	19530
PAW	2625	6.21E+07	23659
H	68	1.29E+06	19019
RV	2	2.39E+04	11967
WSN	2929	4.31E+07	14715
VOG	1569	3.08E+07	19629
VZH	26319	6.12E+08	23240
HCT	13	3.82E+05	29349
WTA	57	1.33E+06	23313
GDP	3	3.51E+04	11690
PDR	557	1.26E+07	22640
RSS	10	1.86E+05	18601
MEO	33	9.09E+05	27560
MST	1	1.91E+04	19100
SLE	8	1.65E+05	20575

Figure A.0.1: Average coil weight and total transported coils and weight in Q4 2016 and Q1 2017 combined

The objective of a optimization is to minimize the overall costs that are effected by performing the transport tasks. In general, two types of costs can be identified. The first is the cost of the rail transport. This type of cost consist of fuel consumption, personnel cost, maintenance and overhead. The second is the costs of delays in the pick-up and drop-off. This second type of cost is less straight forward. Since the task of the rail department is to perform each transport task within the requested time window, and no task can be skipped, a specific cost of delay can be identified per location.

Movements by the trains on the railway network can have different objectives. These consist of picking-up or dropping-off full loaded wagons or empty wagons, driving to or from a destination empty or driving to a specific location for fuelling or maintenance.
NOTE NOTE NOTE TO SELF For simplification, it is assumed that there are unlimited wagons available. The transport of empty wagons is set as a normal transport task. The empty wagons are delivered to a location on the map, and will be added to a queue here with unlimited amount of wagons. So by doing this, the transport of empty wagons can be taken up into the timetable. In reality, wagon transport will have a destination, but it is not yet known from where these wagons will be transported. To construct a model of the system, the suggested simplification is applied.

A.1. Planning of transport tasks

In order to have a heuristic approach for the planning of the transport task, a key performance indicator is needed
Following the research by Dessouky et al [**?**], a mixed integer programming model is introduced. The parameters of the nodal network are made into this model. The notations are the following:

$$Q: \quad \text{Set of all the to be scheduled trains} \tag{A.1}$$

$$N: \quad \text{Set of all rail track nodes} \tag{A.2}$$

$$S_q: \quad \text{Length of train q} \tag{A.3}$$

$$P_q: \quad \text{Path train q takes. Starts with train q's origin node,} n_q^0\text{, to train q's destination node,} n_q^z. \tag{A.4}$$

$$n_{q,1}, n_{q,2}, ..., n_{q,P_q}: \quad \text{All the nodes train q will be traversing} \tag{A.5}$$

$$B^1_{q,g}: \quad \text{The minimal travel time between train q's head entering into node} n_{q,g} \text{and train q's head leaving from node} n_{q,g} \text{to n} \tag{A.6}$$

$$B^2_{q,g}: \quad \text{The minimal travel time between train q's head entering into node} n_{q,g} \text{and train q's tail leaving from node} n_{q,g} \tag{A.7}$$

$$t^a_{q,g}: \quad \text{The time train q's head arrives at node} n_{q,g} \tag{A.8}$$

$$t^d_{q,g}: \quad \text{The time train q's tail leaves from node} n_{q,g} \tag{A.9}$$

$$m: \quad \text{Minimal safety headway between two consecutive trains} \tag{A.10}$$

$$x_{q_1,q_2,k}: \quad \text{Binary variable indicates which train gets to pass node k first. 1 q1 goes before q2, 0 q2 goes before q1 at node k} \tag{A.11}$$

$$M: \quad \text{An arbitrarily large number} \tag{A.12}$$

The objective of the model is to minimize the sum of the arrival times of all trains combined (1). This is equal as the sum of all delays. The minimum travel time forms a constraint (2). The next constraint is the minimum time a trains needs in order to fully drive over a certain section (3), from the moment the head starts entering the section until the tail leaves the section. Deadlock avoidance is formed in the next two constraints (5,6).

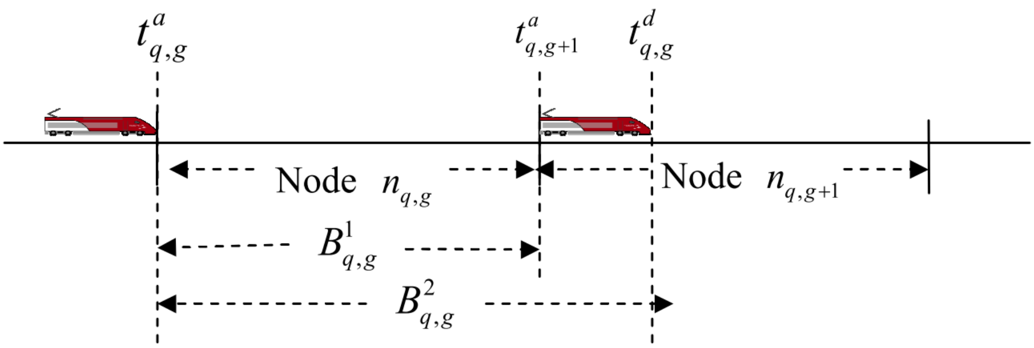


Figure A.1.1: Variables of the mixed linear integer programming model

$$\min \sum_{q \in Q} t^a_{q,|P_q|} \tag{1}$$

$s.t.$

$$t^a_{q,g+1} - t^a_{q,g} \geq B^1_{q,g}, \qquad \text{for all } q \in Q \text{ and } 1 \leq g \leq |P_q| - 1 \tag{2}$$

$$t^d_{q,g} - t^a_{q,g+1} \geq B^2_{q,g} - B^1_{q,g}, \qquad \text{for all } q \in Q \text{ and } 1 \leq g \leq |P_q| - 1 \tag{3}$$

$$t^d_{q,|P_q|} - t^a_{q,|P_q|} \geq B^2_{q,|P_q|}, \qquad \text{for all } q \in Q \tag{4}$$

$$x_{q_1,q_2,k} M + t^a_{q_1,g} \geq t^d_{q_2,h} + \mu \qquad \text{for all } q_1, q_2 \in Q \text{ and node } k = n_{q_1,g} = n_{q_2,h} \tag{5}$$

$$(1 - x_{q_1,q_2,k}) M + t^a_{q_2,h} \geq t^d_{q_1,g} + \mu \qquad \text{for all } q_1, q_2 \in Q \text{ and node } k = n_{q_1,g} = n_{q_2,h} \tag{6}$$

$$x_{q_1,q_2,k} = \{0,1\} \qquad \text{for all } q_1, q_2 \in Q \text{ and } 1 \leq k \leq |N| \tag{7}$$

A.2. Transport demand increase

Steel production [m tons]	6	6.5	7	7.5	8	8.5	9
Difference with previous (towards 7m) [m ton]	-0.5	-0.5		0.5	0.5	0.5	0.5
10% efficiency change	-0.05	-0.05		0.05	0.05	0.05	0.05
Rides change from 7m	-15.7%	-7.9%		6.4%	12.9%	19.3%	25.7%

B

XX - Needs review

B.1. Ideal situation

For a first analysis of the system, a look is given at the hypothetical ideal situation. To do so, two questions need to be answered in order to start: What is the system, and what is an ideal situation? Firstly, the system is defined as the Central rail network infrastructure of rail tracks with their specific lengths and switches. The switches do not influence the drive time of a locomotive in this ideal case. So the switch will always lay in the correct position for that specific direction and will not have a turn-around time. Aspects such as the signalling system, rail or switch malfunctions, height differences and track variation qualities are not taken into account for this hypothetical situation. For the rolling equipment holds that the locomotives are taken into account. For every route holds that the maximum amount of wagons with a maximum load is used. No malfunctions are present to cause downfall of capacity. Furthermore, the planning is exactly known and no delays are caused here. All the loads are ready for transport.

