SUMO User Conference 2022
https://doi.org/10.52825/scp.v3i.112

# Combining Operative Train Simulation with Logistics Simulation in SUMO

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**Abstract**

Rail freight logistics is usually planned and analyzed using a macroscopic aggregated view on railway networks and train operations. As a result, disjoint tools have developed for simulating train operations which requires a detailed representation of track assets as well as the signaling architecture and supply chain networks in logistics analyzing the flow of goods where mode-specific capacity and traffic situations are incorporated in an aggregated manner. However, integrating the two areas could help evaluating railway-specific operative implications (such as conflicts and consequent delays) on the level of transport chains and thus single transport units instead of trains or network areas. The simulation tool SUMO is identified to meet criteria from both disciplines. It is shown how a respective methodology can be realized in SUMO to create such a simulation model. A use case of northwestern Germany shows by the means of exemplary container trajectories that the two simulative approaches can be merged.

## 1 Introduction

In view of complex supply chain networks, just-in-time production and growing product individualization, the global flow of goods has reached unprecedented complexity. In order to understand, evaluate and predict these flows and associated processes respectively, logistics simulations can be used to model the flow of goods for specific - often larger - networks or regions. The underlying motivation is to identify bottlenecks and critical links within a distribution system or transportation network, as well as to analyze the effects of changes in the design of a system in order to support decision making.

Logistics networks, in general, may feature different means of transportation contributing to the transport of goods from origin to destination. This study focusses on rail-based transportation featuring comparably low emissions and large capacities. It is, however, bound to a certain infrastructure-related

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inflexibility and accompanied by complex routing and capacity planning problems. In contrast, conventional truck distribution is fast and flexible. It has, on the other side, limited capacity only and accounts for a large share of the CO2 emissions [1]. For this reason, significantly rising the share of goods transported by rail is formulated as a goal of the Rail Freight Forward Coalition [2].

These individual characteristics go along with different operational circumstances specific to certain means of transport. In this context, again, simulation tools are used to model the operational execution of logistics processes. In terms of railway transportation, these models often have a stronger focus on operative performance indicators such as speed, delay or occupancy rates and are usually built on a far higher (often microscopic) level of detail. However, simulation tools rarely combine the detailed microscopic perspective required to model delay propagation in train operations and the strategic planning horizon of goods transportation in supply networks. In the first case, railway specific characteristics such as the signaling system governing infrastructure access and timetable constraints need to be incorporated. In the latter case, a far more macroscopic, logistics perspective is adopted which allows to compare and assess different routes and transportation options. Rail-specific characteristics are considered in coarse-grain resolution and rail freight networks are modeled on a graph-theoretical node-edge representation.

The question arises, if a simulation tool can model the flow of goods in larger railway transportation networks on the basis of single units from a logistical perspective but at the same time consider detailed railway operations with its specifics. By integrating these two perspectives, a deeper understanding of freight railway operations on the level of goods would emerge, uncovering implications from train operations on transport chains. As of now, most train simulations consider trains as the smallest units to be observed. However, the reason for freight train operations is transporting goods from origin to destination in the first place. A combined model, featuring the described aspects, would shift the view from trains to goods as the units to be observed. Thus, the conventionally isolated analysis of either logistical processes or train operation would be integrated in a holistic approach. This can be compared to the change in perspective that has taken place in passenger train operations within the last years: important operational indicators such as delay are now often calculated and communicated on the level of single, specific passengers in addition to trains [3].

In this study, requirements, as well as a methodological framework for the combined simulation of train operations and logistical flow of goods are formulated. We show how the agent-based, microscopic simulation environment SUMO [4] can be used and adapted to integrate these two perspectives. As a result, detailed train operations based on integrated clock-face timetables can be merged with the agent-based flow of goods, given their demand.

