SIMULATING THE IMPACT OF INTER-REGIONAL RAIL DISRUPTIONS

Christian Fikar[(a)], Manfred Gronalt[(b)]

[(a),(b)] University of Natural Resources and Life Sciences, Vienna, Institute of Production and Logistics, Feistmantelstraße 4, 1180 Vienna, Austria

[(a)] christian.fikar@boku.ac.at, [(b)] manfred.gronalt@boku.ac.at

ABSTRACT

Rail disruptions can have severe consequences on inter-regional supply chains. To investigate such impacts and the resulting delays of shipments, this work introduces a simulation-based decision support system to model rail disruptions and corresponding supply chain vulnerabilities. Therefore, to enable a quick modeling approach and the generation of multiple disruptions scenarios, openly available road and rail network data are combined with simulation tools and open source routing and graph-theory libraries. This enables to automatically generate a high-level rail network to investigate various settings. As a result, critical links and industrial locations at risk are identified and decision-support is given.

Keywords: rail vulnerabilities, disruptions, simulation model, decision support system

1. INTRODUCTION

Rail networks are highly vulnerability to a wide-range of internal and external risks. Examples include natural disasters or extreme weather events such as earthquakes, mudslides or avalanches as well as man-made disasters. Impact on industrial locations of such events can be severe and may result in substantial increases in lead times and potentially even shortages in supply. As such disruptions occur with a low frequency; however, results in high damages, preparedness is further difficult to achieve. To improve such critical preparedness, modeling and simulation allows to improve supply chain resilience, improves understanding of supply chain risks and further enables to test various risk scenarios (Longo and Ören 2008).

In the context of rail disruptions and the resulting impact on supply chains, Fikar et al. (2016) introduce a decision support system (DSS) to simulate inter-regional rail networks. The provided computational experiments focuses on industrial locations in Tyrol, Austria and further enables transshipment at various terminals in Central Europe. A disruption of the 'Brenner Pass' is investigated and implications based on various disruptions scenarios are discussed. Expanding on this DSS, this work gives implementation details on the rail network generation based from openly available network data, introduces simulation components to model rail disruptions and further presents ways to incorporate extensions to the model. Consequently, the contribution of this paper is twofold: it introduces a simulation-based DSS to model the impact of inter-regional rail disruptions facilitating openly available network data and further provides guidance for the implementation of various extensions.

The remainder of this work is structured as follows: Section 2 introduces related literature with a focus on simulation literature. The generation of rail networks with openly available rail network data is presented in Section 3. Section 4 introduces the developed simulation to model traffic and rail disruptions. Results of a computational study simulating a disruption of the 'Brenner Pass' are presented in Section 5. Section 6 discusses results and implications of this work and concluding remarks are given in Section 7.

2. RELATED LITERATURE

Rail transportation is highly impacted by disruptions as networks are sparse, limiting the possibility of alternative routes in the case of rail closures. Nevertheless, even though this high importance, relatively little work on the vulnerability of rail networks is found in the literature (Mattsson and Jenelius 2015).

To investigate rail networks and rail disruptions, multiple authors use simulation approaches. Burgholzer et al. (2013) develop a traffic microsimulation to analyze disruptions in intermodal transport networks considering rail, road and inland waterways. Therefore, the authors apply both agent-based and discrete-event based simulation and facilitate various events to trigger changes in the system. In contrast to our work, the network has to be specified manually in advance and no impact on industrial locations in the study area is investigated. Rodríguez-Núñez and García-Palomares (2014) focus on the vulnerability of public transport networks. Therefore, the metro systems of Madrid is modeled and various random disruption scenarios are simulated to identify critical links in the system. Jansons et al. (2015) use Monte-Carlo multidimensional statistical modeling to model transportation risks. Various modes of transportation including rail shipments are considered to derive insurance-related premiums and the impact on cargo costs. In Gronalt and

Schindlbacher (2015), an agent-based simulation is presented to investigate intermodal freight transportation networks. Therefore, road and rail links as well as terminal operations are extensively modeled; however, in contrast to our work, no analysis of railway disruptions is included.
Beside the usage of simulation models, other common methods to study rail disruptions include optimization procedures (e.g., Peterson and Church 2008; Azad et al 2016) as well as semi-empirical methods (e.g., Dawson et al 2016).