In the ideal situation, the transport tasks are to transport different types of coils to storages and locations where the coils are being transshipped for export. The actual steel coils are transported one-way. The system can be seen as a flow network. However, the locomotives do have to drive back.

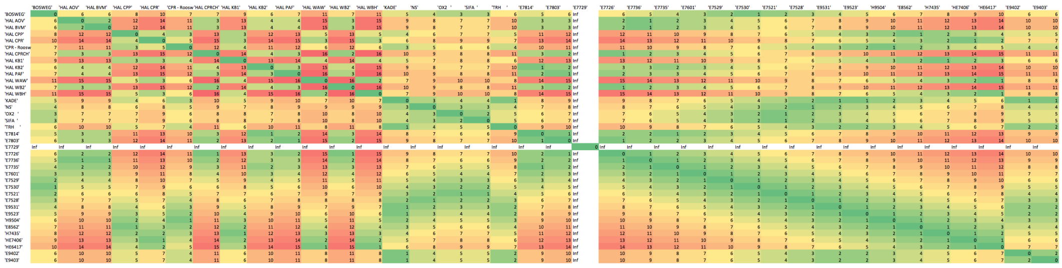


Figure B.1.1: Shortest path of the routes

C
Coding

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% GPS ANALYSE
% Coen van der Linden
% Graduation Project

%Upload GPS data [date / time / lon / lat /speed / locomotive_number]
%A = xlsread('gps6excel.xlsx',1);



%A=gps6excel;
%% GPS Location Plants
% location = lon min ; lon max; lat min; lat max;
Bosweg = [4.6187 4.6235 52.4848 52.4860];
%KB2 = [4.6278  4.6297  52.4959  52.4970];
%WB2= [4.6261  4.6287 52.4931  52.4940];
CPRCH= [4.6169  4.6191  52.4954  52.4962];
%CPP= [4.6221  4.6241  52.4809  52.4818];
CPR= [4.62087  4.62125  52.47941  52.47957];
BUKA1 = [4.6054 4.6089 52.4731 52.4737];
BUKA3 = [4.60614 4.60809 52.47211 52.4724];
TRH = [4.60698 4.60807 52.47152 52.47200];
BIHA = [4.63131 4.63382 52.46952 52.47014];
CPR_ROOSWIJK = [4.63224 4.63306 52.47944 52.47972];
WERKPLAATS = [4.62573 4.62688 52.47912 52.47964];
KB1 = [4.62188 4.62249 52.47945 52.47968];
WBH = [4.61540 4.61641 52.47974 52.48021];
STAALHAVEN = [4.61489 4.61681 52.47733 52.47778];
WAW = [4.61361 4.61705 52.47821 52.47906];
CPP_T = [4.62211 4.62330 52.48090 52.48120];
CPP_W = [4.62218 4.62293 52.48156 52.48181];
BVM = [4.60471 4.60535 52.48853 52.48884];
AOV = [4.60954 4.61171 52.49680 52.49727];
PAA_WEST = [4.62280 4.62356 52.49324 52.49342];
PAA_OOST = [4.62604 4.62662 52.49290 52.49308];
PAB = [4.62654 4.62689 52.49328 52.49347];
PAC_WEST = [4.62518 4.62613 52.49374 52.49394];
PAC_OOST = [4.62767 4.62799 52.49348 52.49361];
PAD = [4.62795 4.62836 52.49397 52.49414];
PAF = [4.62558 4.62786 52.49470 52.49493];
BM = [4.62761 4.62894 52.49590 52.49638];
BO = [4.62884 4.62916 52.49648 52.49662];
BR = [4.62896 4.462928 52.49698 52.49713];
BT = [4.62911 4.62939 52.49728 52.49746];

Locations=[Bosweg ;CPRCH; CPR; BUKA1; BUKA3; TRH; BIHA; CPR_ROOSWIJK; WERKPLAATS; KB1; WBH; STAALHAVEN; ↩
    WAW; CPP_T; CPP_W; BVM; AOV; PAA_WEST; PAA_OOST; PAB; PAC_WEST; PAC_OOST; PAD; PAF; BM; BO; BR; BT↩
    ];

```

```
%% Locomotive separation
loc_column=6;
indL909 = A(:,loc_column) == 909;
indL824 = A(:,loc_column) == 824;
indL901 = A(:,loc_column) == 901;
indL821 = A(:,loc_column) == 821;
indL823 = A(:,loc_column) == 823;
indL906 = A(:,loc_column) == 906;
indL990 = A(:,loc_column) == 990;
indL820 = A(:,loc_column) == 820;
indL992 = A(:,loc_column) == 992;


L909_total = A(indL909,:);
L824_total = A(indL824,:);
L901_total = A(indL901,:);
L821_total = A(indL821,:);
L823_total = A(indL823,:);
L906_total = A(indL906,:);
L990_total = A(indL990,:);
L820_total = A(indL820,:);
L992_total = A(indL992,:);


%% Date separation
%Choose date in DATEVALUE
date_column=1;
date_selection = 42852;
indL909_date = L909_total(:,date_column) == date_selection;
indL824_date = L824_total(:,date_column) == date_selection;
indL901_date = L901_total(:,date_column) == date_selection;
indL821_date = L821_total(:,date_column) == date_selection;
indL823_date = L823_total(:,date_column) == date_selection;
indL906_date = L906_total(:,date_column) == date_selection;
indL990_date = L990_total(:,date_column) == date_selection;
indL820_date = L820_total(:,date_column) == date_selection;
indL992_date = L992_total(:,date_column) == date_selection;

L909_date = L909_total(indL909_date,:);
L824_date = L824_total(indL824_date,:);
L901_date = L901_total(indL901_date,:);
L821_date = L821_total(indL821_date,:);
L823_date = L823_total(indL823_date,:);
L906_date = L906_total(indL906_date,:);
L990_date = L990_total(indL990_date,:);
L820_date = L820_total(indL820_date,:);
L992_date = L992_total(indL992_date,:);



%% Loco selection
%effective_loc = [L824_total ; L909_total ; L901_total ; L821_total; L823_total ; L906_total ; ↩
    L990_total ; L820_total; L992_total];

effective_loc = L824_total;

lon = effective_loc(:,3);
lat = effective_loc(:,4);
spd = effective_loc(:,5);

%% Speed Bin Colors
nBins = 15;
binSpacing = (max(spd) - min(spd))/nBins;
binRanges = min(spd):binSpacing:max(spd)-binSpacing;

% Add an inf to binRanges to enclose the values above the last bin.
binRanges(end+1) = inf;

% histc determines which bin each speed value falls into.
[~, spdBins] = histc(spd, binRanges);

```

```
lat = lat';
lon = lon';
spdBins = spdBins';

% Create a geographical shape vector, which stores the line segments as
% features.
s = geoshape();


for k = 1:nBins

    % Keep only the lat/lon values which match the current bin. Leave the
    % rest as NaN, which are interpreted as breaks in the line segments.
    latValid = nan(1, length(lat));
    latValid(spdBins==k) = lat(spdBins==k);

    lonValid = nan(1, length(lon));
    lonValid(spdBins==k) = lon(spdBins==k);

