Evaluating Logistical Concepts with Simulation: A Case Study of Increasing Freight Train Length at ports

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Abstract. The European freight rail network will have to handle increasing volumes largely due to a shift from road to rail to reach the sustainability goals defined in the European Green Deal. Efforts are being undertaken to define and evaluate measures that will allow an already busy network to handle more volumes. One of the promising measures is the usage of longer freight trains going up to 740 metres. Increased length of trains means more cargo per service, but also means new challenges. Although this measure seems straightforward, the devil sits in the details, most notably operational details. In this paper, we present our investigations into the operational details of freight trains handling at one of the important endpoints of the network, the Port of Rotterdam. In order to account for details, we have developed a micro-simulation that incorporates the operational processes of freight train handling. Using this model, we have compared scenarios using various compositions of trains, among which a scenario with a high level of long trains. In the experiments, we have considered each individual siding and shunting yard of the port to have insights into the operations. While longer trains can help in handling more volumes, it will also create more additional congestion at shunting yards that needs to be considered.

Introduction

Increasing freight train length is often given as a simple and effective solution to either increase transport volume at a low cost, or to alleviate congestion and reduce bottlenecks while retaining the same cargo flow with lower train number. This is necessary given increasing volumes that need to be transported in an ever so important sustainable way. Current predictions and plans in the European Union show a doubling of volume by rail by 2030 [1]. Often analysis of the effects of increasing train length considers only the corridor or line requirements and possible gains are evaluated by congesting cargo on tracks and resulting headways [2], [3].

Yet careful consideration is required in analysing expected capacity increase resulting from longer trains. In the case of a high-level analysis, we risk on missing operational issues that will hurt future capacity. We therefore opt for microlevel modelling that incorporates operational and physical properties, as the length of trains is not merely a volume parameter but imposes physical limitations.

In this paper we argue that from a tactical logistics standpoint, the problem is not that straightforward and requires detailed analysis in several key areas, especially around the transportation hubs and cargo terminals.

Background

Rail freight transportation volume is increasing in the EU much faster than the network capacity [4]. More trains are being run which increases network congestion and in turn intensifies detrimental network effects like queuing or proliferating delays. Freight trains are especially affected as they are slower and less visible than the generally prioritised passenger trains.

There are many proposed interventions to improve the network capacity in the European Union, one of which is to promote usage of longer freight trains, going up to 740 metres in length instead of the current maximum of 650 metres. If more cargo can be transported by a single train, then fewer of those trains are needed in total. Additionally, expected line effects from a single longer train are negligible, with trains generally achieving the same top speeds, and only marginally increased headways, block occupation, or acceleration as well as braking times. Finally, most modern freight train processing facilities were designed to handle 740-metre-long trains.

Yet, the main difficulty for long freight trains does not occur on the main line, but rather near its destination. Firstly, there are typically fewer sidings where long train can stop and sometimes even splitting is necessary. In busy networks, occupying an additional siding might already be a problem. Still, inspection and shunting operations typically would not take much more time in comparison with processing times for loading and/or unloading the train. These, due to greater volume of cargo, can take up significantly more time per train. Terminal operators favour that as their production siding occupancy rises and is more predictable.

Related research

Increasing the length of freight trains is currently being considered broadly within the European Union. Extensive research is thus available on the topic. Recent publications have considered this: [5], [6], and [7] all introduce some of the research being done in the European Union to face increased volumes on rail. Their main aim is enabling transition from road to rail transportation and ensuring network-level capacity only. [8] offer an extensive overview of all measures being evaluated worldwide to increase capacity on freight rail networks, where optimisation and simulation are named as leading evaluation methods. More specifically to modelling increasing train lengths, [9] introduce a model in OpenTrack focussing on corridors. Yet, it concentrates line effects and does not cover cargo handling operations.

Some research applies economic costs analysis aspects to transportation, where long intermodal freight trains are just one viable alternative to other trains or modes of transport [10], [11]. Others focus on tactical and operational issues in rail networks, like [12], where a Simul8 package model explores the dependencies among the rail network elements. Mesoscopic simulation, however, omits important network elements and train interaction. There are also specific case studies in port networks, like [13], [11] or [14], where a particular rail network is studied in part or whole. They, however, generally do not aim at maximising the transported volume or go as far as investigating a full spectrum of train behaviour and network effects.