3. RAIL NETWORK GENERATION

To generate the rail network, the DSS requires an input file specifying terminals and industrial locations with a railway sidings in the study area. Furthermore, a network file acquired from OSM (2016), preferably filtered to exclude redundant data such as walking and bike paths, has to be specified. This openly-available network includes both rail and street segments and is used in the DSS to generate a routing graph. Therefore, the open source routing library GraphHopper (2016) is facilitated.
In the first step, all terminals and industrial locations are geocoded and the network data is imported. Based on the coordinates of the locations, shortest paths between all locations on the rail network are calculated. In the following step, to exclude duplicate routes, each path is checked if it crosses any of the geocoded locations. If so, the path is removed. On the remaining paths, every single point of the route is compared to all points on other routes. If two paths merge or diverge at the same point, this location is stored as an intersection, the corresponding paths are split and the duplicates are removed. As a result of this procedure, each unique railway path between two intersections is modeled as an individual railway link, i.e. to travel between two locations, the train potentially passes multiple railway links crossing various intersections. This is required to consider capacity of the railway link in the simulation. In a final step, to model alternative routes in case of a disruption, the same procedure is repeated considering that each link is currently not available due to a disruption. Therefore, the weight of the link in the network is set to infinity. As a consequence, the shortest path does not contain this link, but instead takes the fastest alternative route. After all additional paths and intersections are added, the list of railway links and intersections is saved.
To reduce the set-up time, this data is imported at the start of each simulation experiments. At the start of a simulation run, a directed weighted graph is generated from the imported list of paths and intersections. Therefore, each path represent an arc in the graph, associated with the travel duration derived by GraphHopper (2016), while each intersection and imported location represent a vertex. This graph is used in the simulation to decide on routing decisions of each shipment.

To summarize, the following steps are performed to automatically generate the rail network from openly available network data:

1. Geocode locations and load network data.
2. Calculate shortest paths between each location.
3. Remove paths crossing any other location between origin and destination.
4. Find and add intersections between the remaining shortest paths.
5. Calculate alternative routes and add new paths and intersections.
6. Save paths and intersections to generate the routing graph for the simulation at the start of each simulation run.

Depending on the size of the study area, a symmetric or asymmetric representation can be selected. While the earlier allows one to reduce memory requirements and speeds up the generation of the rail network, the latter enables a more detailed modeling of rail capacities by considering driving directions. In our implementation, an asymmetric representation was selected.

3.1. Intermodality

To enable the option of switching the mode of transportation as a result of a rail disruptions, the routing graph is further extended by road links. Therefore, each shortest path on the road network between two locations is calculated and an arc for each connection is added to the graph. In our implementation, no capacities on the street network are considered. To model transshipments, additional arcs at the terminals are added. These arcs enable switching from the road to the rail network or vice versa. To consider time delays, the weight is set based on expected transshipment times at the terminal.
The same procedure can further be utilized to generate various mode of transportation such as inland waterways if network data is available.

4. DISRUPTION SIMULATION

Based on the generated rail network, a traffic simulation was developed to investigate the impact of disruptions (Fikar et al. 2016). Therefore, both elements from agent-based simulations, to model railway links as well as shipments and vehicles, and from discrete event simulations, to model queues at crowded railway segments and terminals, were incorporated.