    % To make the path continuous despite being segmented into different
    % colors, the lat/lon values that occur after transitioning from the
    % current speed bin to another speed bin will need to be kept.
    transitions = [diff(spdBins) 0];
    insertionInd = find(spdBins==k & transitions~=0) + 1;

    % Preallocate space for and insert the extra lat/lon values.
    latSeg = zeros(1, length(latValid) + length(insertionInd));
    latSeg(insertionInd + (0:length(insertionInd)-1)) = lat(insertionInd);
    latSeg(~latSeg) = latValid;

    lonSeg = zeros(1, length(lonValid) + length(insertionInd));
    lonSeg(insertionInd + (0:length(insertionInd)-1)) = lon(insertionInd);
    lonSeg(~lonSeg) = lonValid;
    % Add the lat/lon segments to the geographic shape vector.
    s(k) = geoshape(latSeg, lonSeg);

end

% for i=1:length(Locations)
%     p(i) = geopoint(Locations(i,3),Locations(i,1));
% end

%s(k) = geoshape(latSeg, lonSeg);

wm = webmap('World Topographic Map');
mwLat = 52.48036;
mwLon = 4.63595;
name = 'MathWorks';
iconDir = fullfile(matlabroot,'toolbox','matlab','icons');
iconFilename = fullfile(iconDir, 'matlabicon.gif');
%wmmarker(mwLat, mwLon, 'FeatureName', name, 'Icon', iconFilename);