The paper is arranged as follows: Section 2 gives an overview of related work and existing literature from the two different disciplines, as well as interfaces in between. Section 3 describes the proposed methodological approach from both an abstract and a technical perspective. In section 4 the proposed methodology is applied to a use case based on a freight rail network in northwestern Germany. A proof-of-concept for combined simulation of operative train simulation and container-based goods transportation is provided based on the presentation of trajectories of individual containers and their dependency on the underlying operative train simulation. Section 5 discusses the further potential of the proposed approach, with a special focus on further evaluation criteria and changes in design of the system.

# 2 Literature

Simulation is used for planning, realizing and operationalizing logistic systems. Simulation-based approaches contrast analytic and optimization-based methods [5]. The field of logistics simulations we are focusing on in this paper can be further grouped into different areas. From a methodological view, agent-based, discrete event and system dynamic simulations can be distinguished [6]. From another perspective, logistics simulation approaches can also be categorized by fields of application: One important context is to model Supply Chains with the aim of decision support and optimizing processes [7]. In this area, agent-based simulations provide detailed insights. They have a strong focus on individuals and their interaction within a system and can at the same time be used to model complex supply chains (cf. [8] for an overview of different approaches). However, Supply Chain simulation often has a rather macroscopic network perspective, frequently addressing network design issues. Other objectives of logistic simulation are modeling production systems with the aim of optimizing material flow [9]. Last, node-related distribution systems such as yards, terminals or ports are modeled and optimized by simulation [10]. In terms of transportation, especially network logistics simulation often has an abstract understanding of processes, sometimes not considering specifics of certain means of transport but rather systemically modeling transportation by parameters.

Mode-specific simulations of train operations in railway systems can be divided into microscopic and macroscopic approaches [11]. Microscopic simulation models have a strong link to real-life operations and focus on the detailed operational context (such as driving dynamics and the representation of the signaling system). Usually, a specific timetable is required as input and the effects of operational disturbances including the emergence and transfer of delay are studied. However, these detailed simulations are often bound to limited network sizes. Prominent examples of tools can be found in [12] and [13]. Meso- or macroscopic simulations, by contrast, investigate train operations on a station-by-station view. Here, train interactions and delay transfer are integrated and analyzed by means of aggregate train-following or headway constraints, making this class of simulation fast and capable of analyzing large-scale networks while delimiting the resolution locally [11].

Simulation applications range from microscopic timetable robustness analysis to capacity planning of railway lines, nodes and networks. In timetable assessment, different versions of timetables are simulated with the aim of evaluating the stability of timetables in case of disruptions. Their objective is to identify optimal timetables and their combination respectively [14]. Capacity assessment, by contrast, aims to provide insights into the dependency between traffic load and service quality [15], focusing on the available capacity of railway networks, single lines, nodes or a combination thereof [16]. With respect to freight logistics, capacity assessment often deals with the insertion of additional trains into existing timetable concepts [17 until 19]. While evaluation of traffic with respect to passenger trajectories and service experience is common (see, e.g. [20]), the underlying simulation remains based on trains as the elementary units, especially in freight transportation.

There has been some research in the thematic intersection of logistics simulation and railway simulation: [6] propose a Multi-Agent GIS Simulation approach for Railway Logistics Optimization with the objective of identifying the best possible program. Also, linear programming is frequently used to model railway operations in either yards or networks as part of intermodal transport chains, some of which model the context of harbors and hinterland traffic [21, 22]. These models, however, focus on analytical approaches rather than simulation in an operational sense. There are also agent-based simulation approaches in railway research: [23] propose a MATSim-based methodology to model railway operations with single-wagonload-units being the agents. While they do consider capacity constraints and present an approach suitable for large networks, they do not focus on operational aspects such as delay but rather interpret and model the respective network on a node-edge-basis. Their approach aims for optimizing production schemes.

# 3 Methodology

This section identifies requirements a simulation tool must fulfil in order to create a combined logistical and railway-specific simulation model and explains the subsequent choice of the simulation tool SUMO. It further proposes and illustrates a methodological framework to create a suitable model respectively.