4.1. Agent-based Modeling

Each arc in the graph is modeled as an agent. Therefore, the agent is specified with a capacity as well as with the calculated expected travel duration. To model rail movements, a FIFO-queue is assumed, i.e. the train which arrived first, is processed first and if the process is fully utilized, the remaining shipments wait. A similar approach is further implemented to model transshipments at terminals, for which only a limited number of resources are available to perform such tasks.
To generate freight movements, each industrial location requests, based on a Poisson-distributed arrival rate,

shipments from uniformly random terminal locations. Additionally, to set up a base utilization of the rail network, random transit shipments as well as passenger trains are added to the rail network. Therefore, it is assumed that passenger trains are always prioritized in the queues. Furthermore, a day-night cycle is implemented to consider the fact that less passenger trains travel at night by dynamically adjusting arrival rates.

4.2. Modeling of Rail Disruptions

To model disruptions, the simulation further includes an agent for each disruption. This agent is initialized with the coordinates of the disruption as well as a start and end time. These times trigger an event to start or end the disruption and to adjust the weight of the corresponding disrupted railway link, e.g. to set the travel duration on the arc to infinity in case of a complete closure. In the case of the start of a disruption, all agents currently on the railway link or in the queue, are rerouted. Therefore, as shown in Figure 1, the shipment agent can either wait at the disrupted railway link until the disruption is over or travel on an alternative route, which potentially includes a transshipment to the road network.

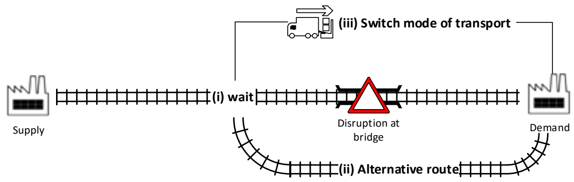

Figure 1: Potential agent decisions to a disruption

4.3. Modeling of Routing Decisions

In the simulation, it is assumed that each shipment aims to minimize its travel time to the destination and further has no knowledge on the planned routes of other shipments in the system; however, complete information on the current situation as well as the disruption duration is present. To perform routing decisions, each time a shipment agent reaches an intermediary stop, e.g., an intersection or a terminal, the agent calculates the remaining shortest path to the final destination and performs the next link on the derived route.

To consider utilization in the network, the corresponding weight of each railway link is constantly updated depending on the current number of agents waiting in the queue. Furthermore, in the case of a disruption, the remaining time until the disruption is over is added to the weight of the arc. As a consequence, the shipment either waits for the disruption to be over or travels a detour on open arcs, potentially including transshipments at terminals.

4.4. Modeling of Rail Restrictions

In the OSM data, various railway links are included. These are further specified with keys indicating the type of railway as well as specific features such as if the corresponding link is electrified or passenger-only. In specific cases, it can be of interest to exclude certain links as these are not relevant for the simulation experiments. This is enables in the DSS by simply setting a disruption, which is active for the entire simulation horizon, to the restricted link. As a consequence, both the rail network generation and the traffic simulation do not consider this link.

Additionally, it can be possible that certain trains are not enabled to traverse specific railway links, while other trains can. Potential reasons include operational restrictions such as gauges and the slope of the railway link as well as various regulative restrictions, e.g., driving bans for hazardous material. Therefore, each shipment agent is initiated with a list of restricted railway links based on the vehicle and shipment type. Before the routing is performed, these links on the routing graph are set to infinity. As a result, the routing algorithm calculates the shortest path on enabled railway links, while restricted links for this train are excluded from the routing procedure. After the calculation is performed, restricted arcs are reset to the initial value to reopen this connections for the following routing requests.

4.5. Modeling of Transshipment Restrictions

Additional restrictions may occur due to limited transshipment possibilities at terminals, e.g., due to a lack of specific equipment required to transship certain cargo types. To model such requirements, a similar approach as presented in the previous subsection is implemented. Therefore, each train is initialized with a list of restricted terminals and restricted arcs are set to infinity before the shortest path is calculated.

5. COMPUTATIONAL EXPERIMENTS

The simulation was developed with AnyLogic 7.2 (AnyLogic 2016) with network data from OSM (2016) to represent both road and rail networks. GraphHopper 0.4 (2016) was used to generate routing graphs and to calculate initial arc weights. The graph within the DSS was implemented with the Java library JGraphT (2016).