1 Rail Scheduling and Simulation Tooling

As introduced before, the challenge of analysing increased train lengths go beyond the mere volume calculations. In order to have a proper understanding of the operational capacity, we need to understand several aspects, among which:

- Physical constraints and operations: the rail infrastructure needs to be proper for handling lengthened trains. Due to the physical aspect of the problem the analysis should include a precise use of trains on the infrastructure to provide insight into capacity constraints.
- Train handling: freight trains do not have a simple point-to-point route that they follow, rather a complex set of operations are undertaken to attribute individual cargo to any of the many terminals present at a port.
- Logistical concepts: due to the increased cargo on individual lengthened trains, the cargo mix will likely be more scattered in terms of source of destination of it within the port. Due to this, increased complexity arises in determining operations that are required to isolate the right cargo for the right terminal.

To address the physicality of the analysis and the operational details, we have developed a microsimulation for freight rail operations called RailGenie [15]. It takes advantage of discrete event simulation to give a data-driven prediction of what is to come. In RailGenie Macomi utilises a two-step approach. The first step is to run an optimisation algorithm to schedule arrivals and compositions of trains as well as determine their routes. The second step is to execute a discrete event simulation run to determine the performance of that schedule and analyse the interdependencies among the trains.

As rail freight operations differ from passenger ones, different requirements are set to model them. Firstly, train dynamics is an outcome of the type of locomotive(s) used and the load it needs to pull, that changes after discharge and loading. A locomotive has a tractive force that pulls the weight of an entire train. Drag is applied to counteract that force, as a function of speed. Another important aspect is to account for acceleration resulting from track gradient. Slow acceleration is common among heavy trains and causes operational issues.

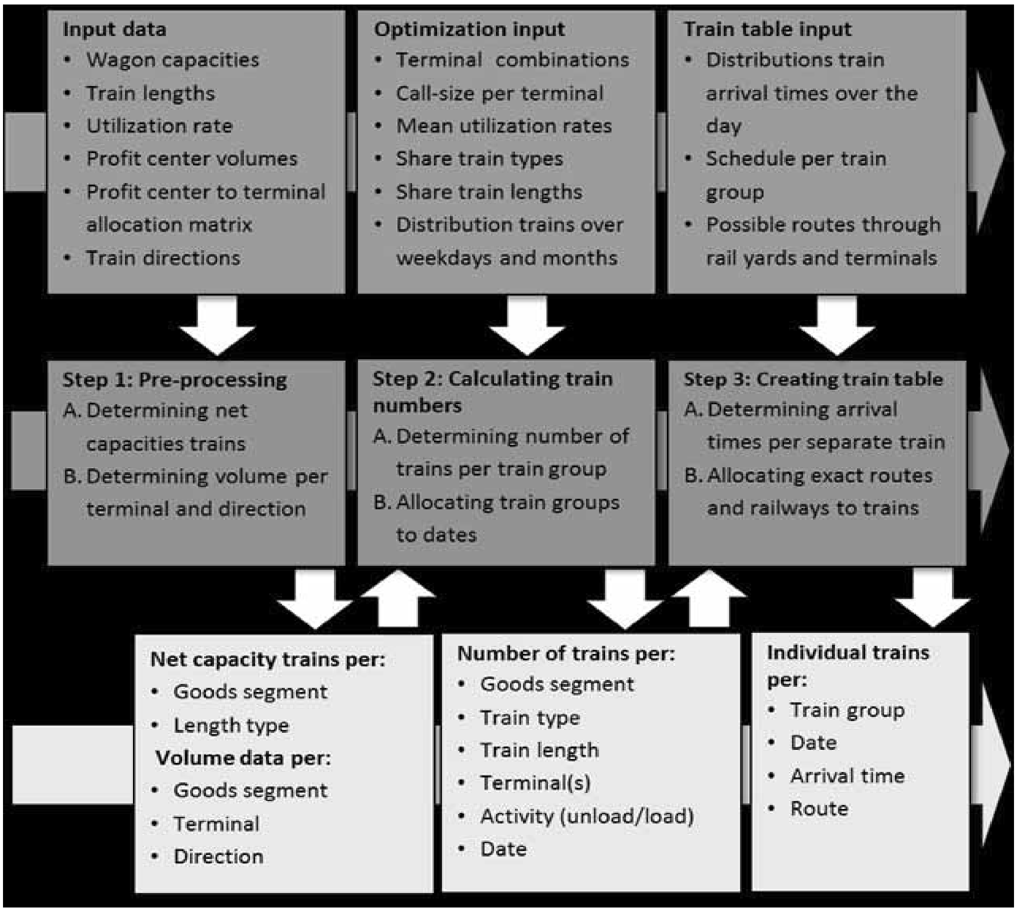

Figure 1: Volume to Trains scheduling algorithm operation [13].