## 3.1 Requirements of a combined simulation framework for railway operations and freight logistics

A combined simulation model of both a logistics and railway-specific level will have to fulfill certain criteria from both disciplines mentioned. Table 1 shows an overview of requirements to such a model and from which discipline they derive:

| | discipline | |
|---|---|---|
| Requirement to a combined model | railway | logistics |
| Processing of timetables | x | |
| Signaling and train control | x | |
| Operative Modeling of rolling stock incl. driving dynamics | x | |
| Import of detailed, microscopic infrastructure | x | |
| Inclusion of capacity constraints | x | |
| Handling of large networks | (x) | x |
| Routing of vehicles (trains) | x | x |
| Modeling of single goods (e.g. containers) as agents | | x |
| Merging goods and trains: routing of goods (transport chain) | | x |
| Processing of OD demand on level of goods | | x |
| Extensive output possibilities (e.g., punctuality, reliability, routes, network utilization…) | x | x |
| Easy adjustments on input criteria to evaluate systemic or individual effects | x | x |
| Acceptable calculation time | x | x |

**Table 1:** requirements to a combined model

Railway-related requirements can be categorized as follows: first, a suitable simulation tool needs to model railway operation with its specifics: As signals govern the access to railway infrastructure, both their locations and functionality need to be implemented. Further, train-specific driving dynamic needs to be implemented in order to correctly model the occupation of infrastructure and how trains interact and propagate delay. Basis for both mentioned criteria is a detailed, microscopic infrastructure model. Second, the concept of timetabling needs to be implementable in order to model railway operations. Here, in addition to relation-wise departure and arrival times, the concept of minimal stopping times is of importance.

Further requirements derive from the logistical perspective, such as the implementation of the flow of goods on an individual, agent-based level to enable a detailed evaluation, e.g. of routes or transportation options. However, at the same time a network-wide analysis should still be possible by aggregating the agent-based output. Furthermore, the assignment of goods to a certain vehicle must be implementable as well. This allows the routing of goods, given transportation vehicles and their route. Coming from a demand perspective, OD matrices as an input on the level of simulative individuals must be processable. As logistical processes often are of complex and interconnected structure, the simulation tool must be capable of dealing with larger networks.

Last, some criteria have a more general simulative context, such as detailed output possibilities fitting the evaluation objective of the model: processable output in order to analyze delay on the basis of simulative agents as well as the correlated reliability can be mentioned here. Furthermore, network-related output (e.g. its utilization) is of importance, as well as routing-related output possibilities such as operationalized trajectories. Given all the different criteria from different perspectives, simulation and thus calculation time must still be acceptable.

It can be seen that railway operations planning goes along with detailed and specific operative processes (and thus requirements) whereas logistics simulation focusses on modeling and analyzing the flow of goods, given a demand and transportation network.

## 3.2 The SUMO software package

The simulation software package SUMO (Simulation of Urban Mobility) is an open-source microscopic simulation tool that uses an agent-based simulation approach to model mobility. It was originally designed as a digital twin of urban areas and had a focus on private cars. However, extensive development has been made in recent years in order to include non-urban use cases and other means of transports such as harbor processes [24] or railway operations [25, 26]. Even though operative train simulation in SUMO does not cover every single detail of train operation included in specialized railway simulation software tools (such as, e.g. RailSys [12], LUKS [27] or OpenTrack [13]), yet, it provides all functionalities required to analyze and simulate train operations on a microscopic switch-by-switch and signal-by-signal level of the infrastructure. In particular, it features several detailed train following models and respective driving dynamics. Moreover, standardized OSM imports including attribute-related selection is implemented. As normally much fewer train units than cars can be observed in a defined area, large railway networks can be simulated as the numbers of units/agents are comparable to dense mobility in an urban area. Finally, SUMO allows intermodal routing for passengers in public transport, which could possibly be adopted to container routing as well. While SUMO has standardized outputs, it does not yet have many agent-specific output possibilities in the sense of combined, multi-modal transport chains. Here, the existing output can be extended by individual approaches.