In the following part, results based from a study on the impact of a sudden closure of the alpine mountain range ‘Brenner Pass’, which connects Austria with Italy, are presented. The study area with a disruption of the Brenner Pass is shown in Figure 2.

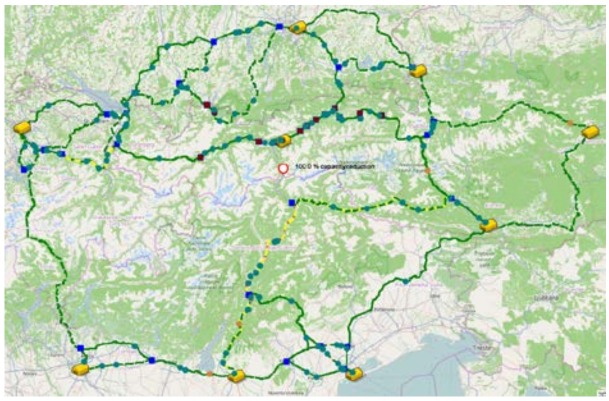
Figure 2: User interface showing the study region

To evaluate a disruption, the average disruption delay time (ADDT) is calculated, which states by how much time shipments are on average delayed (Burgholzer et al. 2013). Therefore, the actual travel duration is compared to the theoretical travel duration derived on the shortest path considering no wait times. Without disruptions of railway links, delays result from wait times at railway links due to insufficient capacity. In all scenarios, the simulation starts at midnight and simulates a full day to generate a base utilization. The disruption starts occurring at 11 am on the second day and lasts for a user-defined duration. Additionally, a full day after the disruption is over is simulated to consider the ramp-down period in which the system restabilizes. The impact of a 24 disruption scenario is shown in Figure 3. Therefore, the ADDT is reported with a single data point representing all shipments, which started in the stated hour, i.e. a value of 20 includes all shipments, which left a supply agent between 8 pm and 9 pm on the first day. All simulation experiments were executed with 250 replication runs and average values are reported in this section. Fluctuations are a result of the stochastic components of the individual simulation runs.

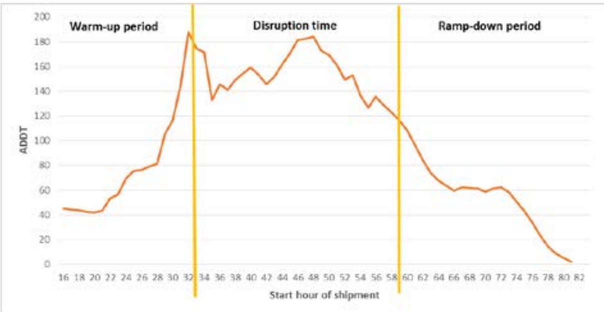

Figure 3: Development of the ADDT of all shipments started in the stated hour considering a 24-hour disruption of the Brenner Pass.

The results show that, as a consequence of the disruption, shipments are substantially delayed. Compared to a situation before or after the disruption, lead times are increased by up to 4.5 times. Additionally, even shipments, which are starting after the disruption is over, are severely affected as indicated in the first hours of the ramp-down period. As the system is overutilized as a consequence of the disruption, it takes multiple hours until the rail network restabilizes and delays are reduced.

In contrast, Figure 4 shows the development of the ADDT for a 72 hour disruption scenario.

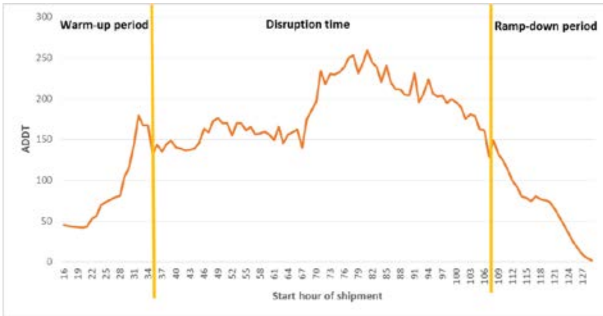

Figure 4: Development of the ADDT of all shipments started in the stated hour considering a 72-hour disruption of the Brenner Pass.