c = jet(nBins);
colors = flipud(c);
%colors = autumn(nBins);
wmline(s, 'Color', colors, 'Width', 3);
%wmline(p, 'Width', 3);
zoom = 30;
```

D

Network data

Weekly average instances 4-feb / 12-july

		Total	To Centraal	NS	Bosweg	CPRCH	CPR	BUKA1	BUKA3	TRH	BIHA	CPR_Roosw	KB1	WBH	WAW	CPP_T	CPP_W	PAA_West	PAA_Oost	PAC_Oost	PAD	PAF	BM	BO	BR	BT
	Total	1336	483	79	95	56	21	16	36	28	56	11	43	33	20	31	31	24	38	15	42	50	49	31	30	19
From	Centraal	488		43.6	54.1	29.6	17.2	9.7	25.9	12.6	55.0	11.0	34.8	26.5	11.6	25.7	25.5	6.4	14.1	6.7	18.8	10.1	13.2	13.6	14.8	7.9
	NS	76	42.5		11.3	1.6												0.6	2.1	1.1	3.1	3.5	2.1	3.4	2.4	2.3
	Bosweg	97	52.3	11.8		1.4												2.6	3.6	0.6	1.8	19.1	1.6	1.0	0.5	0.4
	CPRCH	56	23.4	1.1	2.3													4.4	3.2	0.9	1.9	2.5	12.9	1.2	1.7	0.8
	CPR	22	17.9										1.6	1.1	0.5	0.1	0.3									
	BUKA1	16	12.4						1.8	1.8	0.1															
	BUKA3	37	23.6					2.5		10.2	0.5															
	TRH	27	19.0					1.3	6.8		0.3															
	BIHA	57	48.9					2.6	1.5	3.5																
	CPR_Roosw	5	5.3																							
	KB1	43	36.9				1.3							2.3	1.0	0.9	1.0									
	WBH	33	27.6				1.3						2.3		0.4	0.9	0.4									
	WAW	20	14.3				0.5						1.6	1.5		1.2	1.3									
	CPP_T	31	24.8				0.5						1.1	0.6	1.9		2.2									
	CPP_W	31	21.9				0.5						1.4	0.9	4.3	1.9										
	PAA_West	24	5.4	0.6	7.1	3.8													2.0	0.4	1.1	1.6	1.1	0.3	0.3	0.2
	PAA_Oost	37	12.6	1.5	9.5	1.7												1.4		0.8	2.1	2.9	2.0	1.1	0.8	0.8
	PAC_Oost	15	6.8	1.1	1.4	0.6												0.3	0.6		1.2	1.0	1.0	0.5	0.3	0.4
	PAD	43	18.4	3.9	1.9	1.9												1.4	1.8	1.3		3.1	3.8	2.2	1.7	1.3
	PAF	46	13.1	1.2	4.0	2.2												4.5	6.4	1.5	3.5		4.6	2.2	2.1	1.0
	BM	50	19.2	1.3	1.2	11.0												1.1	2.1	0.8	3.3	2.5		3.0	2.5	1.7
	BO	32	14.2	5.8	0.8	0.9												0.4	0.9	0.4	2.0	1.4	3.0		1.6	1.0
	BR	29	13.3	4.0	0.7	1.0												0.4	0.7	0.6	1.8	1.8	2.4	1.4		1.1
	BT	20	9.0	3.2	0.2	0.7												0.3	0.2	0.1	1.2	0.6	1.6	1.2	1.2	

Average route time from departure [minutes]

		To																						
		Centraal	**NS**	**Bosweg**	**CPRCH**	**CPR**	**BUKA1**	**BUKA3**	**TRH**	**BIHA**	**CPR_Roos**	**KB1**	**WBH**	**WAW**	**CPP_T**	**CPP_W**	**PAA_West**	**PAA_Oost**	**PAC_Oost**	**PAD**	**PAF**	**BM**	**BO**	**BR**	**BT**
From	**Centraal**		0:04	0:06	0:15	0:05	0:21	0:22	0:21	0:10	0:01	0:05	0:07	0:07	0:04	0:04	0:15	0:14	0:13	0:14	0:13	0:17	0:16	0:16	0:16
	NS	0:03		0:06	0:19			0:00	0:00								0:17	0:15	0:17	0:17	0:13	0:17	0:20	0:19	0:22
	Bosweg	0:06	0:05		0:16												0:18	0:17	0:19	0:17	0:16	0:21	0:22	0:21	0:24
	CPRCH	0:14	0:20	0:21													0:05	0:11	0:13	0:13	0:11	0:13	0:14	0:15	0:14
	CPR	0:04										0:03	0:05	0:04		0:06									
	BUKA1	0:20						0:13	0:13																
	BUKA3	0:20	0:00				0:16		0:05	0:12															
	TRH	0:19	0:03				0:13	0:06		0:10															
	BIHA	0:14					0:15	0:15	0:13																
	CPR_Rooswi	0:02																							
	KB1	0:05				0:07							0:08	0:05	0:05	0:05									
	WBH	0:06				0:04						0:05		0:05	0:06	0:07									
	WAW	0:05				0:04						0:04	0:04		0:07	0:08									
	CPP_T	0:04				0:09						0:07	0:06	0:08		0:03									
	CPP_W	0:04				0:09						0:07	0:08	0:10	0:03										
	PAA_West	0:13	0:17	0:13	0:04													0:08	0:09	0:09	0:09	0:14	0:16	0:13	0:13
	PAA_Oost	0:12	0:14	0:15	0:09												0:08		0:07	0:07	0:07	0:12	0:13	0:12	0:13
	PAC_Oost	0:13	0:16	0:14	0:09												0:08	0:05		0:06	0:09	0:11	0:15	0:14	0:17
	PAD	0:13	0:15	0:18	0:10												0:07	0:09	0:07		0:07	0:09	0:11	0:09	0:11
	PAF	0:14	0:15	0:16	0:11												0:09	0:08	0:07	0:06		0:11	0:12	0:11	0:12
	BM	0:14	0:17	0:18	0:11												0:13	0:13	0:09	0:07	0:06		0:05	0:07	0:06
	BO	0:13	0:15	0:18	0:10												0:11	0:10	0:08	0:08	0:08	0:07		0:07	0:07
	BR	0:14	0:15	0:18	0:12												0:07	0:10	0:08	0:08	0:08	0:06	0:09		0:05
	BT	0:14	0:15	0:18	0:11												0:15			0:08	0:05	0:07	0:08	0:04	

Start Time	Duration	End Time	Value
12:00 AM	1.5 hours	1:30 AM	1
1:30 AM	1 hour	2:30 AM	0
2:30 AM	1.5 hours	4:00 AM	1
4:00 AM	30 minutes	4:30 AM	0
4:30 AM	1.5 hours	6:00 AM	1
6:00 AM	1.5 hours	7:30 AM	1
7:30 AM	30 minutes	8:00 AM	0
8:00 AM	1.5 hours	9:30 AM	1
9:30 AM	1 hour	10:30 AM	0
10:30 AM	1.5 hours	12:00 PM	1
12:00 PM	30 minutes	12:30 PM	0
12:30 PM	1.5 hours	2:00 PM	1
2:00 PM	1.5 hours	3:30 PM	1
3:30 PM	30 minutes	4:00 PM	0
4:00 PM	1.5 hours	5:30 PM	1
5:30 PM	1 hour	6:30 PM	0
6:30 PM	1.5 hours	8:00 PM	1
8:00 PM	30 minutes	8:30 PM	0
8:30 PM	1.5 hours	10:00 PM	1
10:00 PM	1.5 hours	11:30 PM	1
11:30 PM	30 minutes	12:00 AM	0

Kosten Rail Centraal (P52200)	AP2017/18 x 1000 euro		Kosten		% voo DB-S
Personeel	k€	4 519		4 519	100%
Afschrijvingen	k€	392		392	100%
Huur gebouwen	k€	-		61	0%
Overige kosten*	k€	2 202		2 352	94%
Interne doorbelasting**	k€	2 958		5 916	50%
	k€	10 070	k€	13 240	

Berekening uurtarief loco's Centraal (obv AP2017/18)

te dekken kosten	10 070 183	euro
per loco (uitgaande van 5 loco's)	2 014 037	euro
beschikbare uren obv 75% beschikbaar	6 570	uur
kosten per loco	**306.55**	euro/uur

Overige kosten*			Kosten		% voo DB-S
Brandstof	k€	1 302	k€	1 302	100%
NS-spooraansluiting	k€	900	k€	900	100%
Schade	k€	-	k€	150	0%
					100%
	k€	2 202	k€	2 352	

Onderhoud Loc's	k€ 2 626	17	k€	154	1	k€	154	
NS-spoor	k€ 900	100%	k€	900	0.3	k€	270	
Bemanning	k€ 4 204	155	k€	27	2	k€	54	
Brandstof	k€ 1 302	5	k€	260	1	k€	260	
						k€	370	1589.467 uur/jr
						€	**232**	/uur

Interne doorbelasting**			Kosten		% voo DB-S
P52100 Verdeling ex-leerlingen	k€	-	k€	-	0%
P50000 Railvervoer Algemeen	k€	1 514	k€	4 204	36%
P50300 K&T algemeen	k€	-	k€	-	0%
P52000 Uitvoerend	k€	-	k€	-	100%
P52600 Leerlingen	k€	-	k€	-	0%
P50500 Niet produktieven	k€	-	k€	-	0%
P50320 Onderhoud TIB Loco's	k€	1 444	k€	1 444	100%
P50330 Onderhoud TIB Wagens	k€	-	k€	267	0%
	k€	2 958	k€	5 916	

Scenarios toekomst

Aantal locomotieven		Overhead per uur		Variabel per uur		Totaal per uur
1	€	1 532.75	€	232	€	1765.24
2	€	766.38	€	232	€	998.86
3	€	510.92	€	232	€	743.40
4	€	383.19	€	232	€	615.67
5	€	306.55	€	232	€	539.04
6	€	255.46	€	232	€	487.94
7	€	218.96	€	232	€	451.45
8	€	191.59	€	232	€	424.08
9	€	170.31	€	232	€	402.79
10	€	153.28	€	232	€	385.76

Figure D.0.1: Fuel consumption source: Tata Steel Finance

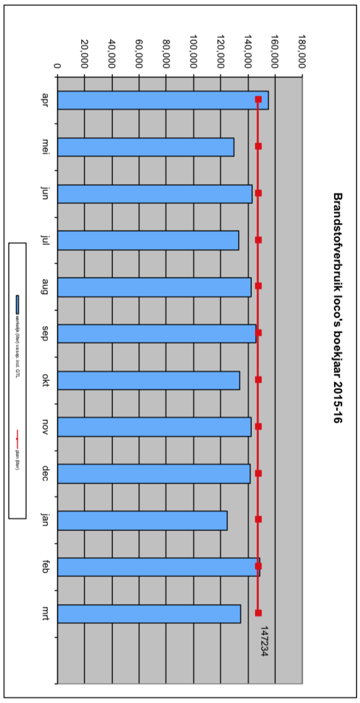
Bron: opgave BOHA **2016/17** incl. GTL

rapprteringsmaand	apr	mei	jun	jul	aug	sep	okt	nov	dec	jan	feb	mrt			
	mrt	**apr**	**mei**	**jun**	**jul**	**aug**	**sep**	**okt**	**nov**	**dec**	**jan**	**feb**	**totaal**		
plan (liter)	147234	147234	147234	147234	147234	147234	147234	147234	147234	147234	147234	147234	1766811	liter	incl. taakkstelling