Given the fact that the SUMO package provides functionalities for both railway infrastructure modeling and train simulation, as well as agent-based approaches including cross-modal mobility patterns incorporating different mobility-related agents such as cars, trains, persons and containers amongst others, it already fulfills a wide span of the requirements defined in the previous package. We therefore choose SUMO as the fundamental building block of our combined rail freight logistics-simulation approach and show how it can be used and adapted to meet the criteria for simulating and analyzing the trajectories of individual freight units within the context of a rail freight logistics.

## 3.3 Methodological approach

Against the background of the two different disciplines explained in section 2 (logistics and railway simulation) and the choice of SUMO as simulation tool (cf. section 3.2), the methodological approach to generate a combined simulation model is explained in the following. Figure 1 shows different processes, which level they can be assigned to and how they interact to create the proposed model:

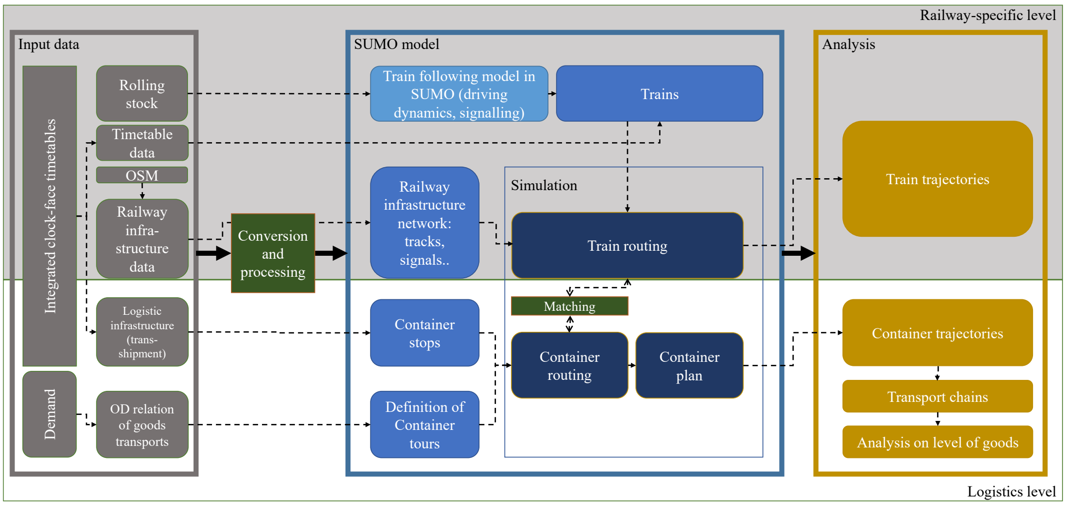

**Figure 1: methodology to create a combined model**

## Train traffic representation

Various input data is used to create the model. In railway operations, timetables comprise information on departure and arrival times of trains as well as their route. Timetables, where trains move according to a regular pattern that cyclically repeats after a defined interval (e.g. one hour), are referred to as periodic or clock-face timetables. More specifically, integrated clock-face timetables are symmetric clock-face timetables where connections between trains in multiple directions are coordinated on the network-scale with the aim of reducing transfer times. They are also referred to as integrated fixed-interval timetables and often visualized as network timetables (see [28] for an example) [29]. These kind of timetables are of importance to both railway-specific and logistical input data, as they have deep correlations on a planning and infrastructural level: first, they do not only fix passenger transport, but also integrate fixed train paths for freight trains, so called "system paths" [30]. Second, they try to mathematically arrange train paths within a network so as to minimize transfer times in the nodes accordingly. In terms of input for a simulation model, these kinds of timetables do not only contain information on timetables of both passenger and freight trains, but also comprise details on logistical connections as follows: freight train paths are usually integrated into the timetable between larger shunting yards where freight train wagons are arranged to freight trains. Extracting logistical information from system paths and thus defining their stations of origin and destination as logistical distribution points means that no further modeling of logistical infrastructure or production systems (in the sense of which container is transshipped at which yard) is needed. System paths are rather interpreted as potentials for goods to find their way through the system. On a SUMO level, both container stops and timetables can be extracted from integrated clock-face timetable data. Information on rolling stock serves as parameters for the train following model applied in SUMO and thus the driving dynamic of the different trains (e.g. high speed, regional or freight trains).