Braking and safety distance calculations differ between freight and passenger trains as according to ETCS and freight trains utilise braking percentage coefficient

A train model must look ahead at least its braking distance to make sure the speed limit will not be breached at any point, while the maximum allowed lane speed might change even several times in that braking distance.

Secondly, freight trains require a lot of supporting processes at transportation hubs, which include loading/discharge operations, train splitting, locomotive swaps, and cargo/train inspections. These processes have varying durations and often further process or resource dependencies. Finally, freight trains have higher flexibility on routing changes.

For the abovementioned reasons, a typical train simulator where the vehicles follow a detailed schedule (i.e. passenger trains having pre-determined minute-based stops at the stations) is not sufficient for the problem area.

1.1 Scheduling Algorithm

Scheduling freight trains differs significantly from the scheduling of passenger trains. The future transportation volume requirements per destination per goods type are used to comprise an overall schedule for the port. Allowed physical characteristics of the trains, timing constraints as well as routing types are part of the optimisation input.

A mixed integer linear programming (MILP) method is used to solve three main optimisation problems: transport all the goods, minimize the number of trains in groups, create a realistic train schedule. See Figure 1 for details.

The optimisation algorithm distributes business (profit centre) volumes per commodity types per import/export direction to locations (cargo terminals). Yearly volumes have monthly/weekly/daily distributions to account for variability, like commodity seasonal patterns. Trains might be direct to a single terminal or visit multiple terminals to discharge and/or load cargo.

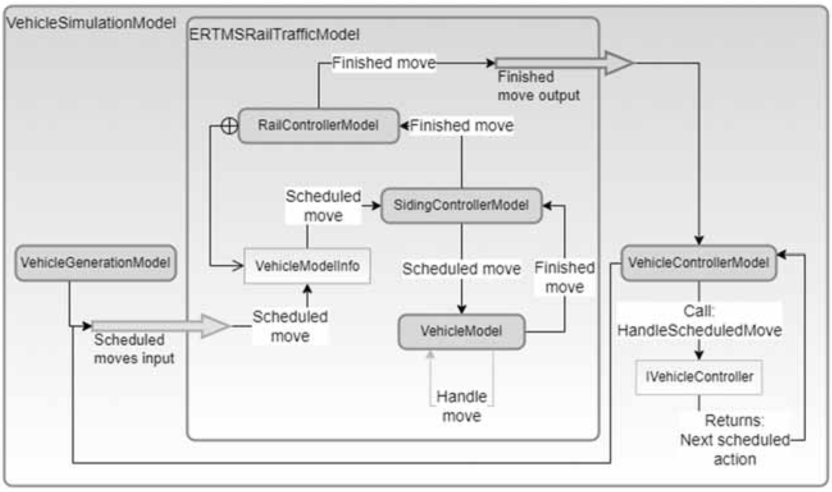

Figure 2: Main vehicle flow in the simulation.

Choosing from available physical train configurations, the algorithm tries to fill the desired distribution patterns. Constraints can be imposed on commodity direction, load factors or daily schedule.

A schedule describes physical composition, cargo, arrival time and exact route and stops of every train. Train turnaround time, i.e., difference between train arrival at and departure from the port is determined by the simulation based on process duration and network interdependencies.