werkelijk (liter) va sep. incl. GTL	155328	129674	143180	133393	142734	145786	134018	142586	141595	125054	148749	134557	1676652	liter	
plan (euro)	155291	155291	155291	155291	155291	155291	155291	155291	155291	155291	155291	155291	1863492	euro	incl. taakstelling van 80 k€
werkelijk (euro)	148419	124820	143244	136351	143406	139660	130920	140852	141541	130009	157052	142224	1678500	euro	
prijs jaarplan	1	1	1	1	1	1	1	1	1	1	1	1	1	euro/liter	incl. taakkstelling
gemiddelde prijs diesel werkelijk	1	1	1	1	1	1	1	1	1	1	1	1	1	euro/liter	

Analyse afwijking:

	apr	mei	jun	jul	aug	sep	okt	nov	dec	jan	feb	mrt	**totaal**	
prijs-efftect	15408	11949	7771	4341	7138	14103	10431	9536	7801	1889	-163	-304	74492	euro
volume-effect	-8536	18522	4276	14598	4747	1528	13940	4903	5948	23394	-1598	13371	103629	euro
totaal verschil	6872	30471	12047	18940	11885	15631	24371	14439	13750	25282	-1760	13067	178121	

ANALAYSE DIESELVERBRUIKEN LOCO'S



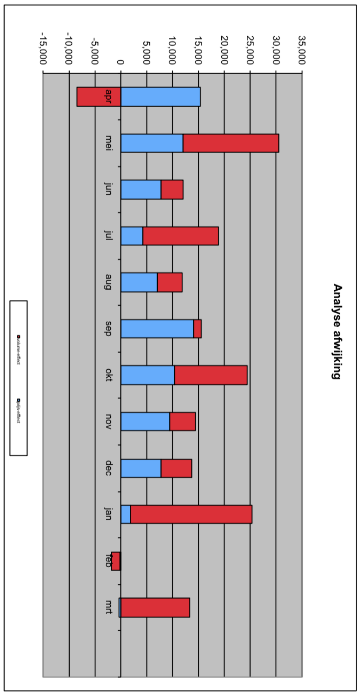


Figure D.0.2: Locomotive driving hours source: Tata Steel Finance

DRAAI-UREN LOCO'S

loco uren

loko uren overzicht

weekcorrectie	excel-berekening	2		#NAME?		#NAME?		#NAME?		#NAME?	
		Beginstanden		april		mei		juni		juli	
GE-loco's	opnamedatum	31-Mar-16		01-May-16		29-May-16		26-Jun-16		31-Jul-16	
Loco	inzet	motoruren beginstand	rij-uren beginstand	motoruren stand	rij-uren stand	motoruren stand	rij-uren stand	motoruren stand	rij-uren stand	motoruren stand	rij-uren stand
901	centraal	5 201	69 398	5 433	69 561	5 808	69 821	6 069	70 003	6 252	70 128
902	west	3 193	58 620	3 491	58 806	4 040	59 140	4 465	59 407	4 800	59 600
904	west	69 704	41 651	69 990	41 814	70 384	42 059	70 674	42 209	70 962	42 399
905	west	66 582	39 819	66 822	39 970	67 271	40 274	67 655	40 568	67 974	40 799
906	west	77 084	45 441	77 358	45 608	77 619	45 785	78 059	46 068	78 350	46 255
907	west	77 726	44 923	77 726	44 923	77 726	44 923	77 726	44 923	77 726	44 923
908	west	31 356	64 205	31 506	64 235	31 999	64 545	32 345	64 754	32 716	64 972
909	west	35 080	21 880	35 333	22 026	35 446	22 092	35 728	22 262	36 030	22 440
990	centraal	348	42 107	583	42 284	955	42 564	1 226	42 770	1 566	43 029
992	west	91 092	37 784	91 410	37 967	91 740	38 172	91 943	38 287	92 213	38 437
996	centraal	21 913	15 028	22 088	15 153	22 285	15 288	22 532	15 468	22 781	15 647
998	centraal	42 603	29 068	42 751	29 180	42 999	29 337	43 167	29 456	43 294	29 545
O&K											
820	centraal	56 794	41 893	57 123	42 145	57 617	42 533	57 982	42 824	58 385	43 146
821	centraal	52 675	39 542	52 950	39 756	53 379	40 087	53 695	40 334	54 043	40 604
823	centraal	45 627	476	45 647	486	46 109	719	46 542	930	46 850	1 082
824	centraal	50 375	37 081	50 562	37 227	50 847	37 444	51 115	37 663	51 410	37 891
825	centraal	46 613	34 855	46 826	35 020	47 119	35 243	47 357	35 425	47 682	35 681
Totaal	centraal	322 148	309 447	323 963	310 812	327 119	313 037	329 685	314 871	332 264	316 752
	west	451 817	354 323	453 636	355 349	456 225	356 990	458 594	358 479	460 771	359 825
uren	centraal			1 815	1 366	3 156	2 225	2 566	1 835	2 579	1 881
	west			1 819	1 026	2 589	1 641	2 369	1 489	2 177	1 346

		#NAME?		#NAME?		#NAME?		#NAME?	
		augustus		september		oktober		november	
		28-Aug-16		02-Oct-16		30-Oct-16		27-Nov-16	
Loco	inzet	motoruren stand	rij-uren stand	motoruren stand	rij-uren stand	motoruren stand	rij-uren stand	motoruren stand	rij-uren stand
901	centraal	6 653	70 406	7 049	70 684	7 295	70 852	7 719	71 153
902	west	5 310	59 956	5 706	60 226	6 174	60 505	6 359	60 615
904	west	71 520	42 758	71 842	42 952	72 314	43 283	72 559	43 391
905	west	68 429	41 097	68 787	41 346	69 111	41 546	69 520	41 793
906	west	78 771	46 431	79 055	46 617	79 495	46 991	79 916	47 291
907	west	77 726	44 923	77 726	44 923	77 726	44 923	77 726	44 923
908	west	33 092	65 230	33 271	65 326	33 627	65 534	34 027	65 779
909	west	36 573	22 794	36 972	23 041	37 236	23 237	37 392	23 350
990	centraal	1 927	43 309	2 361	43 643	2 616	43 839	2 854	44 016
992	west	92 347	38 546	92 843	38 789	93 066	38 928	93 502	39 118
996	centraal	22 952	15 771	23 274	16 006	23 634	16 262	23 763	16 356
998	centraal	43 706	29 742	43 845	29 907	44 204	30 137	44 550	30 366
O&K									
820	centraal	58 954	43 601	59 389	43 948	59 851	44 309	60 220	44 594
821	centraal	54 094	40 642	54 094	40 642	54 094	40 642	54 094	40 642
823	centraal	47 364	1 345	47 866	1 640	48 163	1 759	48 593	28 441
824	centraal	51 740	38 145	52 286	38 585	52 707	38 919	53 020	39 161
825	centraal	48 159	36 059	48 622	36 427	49 065	36 782	49 478	37 107
Totaal	centraal	335 548	319 020	338 786	321 481	341 627	323 501	344 290	351 835
	west	463 768	361 735	466 202	363 221	468 749	364 947	471 001	366 260
uren	centraal	3 284	2 268	3 238	2 461	2 842	2 020	2 663	28 334
	west	2 997	1 910	2 434	1 486	2 547	1 726	2 252	1 313

		#NAME?		#NAME?		#NAME?		#NAME?	
		december		januari		februari		maart	
		01-Jan-17		29-Jan-17		26-Feb-17		02-Apr-17	
Loco	inzet	motoruren stand	rij-uren stand	motoruren stand	rij-uren stand	motoruren stand	rij-uren stand	motoruren stand	rij-uren stand
901	centraal	8 090	71 399	8 434	71 634	8 658	71 784	9 177	72 135
902	west	6 700	60 815	7 125	61 065	7 474	61 266	7 862	61 475
904	west	73 070	43 687	73 376	43 866	73 801	44 168	74 373	44 400
905	west	69 910	42 044	70 143	42 178	70 356	42 300	70 866	42 647
906	west	80 288	47 591	80 681	47 900	80 792	47 969	80 792	47 969
907	west	77 726	44 923	77 726	44 923	77 726	44 923	77 726	44 923
908	west	34 171	65 871	34 476	66 060	34 476	66 060	35 094	66 474
909	west	37 775	23 578	37 791	23 588	38 324	23 932	38 762	24 191
990	centraal	3 339	44 302	3 651	44 612	4 026	44 894	4 502	45 250
992	west	94 094	39 294	94 881	39 401	95 136	39 572	95 518	39 871
996	centraal	24 053	16 537	24 373	16 747	24 757	16 994	25 156	17 274
998	centraal	44 758	30 510	45 119	30 769	45 443	31 000	45 878	31 267
O&K									
820	centraal	60 573	44 858	60 930	45 125	61 303	45 408	61 655	45 680
821	centraal	54 318	40 801	54 615	41 021	54 885	41 228	55 365	41 606
823	centraal	48 849	28 638	49 082	28 815	49 362	29 025	49 775	29 348
824	centraal	53 328	39 392	53 681	39 660	54 081	39 974	54 391	40 220
825	centraal	49 749	37 307	50 069	37 554	50 317	37 739	50 779	38 109
Totaal	centraal	347 056	353 743	349 954	355 937	352 833	358 044	356 677	360 889
	west	473 734	367 803	476 199	368 981	478 085	370 190	480 993	371 950
uren	centraal	2 766	1 908	2 898	2 195	2 879	2 107	3 844	2 845
	west	2 733	1 543	2 465	1 178	1 886	1 209	2 908	1 760

Bibliography