In terms of demand, detailed data on the level of single units and their respective origin and destination have to be provided. As of now, the proposed approach interprets units in the sense of batches of goods or containers and models them as containers in SUMO.

## Rail infrastructure data usage and conversion for usage in SUMO

Physical infrastructure is imported from Open Street Map via a common interface. For reasons of data size, only railway-specific objects are imported in the very first step, such as tracks and signals. The gathered data needs extensive conversion and processing in order to be converted to a SUMO model: OSM railway data is converted to a SUMO network by means of the tools SUMO netconvert. A major challenge when using publicly accessible data is that directed connections (in the sense of which OSM links are connected to each other in which direction) are not "straightened", meaning that directions of tracks can at times lead to dead ends in the system. Two possible ways to handle this can be thought of: either to declare all edges as bidirectional ones, allowing trains to use them in both directions, or to erase dead ends. The first solution is chosen in the course of the proposed methodology for reasons of minimizing manual network correction work and thus human errors. While it might lead to a high number of available routes for a certain train, it ensures that a "realistic" route is amongst the possible route options. Therefore, depending on the quality of input data and the size of the network, this approach might need adjustments in track priorities to ensure that trains use preferred routes as well as operational directions and thus deadlocks are avoided. SUMO netconvert provides an algorithm to change railway edge priorities on the basis of manually declared priorities of single edges.

### Container routing options

Timetable data is transferred to SUMO additional-files and route-files. Here, passenger train stops can be transferred to public transport stops and freight train stops to container stops. In terms of container tours, as of now, static tours are used: this means that every single container has a predefined order of container stops, its origin, transshipment stops if applicable and its destination. It is, however, not specifically defined which trains the respective containers are assigned to. This allows the flexibility to transport containers with any train on a specific route, given capacity and time constraints. Railway shunting yards are usually of very complex track topology and its processes subject of various research (cf. section 2). Here, transshipment stations are defined with container stops, not considering shunting processes in simulation but rather realizing them by process times respectively.

### Simulation model

The steps described lead to a SUMO simulation model with realistic railway infrastructure, both passenger and freight trains running according to timetables and containers assigned to tours of container stops. When starting the simulation, trains will enter the network with a specific initial route automatically created by SUMO based on shortest path algorithms. This path can, however, be influenced by edge priorities as explained above. Freight trains will, if defined, load or unload containers at container stops, considering process times as described above. As agent-based microscopic simulations focus on individuals interacting, here trains will most probably interact and influence each other. This is due to various reasons: first, delays are inevitable in train operation e.g. for reasons of unexpected disruptions due to infrastructural or technical issues. Delayed trains have to "keep up" to their schedule, but might not have a free slot within the timetable construct anymore, especially on congested lines or networks. In this moment, trains will influence each other. This impact can be significantly at times, for example when a delayed high-speed train has to follow a slow freight train on a mixed-traffic line. SUMO can model this mutual impact (on the basis of driving dynamics, timetables and signaling) of trains and will at the same time transfer this information to the containers loaded. In this way, container transport can be modeled from a railway-specific perspective, with delay implications being transferred onto single units. Thus, a combined train and logistic simulation can be created.