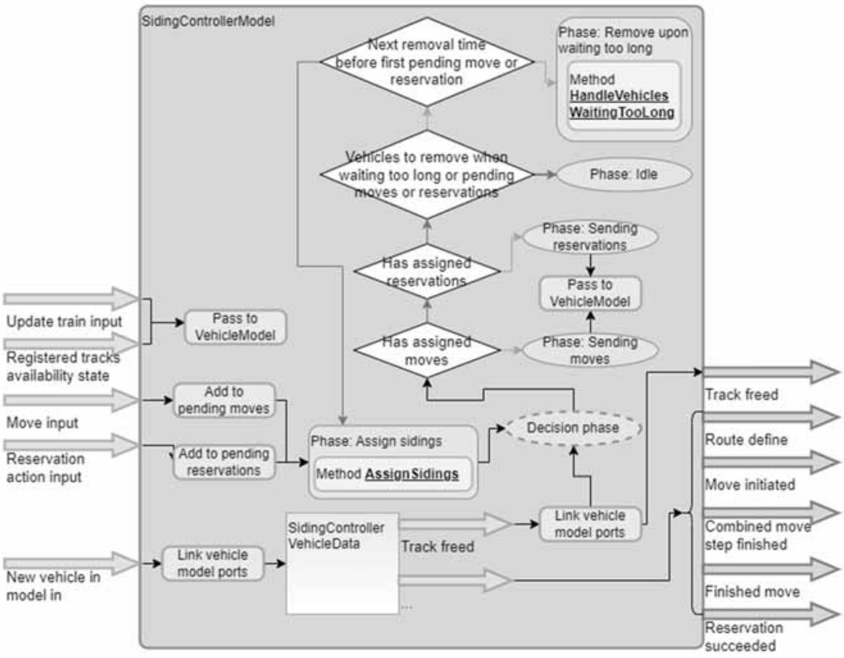

Figure 3: Siding controller logic schematic.

1.2 Simulation Engine

A generated schedule is simulated for performance using Macomi's proprietary simulation engine, which bases on the discrete event system specification (DEVS). It is inspired by the service-based simulation library called DSOL made by TU Delft [16], later refined and extended in .Net and using the Azure infrastructure for computational scaling.

The simulator conforms to fundamentals and structure as set out in the Framework for Modelling & Simulation [17].

In any rail simulation, the most important logic concentrates on how rail vehicles move on the rail network. Figure 2 provides an overview that logic in RailGenie.

In RailGenie a train schedule is divided into individual moves that together comprise the total route of the train in the system, from a source to a sink (network end points). In between moves processes can be performed on the trains (e.g., loading), and these can only happen on designated tracks called sidings. These need to have sufficient length for a train to fit.

Before a move can be performed, the algorithm must make sure the next siding will be available when the train reaches it. As such trains can wait on sidings indefinitely for their next destination to become available.

Concurrently, deadlock prevention becomes important for the system in two main aspects:

- Avoiding trains being unable to move from their sidings due to interdependency with other train locations.
- Execute the move while making sure no trains facing opposite directions get stuck.

Figure 4: Port of Rotterdam rail network schematic in RailGenie.

For dedicated freight train networks deadlock problem has different characteristics than in passenger networks due to less frequent logical track designation as unidirectional, much higher unpredictability of the time the individual move needs to start (lower reliance on schedule), and generally higher complexity of network (due to number of endpoints as well as e.g., use of dated signalling and protection systems). Yet, a reservation system for all tracks in the entire move would be inefficient as these can be lengthy and such reservation would block position of switches and in the end perform worse than in a real system. Figure 3 provides a concept for the siding controller.

A RailGenie configuration for a specific case creates a simulation model, then utilises the simulation engine to execute experiments that can be further analysed.

2 Case Study: Port of Rotterdam

A case study is carried out utilising the infrastructure of the Port of Rotterdam as a representative example of a major and complex European transportation hub, where only freight trains are operated. A network layout is presented in Figure 4. There is only a single point of rail entry and exit to the hinterland that amplifies interdependencies in the network.

In the future rail volumes are projected to increase significantly, requiring more trains to carry the cargo. It is expected that even with the currently envisioned infrastructure investments, the future rail network will experience significant operational difficulties and delays due to congestion.

Furthermore, it will likely not be possible to service all destinations fully, unless additional improvements are made.

One of the possible interventions is to increase the length of trains. This case study explores the extent of benefit of that solution and whether it alone is sufficient to attain the desired cargo volumes. The following main assumptions as preferences from the Port Authority are used: only direct shuttles, no train splitting, mimic current train distributions and process times.