[1] Salinas | Industrial Railways | Railroad Track Contractors, Designers & Engineers. URL `http://www.industrialrailways.com/transloading-sites/salinas`, Accessed on: 2017-12-27.

[2] A comparison of algorithms for minimising delay costs in disturbed railway traffic scenarios. *Journal of Rail Transport Planning & Management*, 2(1-2):23–33, nov 2012.

[3] Sustainability Report Tata Steel in the Netherlands, 2015. ISSN 2015/2016. URL `http://www.tatasteel.nl/static{_}files/Downloads/Corporate/GlobalNetherlands/Sustainability/TSNSustainabilityreport15{_}16.pdf`.

[4] Dominion Railway Services, 2017. URL `http://dominionrailserv.ca/`, Accessed on: 2017-12-23.

[5] Alberta Midland Railway Terminal - About AMRT, 2017. URL `http://www.albertamidlandrail.ca/about{_}amrt.html`, Accessed on: 2017-12-23.

[6] Penny Newmain Grain - Fresno, CA | Industrial Railways | Railroad Track Contractors, Designers & Engineers, 2017. URL `http://www.industrialrailways.com/portfolio/penny-newmain-grain-fresno-ca`, Accessed on: 2017-12-23.

[7] HIsarna process – Tata Steel - M2i - Materials innovation institute, 2017. URL `http://www.m2i.nl/portfolio-items/hisarna-process-tata-steel/`, Accessed on: 2017-11-26.

[8] Salinas | Industrial Railways | Railroad Track Contractors, Designers & Engineers, 2017. URL `http://www.industrialrailways.com/transloading-sites/salinashttp://www.industrialrailways.com/transloading-sites/milpitas`, Accessed on: 2017-12-23.

[9] Strip Products UK | Tata Steel in Europe, 2017. URL `https://www.tatasteeleurope.com/en/about-us/Activities/Strip-Products-UK`, Accessed on: 2017-08-01.

[10] Tata Steel in IJmuiden | Tata Steel Nederlands, 2017. URL `http://www.tatasteel.nl/nl/over/organisatie/in\T1\textendashijmuiden`, Accessed on: 2017-06-12.

[11] Vehicle Safety and Steel, 2017. URL `http://www.worldautosteel.org/why-steel/safety/vehicle-safety-and-steel/`, Accessed on: 2017-06-13.

[12] Estelle Altazin, Stéphane Dauzère-Pérès, François Ramond, and Sabine Tréfond. Rescheduling through stop-skipping in dense railway systems. *Transportation Research Part C: Emerging Technologies*, 2017.

[13] Islamic Azad. Performance analysis of OFDM modulation on indoor broadband PLC channels. *Journal of Industrial Engineering International*, 8:2251–712, 2011.

[14] Lars Backåker and Johanna Törnquist Krasemann. Trip Plan Generation using Optimization: A Benchmark of Freight Routing and Scheduling Policies within the Carload Service Segment. *Journal of Rail Transport Planning and Management*, 2012.

[15] W.A.M. Barter. ERTMS Level2: effect on capacity compared with best practice conventional signalling. In *Proceedings of the 11th International Conference on Computers in Railways, eds. J. Allan, E. Arias, C.A. Brebbia*, page 213, Great Britain, 2008. WIT Press.

[16] Arne Beck, Heiner Bente, Martin Schilling, / Heiner, and Bente /. Railway Efficiency – An Overview and a Look at Opportunities for Improvement. *The International Transport Forum's Discussion Paper Series*, 2013.

[17] Ilse-Valeria Benavides-Peña, Valeria Garza-Amaya, Cecilia Garza-Madero, and Bernardo Villarreal. Improving On-Time Delivery Eliminating Routing Waste: A Case Study, 2017. URL `http://ieomsociety.org/ieom2017/papers/36.pdf`.

[18] Glencora Borradaile, Philip N Klein, Shay Mozes, and Christian Wulff-Nilsen. Multiple-Source Multiple-Sink Maximum Flow in Directed Planar Graphs in Near-Linear Time, 2011. URL `https://pdfs.semanticscholar.org/a090/37473607f3b256f9f397901de16b65f88e7d.pdf`.

[19] Wojciech Bożejko, Radosław Grymin, and Jarosław Pempera. ScienceDirect Scheduling and Routing Algorithms for Rail Freight Transportation. *Procedia Engineering*, 178:206–212, 2017.

[20] Malachy Carey and Ivan Crawford. Scheduling trains on a network of busy complex stations. *Transportation Research Part B: Methodological*, 2007.

[21] Charles E. Ebeling. An Introduction to Reliability and Maintainability Engineering. In *O&M Best Practices Guide*. McGraw Hill College Division, 1996.

[22] Uwe Clausen and Maike Rotmann. *Efficiency and Innovation in Logistics,*. 2014.

[23] F Corman and E Quaglietta. Closing the loop in real-time railway control: Framework design and impacts on operations. *Transportation Research Part C*, 54:15–39, 2015.

[24] F Corman, A D 'ariano, D Pacciarelli, and M Pranzo. Optimal inter-area coordination of train rescheduling decisions. *Transportation Research Part E*, 48:71–88, 2012.

[25] F Corman, A D 'ariano, D Pacciarelli, and M Pranzo. Dispatching and coordination in multi-area railway traffic management. *Computers and Operation Research*, 44:146–160, 2013.

[26] Luís Couto Maia and António Couto. Optimization Model Designed To Model Freight Networks At A Macro Level. In *13th world conference on transport research*, 2013. URL `http://www.wctrs-society.com/wp/wp-content/uploads/abstracts/rio/selected/1248.pdf`.

[27] Luís Couto Maia, Antó Nio, Fidalgo Do Couto, and L C Maia. An innovative freight traffic assignment model for multimodal networks. *Computers in Industry*, 64:121–127, 2013.

[28] Teodor Gabriel Crainic, Antonio Frangioni, and Bernard Gendron. Bundle-based relaxation methods for multicommodity capacitated ÿxed charge network design. *Discrete Applied Mathematics*, 112:73–99, 2001.

[29] Andrea D 'ariano, Dario Pacciarelli, and Marco Pranzo. Discrete Optimization A branch and bound algorithm for scheduling trains in a railway network. *European Journal of Operational Research*, 2006.

[30] Pascal Dennis. *Lean production simplified a plain language guide to the world's most powerful production system*. Productivity Press, 2007.

[31] M J Dorfman and J Medanic. Scheduling trains on a railway network using a discrete event model of railway traffic. *Transportation Research Part B: Methodological*, 2004.

[32] Wout Dullaert and Luca Zamparini. The impact of lead time reliability in freight transport: A logistics assessment of transport economics findings. *Transportation Research Part E: Logistics and Transportation Review*, 2013.

[33] Douglas E. Modelling Train and Passenger Capacity. *NSW*, 2012.

[34] Armin Fügenschuh, Henning Homfeld, Andreas Huck, Alexander Martin, and Zhi Yuan. Scheduling Locomotives and Car Transfers in Freight Transport, 2006. URL `http://131.220.77.52/files/preprints/2006transsci.pdf`.

[35] Tobias Fumasoli, Dirk Bruckmann, and Ulrich Weidmann. Operation of freight railways in densely used mixed traffic networks - An impact model to quantify changes in freight train characteristics. *Research in Transportation Economics*, 2015.