SUMO offers different output functions to create data as input for analysis. In order to show that containers logistically behave according to their plan and at the same time are part of railway operations, a large output called fcd can be used to track trajectories of both vehicles and persons/containers. As this output can be fairly voluminous, it might be suitable to equip only those agents with a so called "fcd-device" that should also be part of the analysis. The trajectory information SUMO provides comprises coordinates of all/selected agents at every single timestep (1 second). Plotting the lateral speed of different container-specific trajectories vs. the simulation time elapsed shows how "smoothly" container run through the system and will show train-specific effects such as unplanned stops, delays or deviations. Moreover, container trajectories can be shown following time-distance-lines, a traditional way of displaying railway timetables.

# 4 Proof of Concept

The methodology proposed in section 3 to combine logistics and railway simulation in SUMO was applied to the network of northwestern Germany and shown on the basis of exemplary container trajectories. Figure 2 shows the according railway network in SUMO:

**Figure 2: container route from Kiel to Hamm via Maschen yard (source: SUMO, edited)**

The network was imported and processed according to the methodology described above. Stops and train timetable data (including system paths for freight trains) were imported from the so called “Deutschlandtakt”, a Germany-wide concept of an integrated clock-face timetable that is to be introduced in 2030 [28]. As explained in section 3.3, subsection “container routing options”, train stations and yards are defined as container/public transport stops in a SUMO additional-file. Moreover, train rides are transferred from the input data to SUMO route-files. Figure 2 shows the specific route of a container entering the System in the harbor city of Kiel and being transported by a first train to the large shunting yard of Maschen. This first train is to be seen as the operationalization of the freight train system path between Kiel and Maschen, operated every two hours at a specific departure minute. In Maschen, it is stored and/or transshipped. A yard-specific process time of 7 hours was assumed. The container is then loaded on a second train running on the system path Maschen-Hamm (3 paths in two hours) to be transported to its destination.

The functioning of the combined both logistical and railway-specific simulation can be shown when comparing the trajectory of different containers within the system. Figure 3 shows the container-specific speed profile of three different containers, all having the same initial route and plan (Figure 2):