The port rail network consists of several areas that grew incrementally. Older parts are on the right side, closer to the port exit. Despite investments over time, the original design choices still influence the network. Most modern infrastructure layout is on the left side of Figure 4, in the man-made Maasvlakte area [18].

In this case study we utilise the train length of 740 metres as the maximum according to the European Agreement on Main International Railway Lines (AGC), as well as maximum for studied infrastructure characteristics.

2.1 Base Case Scenario

A base case scenario is created established on the current operational composition of trains in the port network and goods forecast for year 2040 supplied by the Port Authority.

Different commodity types are transported by various types of trains without carrying more than one commodity type per train. 740-metre trains are present in the mix, especially for dry bulk transportation, but also for other uniform import goods.

Train composition, their routing and expected volumes are obtained from the available operational data of the port. The same commodity volume is used for all scenarios, yet based on the train length mix the resulting number of planned trains differs, as per scheduling algorithm described in section 1.1.

In total, a yearly schedule of almost 42 thousand trains is created to transport 12 commodity types on 24 physical train configurations to one of the 44 distinct terminal locations. Longer trains carrying the same commodity type have accordingly a longer processing time at shunting yards and terminals.

2.2 Experiments

Several experiments are carried out to test out the performance with a higher mixture of longer trains. During a configuration of the scheduling algorithm, inputs are configured to include higher ratios of longer trains. No new train configurations are used, yet due to the same transportation volumes there are fewer trains scheduled. All experiments utilise the same duration of a month of operations, same volumes, and processing times per train type. A summary is provided in Table 1.

	Base Case	Longer Trains	Longest Trains
Train Number	3229	2954	2751
Ratio of 740m trains	50% where possible	75% where possible	100% where possible

Table 1. Experiment summary.

3 Results

If it is not possible to execute all trains moves within the set period, the simulation will stop generating new arrivals and only terminate when the last train arrives at a sink. This way it is possible to determine locations suffering from the highest capacity issues. It is a theoretical measure, as in reality some of the trains would need to be cancelled or diverted.

Figure 5 shows the number of arrivals per location that did not fit the desired schedule per location. Every arrival is counted, and trains have at least three of those during a visit. Locations were anonymised, and those with designation "_E_" in the middle are shunting yards, while with "_T_" are terminals.

Increasing train length does have a beneficial effect on the system, as fewer trains overshoot their schedule. The gains are the lowest for the most modern infrastructure, where terminals already prefer as long trains as possible.

When looking at properties of locations where bottlenecks form, these are mainly based on too high number of trains. When the number decreases, the negative network effects are alleviated. This is because a shunting yard, shared among arriving and departing trains, is most common location of delays.

Figure 6 shows the occupation of ten busiest rail truck bundles in the port shunting yards for the three scenarios. A bundle is a set or cluster of tracks with shared entry and exit tracks and full interconnectivity, where trains can stop.

While the average occupation in the entire port decreased from 30%, through 27,5% to 25% accordingly, it differs per area. The occupation in some bundle decreased significantly in some areas with the increased length of trains, for others it rose slightly.

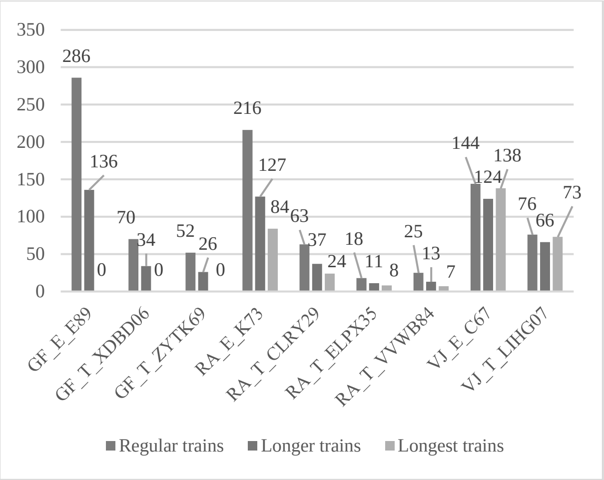

Figure 5: Late train arrivals per selected locations.