[36] Jose Arturo Garza-Reyes, Juan Sebastian Beltran Forero, Vikas Kumar, Bernardo Villarreal, Miguel Gaston Cedillo-Campos, and Luis Rocha-Lona. Improving Road Transport Operations using Lean Thinking. *Procedia Manufacturing*, 11:1900–1907, jan 2017.

[37] Rob M P Goverde, Francesco Corman, and Andrea D 'ariano. Railway line capacity consumption of different railway signalling systems under scheduled and disturbed conditions. *Journal of Rail Transport Planning & Management*, 3:78–94, 2013.

[38] S. Hansen. Large transport infrastructure investments and their strategic impacts with a special focus on enterprises (store transportinfrastrukturprojekter og deres strategiske virkninger med saerlig fokus pa effekter for virksomheder), 2004.

[39] Thai Hoa. TRR 2448. *Transportation Research Record Journal of the Transportation Research Board Transportation Research Board of the National Academies*, (2448):45–52, 2014.

[40] Li Hong-chang, Rong Chao-he, and Song De-xi. Applicability and Methods of Lean Production in Railway Transportation Organization: A Case Study of Urumqi Railway Bureau in China *, 2008. URL `https://uic.org/cdrom/2008/11{_}wcrr2008/pdf/G.1.4.4.3.pdf`.

[41] David Hunt. Return on investment on freight rail capacity improvements. *American Association of State Highway and Transportation Officials*, 2005.

[42] Tibor Illés. Lessons learned and replicability. In *The 5th Workshop on Algorithmic Methods and Models for Optimization of Railways*, volume 63, pages 39–47, 2014. URL `http://www.mav-trakcio.hu`.

[43] S V Ivanov, A I Kibzun, and A V Osokin. Stochastic Optimization Model of Locomotive Assignment to Freight Trains. *Original Russian Text c S.V. Ivanov, A.I. Kibzun, A.V. Osokin*, 77(11), 2016.

[44] Brigitte Jaumard and Huaining Tian. Multi-Column Generation Model for the Locomotive Assignment Problem. In Marc Goerigk and Renato Werneck, editors, *16th Workshop on Algorithmic Approaches for Transportation Modelling, Optimization, and Systems (ATMOS 2016)*, volume 54 of *OpenAccess Series in Informatics (OASIcs)*, pages 6:1–6:13, Dagstuhl, Germany, 2016. Schloss Dagstuhl–Leibniz-Zentrum fuer Informatik. URL `http://drops.dagstuhl.de/opus/volltexte/2016/6530`.

[45] Jernbaneverket. Capacity 2007 (Kapasitetsrapporten 2007), 2007.

[46] Wang Jianjun. The Research on Efficiency and Effectiveness of Rail Transport. *IERI Procedia*, 3:126–130, 2012.

[47] A. H. Kaas. Methods to calculate capacity of railways (Metoder til beregning af jernbanekapacitet), 1998.

[48] A. M. Khan. Railway capacity analysis and related methodology, 1979. URL `https://trid.trb.org/view.aspx?`

id=141733.

[49] Pyung-Hoi Koo, Jaejin Jang, and Jungdae Suh. Estimation of Part Waiting Time and Fleet Sizing in AGV Systems *. *The International Journal of Flexible Manufacturing Systems*, 16:211–228, 2005.

[50] Harald Krueger and Harald. Parametric modeling in rail capacity planning. In *Proceedings of the 31st conference on Winter simulation Simulation—a bridge to the future - WSC '99*, volume 2, pages 1194–1200, New York, New York, USA, 1999. ACM Press. URL http://portal.acm.org/citation.cfm?doid=324898.325036.

[51] April Kuo, Elise Miller-Hooks, and Hani S. Mahmassani. Freight train scheduling with elastic demand. *Transportation Research Part E: Logistics and Transportation Review*, 2010.

[52] A Landex, B Schittenhelm, A H Kaas, and J Schneider-Tilli. Capacity measurement with the UIC 406 capacity method. *Computers in Railways XI*, 2008.

[53] Alex Landex. *Methods to estimate railway capacity and passenger delays.* PhD thesis, DTU, 2008.

[54] Thai Hoa Le. *Freight train optimization and simulation.* PhD thesis, Concordia University, 2013.

[55] Anders Lindfeldt. *Railway capacity analysis - Methods for simulation and evaluation of timetables, delays and infrastructure.* PhD thesis, KTH Royal Institute of Technology, 2015. URL https://www.kth.se/polopoly{_}fs/1.613049{%}21/15{_}002PHD{_}report.pdf.

[56] Quan Lu, Maged Dessouky, and Robert C Leachman. Modeling Train Movements through Complex Rail Networks, 2004. URL http://www-bcf.usc.edu/{~}maged/publications/train{_}paper95.pdf.

[57] T L Magnanti and R T Wong. Network Design and Transportation Planning: Models and Algorithms. *Transportation Science*, 18(1):1–55, 1984.

[58] Monica Malvezzi, Luca Pugi, Roberto Conti, Paolo Toni, Simone Tesi, Enrico Meli, and Andrea Rindi. A Tool for Prediction and Optimization of Railway Traction Systems with Respect to an Expected Mission Profile. *Chemical Engineering Transactions*, 2013.

[59] Mark Lawley. A time–space scheduling model for optimizing recurring bulk railcar deliveries. *Transportation Research Part B*, 2007.

[60] Francisco E Martínez Martínez, Benjamín Colucci Advisor, Francisco E Martínez, Didier Valdés, and Benjamín Colucci. *Application of SIMAN ARENA Discrete Event Simulation Tool in the Operational Planning of a Rail System.* PhD thesis, University of Puerto Rico Mayagüez Campus, 2002.

[61] Nimrod Megiddo. Optimal flow in networks with multiple sources and sinks. *Mathematical Programming*, 7(1), 1974.

[62] Miloš S Milenkovi, Nebojša J Bojovi, Libor Švadlenka, and Vlastimil Melichar. A stochastic model predictive control to heterogeneous rail freight car fleet sizing problem. *Transportation Research Part E*, 82:162–198, 2015.

[63] Sanjin Milinković, Nenad Grubor, Slavko Vesković, Milan Marković, and Norbert Pavlović. Simulation model of a Single Track Railway Line. In *ICIST 2015 5th International Conference on Information Society and Technology Simulation*, 2010.

[64] MIT. Examples of Network Flow Problems. URL http://web.mit.edu/15.053/www/AMP-Chapter-08.pdf.

[65] Martim Moniz, Diogo Silva, and João Telhada. Metaheuristic for the Integrated Approach to the Freight Train Routing and Block-to-train Assignment. *International Journal of Transportation*, 2(1):53–76, 2014.

[66] Shi Mu and Maged Dessouky. Scheduling freight trains traveling on complex networks. *Transportation Research Part B: Methodological*, 45(7):1103–1123, 2011.

[67] Shi Mu, Maged Dessouky, and Daniel J Epstein. Scheduling Freight Trains Traveling on Complex etworks, 2010. URL https://pdfs.semanticscholar.org/c13d/abe0d8b3a2aa77621e627dce3b259834a8e6.pdf.