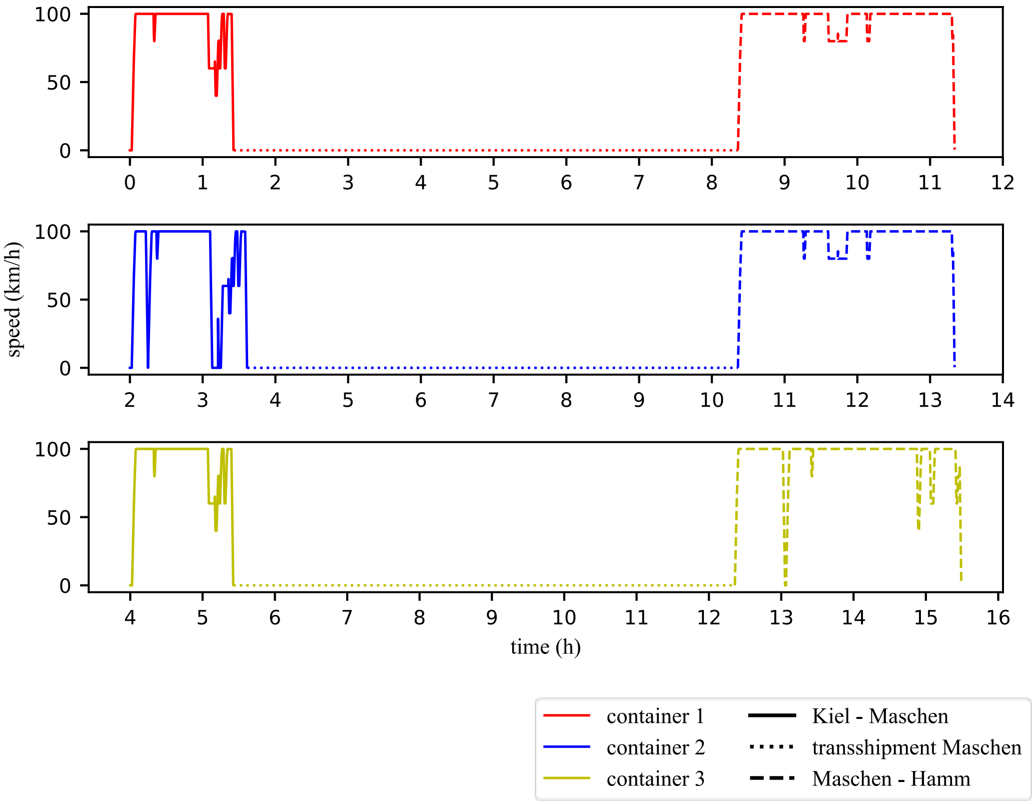

**Figure 3: plot of speed over time for three different containers on the relation Kiel-Maschen-Hamm**

The red curve of container 1 shows an undisturbed and executed-as-planned transportation chain. It can be seen, that most of the time the speed level ranges around the maximum speed level of the train, 100 km/h. At times, the level suddenly falls, for example when the train passes a densely intertwined node of the network, where allowed speed levels are lower. After arriving in the yard of Maschen, the speed of the container decreases to 0 and stays so for roughly 7 hours until the container is processed. This yard-intern process is not modeled explicitly, but in such a way that the container stays at the container stop until it is loaded again. The subsequent ride with a second train on the system path Maschen-Hamm via Bielefeld takes longer than the first one.

Container 2 has the same route as container 1, but is transported with the system path two hours later. The simulation output shows that the train transporting the container encounters some operational disruptions: at first, the freight train has to slow down and even fully stop for small moment, because of signaling and blocking restrictions: its path is conflicting with a delayed passenger commuter train that shares the route of the freight train of the container for a small segment. Shortly before Maschen, the train again encounters implications from other trains, as the very densely operated area around Hamburg forces the train to stop and wait until tracks are free: The figure shows, that for these reasons, the container arrives in Maschen later than container 1.

Container 3 encounters an undisturbed ride to Maschen comparably to container 1 (not identical, however) but its train is disrupted and has to use an alternative route in the second part of its transport chain from Maschen to Hamm. The deviation via Bremen and Osnabrück takes only a little bit longer, but has a quite different speed profile, as can be seen with the yellow curve.

The container trajectories can also be plotted as time-distance-lines, following the conventional way to visualize timetables. Figure 4 shows this information:

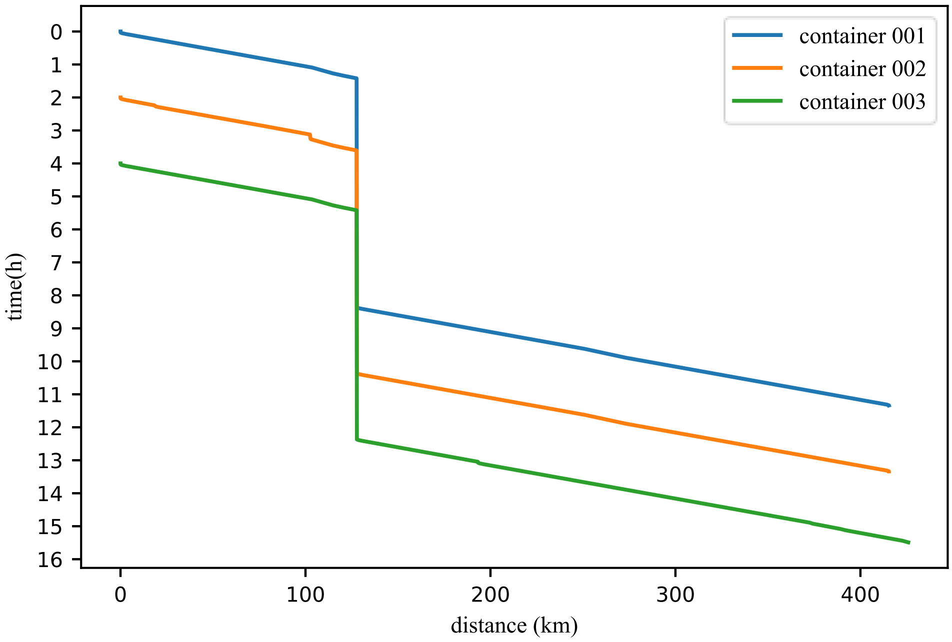

**Figure 4: time-distance-line of containers on the relation Kiel-Maschen-Hamm**

The figure shows the covered distance of a container (not a train) in correlation to elapsed time. At first sight, the curves appear comparably smooth and almost linear. This, however, can be traced back to the comparably long observation period of 14 hours here, which “flattens” the curve. Nevertheless, operational disruptions with container 2, as described above, can be seen here as well in form of a small bend. Also, the path of container 3 is longer in total because of the mentioned deviation of the train transporting it; this results in the longer distance covered by the container represented by the green curve in Figure 4.

Both Figure 3 and Figure 4 show that with the means of the simulation tool SUMO, detailed railway-specific operations and at the same time agent-based logistical transport chains can be modeled and analyzed. A combined simulation has large further potential as described in the following section.

# 5 Discussion and future research

Objective of this paper was to show that operational railway simulation and logistical simulation on the basis of single units (containers) can be combined and merged. This was confirmed by a proof-of-concept based on planned integrated clock-face timetables of northwest Germany. On the basis of three exemplary container trajectories with the same initially planned route it was shown that logistical processes on the level of individual agents (container chain) can be modeled while at the same time considering specifics of railway operation. This means that implications from train operations such as delays and trains conflicting with one another can be analyzed not only on the level of trains, but single agents transported by trains.

The shown merged approach can be extended by further research: container chains can be bundled and aggregated in order to enable a system-wide analysis. This can help identifying bottlenecks of a railway network not only in terms of trains, but also goods transported. By systematically analyzing all transport chains within the network, the delay of containers can be further evaluated (in contrast to the delay of trains) and both identify and quantify its dependencies to the design of the system. The reliability of a railway transportation network can thus be analyzed on the level of that goods which initially effected the transport in the first place. This is especially important against the background of supply chains and complex production processes, where reliability can be even more important than transportation time or speed. In addition to that, dependencies between container delay and transshipment process times can further be analyzed.

The model can also be a starting point for studies on both train- and container-routing. As of now, the model did not yet have dynamic intermodal routing implemented, as already possible for passengers in SUMO. By adopting this to containers, constant rerouting and changing the initial plan of containers can be examined. This could help to more dynamically assign free yard capacities. The model proposed might also help to deepen the understanding of sea harbor hinterland traffic in the sense of pondering harbor-, yard- and railway capacities against each other.

Lastly, the model could enable a feedback loop between operation and planning and thus converge two traditionally separate levels of realizing transportation directly on the level of larger networks.

# Acknowledgements

The authors would like to thank Jakob Erdmann from the German Aerospace Center, Berlin, for his support and help with both railway-specific and general SUMO modeling.

# Declarations

**Conflict of interest:** The authors declare that they have no conflict of interest.

**Data availability**: integrated clock-face timetable data for Germany is publicly available at https://www.mcloud.de/web/guest/suche/-/results/detail/1F36C20A-265A-4A4E-8DEC-863DDBC5C1DF

**CRediT author statement: Jakob Geischberger:** Study conception and design, Methodology, Conduction of analysis, Manuscript preparation and review **Norman Weik:** Advice on methodology, Manuscript preparation and review

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