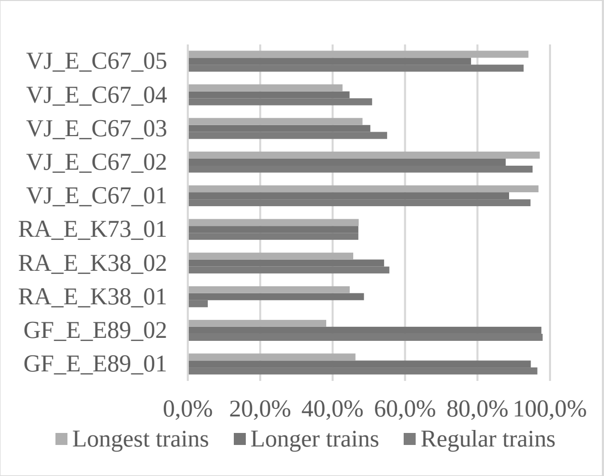

Figure 6: Comparison of occupation in 10 busiest bundles in shunting yards.

The biggest gains in reducing occupation come from alleviating network interdependency effects, when capacity is needed for trains exiting the port network while sidings are used by incoming trains, which in turn cannot proceed due to terminals being full.

	Regular Trains	Longer Trains	Longest Trains
Average [h]	27.2	25.4	24.1
Std. dev. [h]	18.9	16.9	16.1
Min [h]	8.4	8.4	8.4
Max [h]	118.9	107.0	84.3

Table 2: Train turnaround times.

This is especially visible for shunting yards servicing several locations of similar transportation volume, where traffic can overlap. Currently, the deadlock prevention algorithm only ensures that there is a way for trains to carry out their routes but does not balance the incoming and outgoing trains.

In some locations though, where infrastructure is older, a new type of problem starts to occur with a greater percentage of long trains. Where not all sidings can accommodate long trains bottlenecks form around those sidings, while the remaining sidings remain underutilised. Furthermore, the processing times at shunting yards for longer trains are also longer accordingly, thus in some busy, though manageable, locations the total occupancy can increase.

A similar improvement pattern to late arrivals can be seen when looking at the turnaround times of trains, as presented in Table 2. It also shows the extent of congestion experienced in the port, with very high standard deviation and unrealistically high turnaround times of many trains. While such schedule would be impossible to execute, it is possible to model the outcome if one nevertheless tries.

A one-tailed t-test between the regular and longest scenario results shows a significant difference between the means of the subsets with a p-value of 6.63E-12. Thus, using longer trains in this case has a positive impact on reducing train turnaround times. That is despite the effect that longer trains should have longer turnaround times due to longer processing times.

4 Conclusions

This paper investigates how increasing train length can influence transportation of goods in a port rail network, whether it is possible to maintain the total volume while decreasing congestion and delays. Means to carry out the shift to rail in the European Union are urgently needed and the evaluated case has often been proposed as one of the main solutions. It has, however, not been sufficiently studied within port areas and for cargo handling operations. We utilize a MILP optimization to create a schedule and a microscopic discrete-event simulation to evaluate it on the infrastructure of the Port of Rotterdam. Only by accounting for actual train operations and interactions among them a representative picture of network-wide effects be achieved.

Increasing train length has beneficial effects on the overall ability to transport more cargo and reduce train delays. This is visible in the lower number of trains exceeding the schedule, shorter turnaround times, and lower shunting yard occupation on average. While it will not be sufficient to allow the Port of Rotterdam to manage all envisioned cargo, especially that in some areas the benefits are very limited, it certainly is a viable partial solution. Fewer trains transport the same volume that results in lower congestion in the system and less waiting time.

The gains due to longer trains are limited by the maximum train length, existing infrastructure, and the fact that some trains already are this long. Then, with longer processing and supporting operation times on fewer suitable sidings more congestion forms around them, while shorter one may become underutilised.

Further interventions need to be explored before the full expected volumes can be realised. To alleviate congestion on shunting yards with varying siding length, splitting trains should be considered, despite its operational difficulties. Improvements to routing, especially performing supporting processes in less congested shunting yards and then longer shunting with diesel locomotive to the terminal should be considered as well. Furthermore, measures to balance the number of incoming trains with regards to trains already in the system, would likely be advantageous. However, that would require consideration of possible alternatives in the real system, i.e., where to park the trains that is not on the main line. In the end it is possible, that additional infrastructure investments are necessary to realise the predicted cargo volume.

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