[68] A. Oetting. Capacity in Saturated Railway Nodes and Networks. In *Capacity in Saturated Railway Nodes and Networks.* PTRC Education and Research Services on behalf of the Planning and Transport Research and Computation International Association, 2007. Proceedings of the 2nd International Seminar on Railway Operations Modelling and Analysis, eds. I.A. Hansen, A. Radtke, J.P. Pachl and E. Wendler, International Association of Railway Operations Research, Hannover, Germany.

[69] Taiichi Ohno. *Toyota production system : beyond large-scale production.* Productivity Press, 1988.

[70] Oxford Dictionaries. Definition of network in English | Oxford Dictionaries, 2017. URL https://en.oxforddictionaries.com/definition/network, Accessed on: 2017-06-28.

[71] F Piu, V Prem Kumar, M Bierlaire, and M G Speranza. Introducing a preliminary consists selection in the locomotive assignment problem. *Transportation Research Part E*, 82:217–237, 2015.

[72] Francesco Piu. A Mixed Integer Programming Approach to the Locomotive Assignment Problem, 2011. URL http://www.strc.ch/2011/Piu.pdf.

[73] Di Robert Prinz and Josef Höllmüller. Implentation of the UIC 406 capacity calculation method at Austrian Railways, 2006.

[74] Egidio Quaglietta, Francesco Corman, and Rob M P Goverde. Stability analysis of railway dispatching plans in a

stochastic and dynamic environment. *Journal of Rail Transport Planning & Management*, 3:137–149, 2013.

[75] W. Rothergatter. Bottlenecks in European transport infrastructure. In *pan-European transport issues*, page 300, Brunel University, England, 1996. PTRC Education and Research Services on behalf of the Planning and Transport Research and Computation International Association. URL `https://trid.trb.org/view.aspx?id=482660`.

[76] Subhashish Samaddar and Lance Heiko. Waste Elimination: The Common Denominator for Improving Operations. *Industrial Management & Data Systems*, 93(8):13–19, aug 1993.

[77] Robert G Sargent. Verification and validation of simulation models. In *Winter Simulation Conference*, pages 183–198, 2011. URL `http://www.informs-sim.org/wsc11papers/016.pdf`.

[78] R. Schönemann. *Scheduling rail freight node operations through a slot allocation approach*. PhD thesis, Technischen Universität Berlin, 2016. URL `https://depositonce.tu-berlin.de/bitstream/11303/5853/5/schoenemann{_}rene.pdf`.

[79] Alexander Schrijver. On the history of the transportation and maximum flow problems, 2002. URL `http://homepages.cwi.nl/{~}lex/files/histtrpclean.pdf`.

[80] Alexander Schrijver. Flows in railway optimization. *NAW*, 2008.

[81] Jonatan Schroeder, André Pires, Guedes Elias, P Duarte, and Relatório Técnico. Computing the Minimum Cut and Maximum Flow of Undirected Graphs, 2004. URL `http://www.inf.ufpr.br/pos/techreport/RT{_}DINF003{_}2004.pdf`.

[82] H. Schroer. Inter-terminal transport on Maasvlakte 1 and 2 in 2030: Towards a multidisciplinary and innovative approach on future inter-terminal transport options, 2014. URL `http://inter-terminal.net/itt-reports/ITT-D3.2-Evaluation-Operational.pdf`.

[83] Jana Sekulová and Eva Nedeliaková. Application of lean philosophy in terms of railway transport, 2014. URL `http://pernerscontacts.upce.cz/37{_}2014/Sekulova.pdf`.

[84] David Simons, Robert Mason, and Bernard Gardner. Overall vehicle effectiveness. *International Journal of Logistics Research and Applications*, 7(2):119–135, jun 2004.

[85] David J. Smith and David J. Smith. A Cost-Effective Approach to Quality, Reliability and Safety. In *Reliability, Maintainability and Risk*, pages 31–39. Elsevier, 2017.

[86] Julio A Soria-Lara and David Banister. Collaborative backcasting for transport policy scenario building. *Futures*, 2017.

[87] Henrik Sternberg, Gunnar Stefansson, Emma Westernberg, Rikard Boije af Gennäs, Erik Allenström, and Malin Linger Nauska. Applying a lean approach to identify waste in motor carrier operations. *International Journal of Productivity and Performance Management*, 62(1):47–65, nov 2012.

[88] R. Stok. *Estimation of railway capcatiy cunsumption using stochastic differential equations*. PhD thesis, Universita di Trieste, 2007. URL `https://www.openstarts.units.it/dspace/bitstream/10077/2753/1/STOK{_}thesis{_}EN.pdf`.

[89] Fredrik Tallroth and Jonas Rappu. *Evaluating Discrete Event Simulation for Rail Port Operations*. PhD thesis, Chalmers University of Technology, 2016.

[90] Fredrik Tallroth and Jonas Rappu. *Evaluating Discrete Event Simulation for Rail Port Operations A case study made in the Port of Gothenburg using AutoMod Path Mover System Master's thesis in Product and Production development*. PhD thesis, Chalmers University of Technology, 2016. URL `http://publications.lib.chalmers.se/records/fulltext/238534/238534.pdf`.

[91] Guan Tut San, Robert Mason, and Stephen Disney. MOVE: Modified Overall Vehicle Effectiveness, 2003.

[92] UIC. UIC 2004, 2004.

[93] Bernardo Villarreal. The transportation value stream map (TVSM). *European J . Industrial Engineering European J . Industrial Engineering Transportation Journal International Journal of Industrial Engineering*, 6(2):216–233, 2012.

[94] Bernardo Villarreal, Jose Arturo Garza-Reyes, Vikas Kumar, and Andrea Lopez. Eliminating Seven Transportation Extended Wastes to Increase On-Time Delivery: A Case Study, 2015.

[95] Bernardo Villarreal, Jose Arturo Garza-Reyes, and Vikas Kumar. A lean thinking and simulation-based approach for the improvement of routing operations. *Industrial Management & Data Systems*, 116(5):903–925, jun 2016.

[96] D Wood and S Robertson. Planning tomorrow's railway -role of technology in infrastructure and timetable options evaluation. *Computers in Railways VIII*, 2002.

[97] Candace A Yano and Alexandra M Newman. Scheduling Trains and Containers with Due Dates and Dynamic Arrivals. *Transportation Science*, 35(2):181–191, 2001.

[98] Xianying Zhang, David Thompson, Hongseok Jeong, and Giacomo Squicciarini. The effects of ballast on the sound radiation from railway track. *Journal of Sound and Vibration*, 2017.

[99] Yonghua Zhou and Chao Mi. Modeling and simulation of train movements under scheduling and control for a fixed-block railway network using cellular automata. *Simulation*, 89(6):771–783, jun 2013.

[100] Endong Zhu. *Scheduled Service Network Design for Integrated Planning of Rail Freight Transportation Scheduled Service Network Design for Integrated Planning of Rail*. PhD thesis, Cirrelt, 2011.

[101] Endong Zhu, Teodor Gabriel Crainic, and Michel Gendreau. Scheduled Service Network Design for Freight Rail Transportation Bureaux de Montréal : Bureaux de Québec. *Cirrelt*, 2011.