Similar to the 24-hour scenario, high delays result for shipments generated shortly before the disruption started. These shipments are travelling on the regular path and, due to the sudden disruption, required to perform costly rerouting actions. Shipments generated after the disruption occurred have more flexibility in the routing choices and can perform wide-ranging detours. Nevertheless, in case of a long disruption duration, the higher utilization at the alternative routes results in additional wait times, leading to a higher ADDT. As in the 24-hour scenario, at the end of the disruption, the system restabilizes.

In Figure 5, the impact of a disruption on the individual industrial locations in Tyrol is shown. Due to confidentially issues, all locations are anonymized.

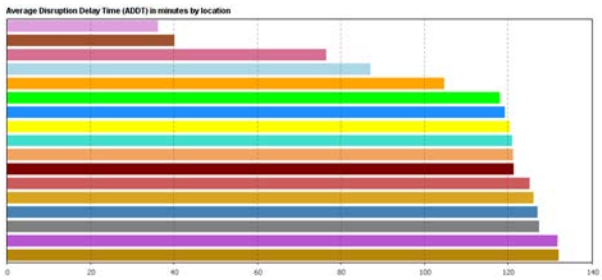

Figure 5: Impact of a 24-hour Brenner Pass disruptions for industrial locations located in Tyrol, Austria.

Depending on the geographic location as well as the individual shipping volumes, some industrial locations are more affected by a disruption. The simulation assists to identify such locations and further gives implications on the impact of various disruption scenarios.

6. DISCUSSION

Disruptions in rail networks can result in substantial delays. To quantify the impact on individual industrial locations as well as on the overall system, simulation is crucial. It allows investigating various disruption scenarios and further enables to test different policies and counter-measures. For instance, by simulating various scenarios, increased capacity as well as the impact of additional terminals or railway links can be analyzed. As a result, improved understanding on the impact of inter-regional rail disruptions is gained and preparedness can be improved.

To counteract rail disruptions, various strategies exists. Common measures to react to transport disruptions include: (i) take alternative routes, (ii) switch mode of transportation, (iii) wait for the disruption to be over or (iv) change to an alternative supplier (Georgia Tech Research Corporation, et al. 2012). While the first three options are included in the method introduced in this work, the fourth is more challenging to implement due to a lack of data and difference between individual industries. Nevertheless, as the focus is set on the critical hours and days after a sudden disruption occurs, it is unlikely that changes in suppliers, which are commonly pursued as a result of long-term disruptions, have a major impact on the shipping volumes assumed in the computational experiments.

7. CONCLUSSION

Combining openly available network data with simulation methods to investigate the impact of rail disruption allows a quick and flexible generation of different scenarios. This allows to identify critical links in the network as well as impacts of disruptions on various industrial and terminal locations in the study area. While this is an important first step to improve understanding of and preparedness to supply chain risks, future work is required to increase the potential of such methods for real-world applications. This includes the investigation of different rerouting policies or the development of optimization procedures to lower the total disruption delay time of all agents in the system.

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AUTHORS BIOGRAPHY

Christian Fikar is a post-doctoral researcher at the Institute for Production and Logistics (PWL). His research fields include logistics, supply chain management and related decision support systems to investigate and optimize delivery processes, particularly in the food industry. He received his Master degree in Supply Chain Management from Vienna University of Economics and Business and Doctoral degree in Social and Economic Sciences at University of Natural Resources, Vienna.

Manfred Gronalt is a Professor and Head of PWL. His expertise lies within production management, logistics and simulation. Up to now, he authored over 100 scientific journal articles and conference contributions. He is a member of ÖGOR (Austrian society of operations research) and the Academic Association for Business Research (VHB).